Spatio-temporal Variation of Soil Respiration and Its Driving Factors in Semi-arid Regions of North China

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Abstract: Soil respiration (*SR*) is the second-largest flux in ecosystem carbon cycling. Due to the large spatio-temporal variability of environmental factors, *SR* varied among different vegetation types, thereby impeding accurate estimation of CO_2 emissions via *SR*. However, studies on spatio-temporal variation of *SR* are still scarce for semi-arid regions of North China. In this study, we conducted 12-month *SR* measurements in six land-use types, including two secondary forests (*Populus tomentosa* (PT) and *Robinia pseudoacacia* (RP)), three artificial plantations (*Armeniaca sibirica* (AS), *Punica granatum* (PG) and *Ziziphus jujuba* (ZJ)) and one natural grassland (GR), to quantify spatio-temporal variation of *SR* and distinguish its controlling factors. Results indicated that *SR* exhibited distinct seasonal patterns for the six sites. Soil respiration peaked in August 2012 and bottomed in April 2013. The temporal coefficient of variation (*CV*) of *SR* for the six sites ranged from 76.98% to 94.08%, while the spatial *CV* of *SR* ranged from 20.28% to 72.97% across the 12-month measurement. Soil temperature and soil moisture were the major controlling factors of temporal variation of *SR* in the six sites, while spatial variation in *SR* was mainly caused by the differences in soil total nitrogen (STN), soil organic carbon (SOC), net photosynthesis rate, and fine root biomass. Our results show that the annual average *SR* and Q_{10} (temperature sensitivity of soil respiration) values tended to decrease from secondary forests and grassland to plantations, indicating that the conversion of natural ecosystems to man-made ecosystems may reduce CO_2 emissions and *SR* temperature sensitivity. Due to the high spatio-temporal variation of *SR* in our study area, care should be taken when converting secondary forests and grassland to plantations from the point view of accurately quantifying CO_2 emissions via *SR* at regional scales.

Keywords: soil respiration; spatio-temporal variation; substrate availability; temperature sensitivity; global carbon cycle; North China

1 Introduction

Studies on carbon cycle have received growing attention in recent years (Wang et al., 2006; Piao et al., 2009a). Soils are the largest carbon reserve in terrestrial ecosystems, and small changes in soil carbon pool size can therefore strongly influence the global carbon budget (Batjes, 1996; Bellamy et al., 2005). Soil respiration (*SR*) is considered as the second largest carbon flux (next to gross primary productivity) between terrestrial ecosystems and the atmosphere (Bahn et al., 2008; Peng et al., 2008). However, due to the large flux, soils are also regarded as the largest source of uncertainty in the terrestrial carbon balance (Piao et al., 2009b). Any

changes in soil CO_2 efflux could have profound influences on atmospheric CO_2 concentration, and potentially aggravate climate warming (Don et al., 2011; Song et al., 2013). Therefore, accurately quantifying CO_2 emissions through *SR* is crucial to understand climate change and global carbon dynamics.

Soil respiration is a complex process which is affected by many factors (Peng et al., 2008; Lai et al., 2012), of which soil temperature is the most significant one and explains most of the variation in *SR* (Wan et al., 2007; Luo et al., 2012). Several studies have found strong exponential relationships between *SR* and soil temperature in different ecosystems (Sheng et al., 2010; Tong et al., 2012). Temperature sensitivity of soil respiration (Q_{10}), defined as the increment of soil respiration rates with an increase of temperature by 10℃, has been widely used to evaluate the response of *SR* to global climate warming (Reichstein et al., 2005b; Peng et al., 2009). The factor Q_{10} is not constant and varies widely among different ecosystem types or different vegetation types within an ecosystem (Lavigne et al., 2003; Zheng et al., 2009). It can be affected by a variety of factors, including temperature range, soil water availability, root biomass, microbial populations, and substrate availability (Ryan and Law, 2005; Davidson et al., 2006; Mahecha et al., 2010).

Soil moisture is also an important factor affecting *SR* (Liu et al., 2011; Zhang et al., 2013). However, the relationship between *SR* and soil moisture is generally weaker, but more complex compared to that between *SR* and soil temperature (Sheng et al., 2010; Lai et al., 2012). Low soil moisture potentially limits soil microbial activity and photosynthesis rates through stomatal regulation, while high soil moisture reduces air-filled porosity, limiting soil CO_2 diffusion rates (Maier et al., 2011; Song et al., 2013). In addition, other factors such as substrate availability (e.g., carbon allocation patterns, SOC, and nutrient storages), belowground metabolism (e.g., root biomass and root turnover rate), and aboveground metabolism (e.g., stand photosynthesis, net primary productivity, and litter input) may also strongly influence *SR* dynamics (Tang et al., 2005; Monson et al., 2006; Wang et al., 2006). These environmental factors vary greatly with vegetation types, leading to significant variation of *SR* among different ecosystems (Sayer et al., 2007; Martin and Bolstad, 2009; Wang et al., 2013). Studies have shown that different ecosystem types or even different vegetation types within an ecosystem had different *SR* values (Luo et al., 2012; Oishi et al., 2013). Therefore, to improve the precision of carbon budget estimation at a regional scale, determining *SR* values across different ecosystems as well as evaluating spatio-temporal variations of *SR* and its controlling factors is crucial under the scenario of global climate change.

The Taihang Mountains cover an area of approximately 42% of northern China (Han et al., 2012). The primary forest in the Taihang Mountains is mainly composed of a mixture of coniferous and deciduous broad-leaved tree species, such as *Larix princi-pis-rupprechti*, *Betula platyphylla*, *Quercus variabilis*, *Quercus wutaishanica*, and *Populus tomentosa* (Li et al., 2013). Since the 1960s, due to the expanding population and economic development, vegetation types in this area have been subjected to significant changes. One of the main factors is large-scale deforestation or industrial logging, replacing substantial amounts of primary forest with secondary forest and cropland or economic plantations (Yang et al., 2009). Currently, secondary forests in this region are mainly composed of *Robinia pseudoacacia* and *Populus tomentosa*, whereas economic plantations are dominated by *Armeniaca sibirica*, *Ziziphus jujuba*, *Punica granatum*, *Diospyros kaki*, and *Carya cathayensis*. Tremendous changes of vegetation strongly influence soil carbon efflux and regional carbon cycling, hampering accurate predictions of the regional carbon budget (Shen et al., 2014). However, studies on soil respiration and its controlling factors after land use change in Taihang Mountains are still scarce. Therefore, the overall objective of our study was to examine spatio-temporal variations and correlations of *SR* with environmental factors in different vegetation types of Taihang Mountains. Our specific objectives were to: 1) quantify temporal variation of *SR* within each vegetation site and spatial variation of *SR* among different vegetation types; 2) explore the major drivers for temporal and spatial variations in *SR*; 3) determine whether Q_{10} varied among different vegetation types.

2 Materials and Methods

2.1 Study area

This study was conducted at the Hilly Ecology Experimentation Station (114°13′–114°16′E, 37°53′–37°56′N,

350 m a.s.l) of the Chinese Academy of Sciences, located in the hilly region of Taihang Mountains, North China (Fig. 1). The area has a semi–arid continental climate with an annual average air temperature of 13.2℃. Minimum and maximum mean air temperature is –1.6℃ in January and 26.3℃ in July, respectively. Mean annual precipitation is 570 mm, of which 65% falls between July and September, and mean annual evapotranspiration is 1934 mm (Zeng et al., 2014). The soil parent material is mainly granitic gneiss with relatively small amounts of shale and limestone. The soil is classified as Cinnamon soil according to the Chinese soil classification (State Soil Survey Service of China, 1998), equivalent to Ustalf in the USDA Soil Taxonomy (Soil Survey Staff, 1999). The average < 0.01 mm soil particle fraction for Cinnamon soil is 28.1%, which is a loam with a textural composition of 51.5% sand, 34.5% silt and 14.0% clay (Zhou and Zhang, 2012). Vegetation is currently comprised of deciduous shrubs, herbs, secondary forest, and economic plantations.

2.2   Experimental design and measurement

According to the dominant natural and man-made vegetation in this region, we selected six study sites, including two secondary forests (PT and RP), three economic plantations (AS, PG and ZJ), and one natural grassland (GR) to conduct our experiment. The PT and RP forests developed from abandoned land after deforestation of natural forest had regenerated naturally for about 30 years since the 1980s. The AS, PG, and ZJ sites have been established on natural grasslands 10 years ago with tree densities of 1111, 1111, and 2500 trees/ha, respectively. No management practices were carried out in PT, RP, and GR sites, while several management practices, such as mechanical weeding and pruning, were implemented in AS, PG, and ZJ sites. Besides, no irrigation and fertilization were applied to the six land-use types. Three randomly selected experimental plots (20 m × 20 m) with similar aspects and altitudes were set up in each site. In each plot of the secondary forests and plantation sites, we measured height (H), diameter (breast height
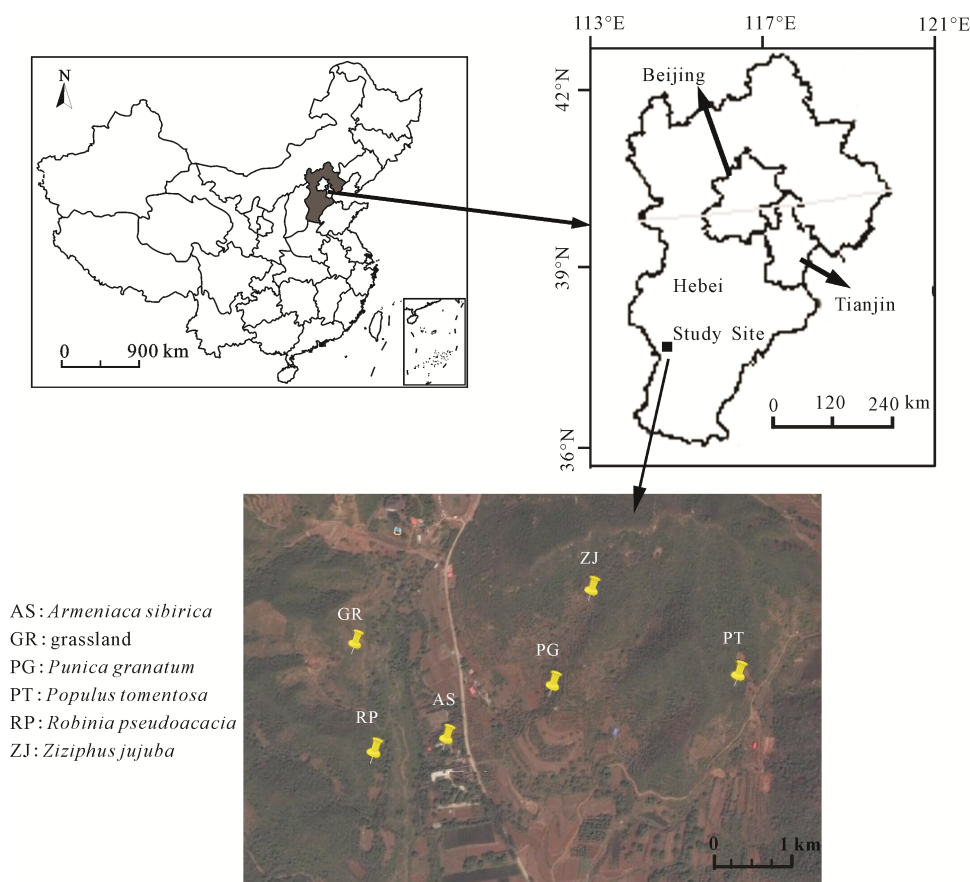

AS : *Armeniaca sibirica*
GR : grassland
PG : *Punica granatum*
PT : *Populus tomentosa*
RP : *Robinia pseudoacacia*
ZJ : *Ziziphus jujuba*

Fig. 1   Geographic location of study area and study sites in study area

Table 1 Characteristics of six different site types in Taihang Mountains, North China

Variable	Age (year)	Density (trees/ha)	Canopy density	SOC (g/kg)	STN (g/kg)	Average growth status	Dominant understory species
Populus tomentosa	30	750	0.65	16	1.20	H: 9.50 m DBRH: 12 cm CA: 1.80 m × 2.10 m	1, 2, 3
Robinia pseudoacacia	30	900	0.70	10.72	0.95	H: 5.50 m DBRH: 3.80 cm CA: 1.80 m × 1.60 m	3, 4
Armeniaca sibirica	10	1111	0.60	9.33	0.81	H: 4.50 m DBAH: 7.50 cm CA: 2.20 m × 2.50 m	3, 5, 6
Punica granatum	10	1111	0.55	6.95	0.61	H: 3.50 m DBAH: 7.20 cm CA: 2.00 m × 2.30 m	2, 3
Ziziphus jujuba	10	2500	0.50	7.40	0.75	H: 4.20 m DBAH: 6.20 cm CA: 1.50 m × 1.80 m	2, 6
Grassland				11.21	1.04	H: 0.90 m	2, 3, 4, 7

Notes: H is plant height, DBRH is diameter at breast height, DBAH is diameter at base height, and CA is canopy area. 1, *Vitex negundo*; 2, *Dendranthema indicum*; 3, *Setaria viridis*; 4, *Artemisia sacrorum*; 5, *Chenopodium album*; 6, *Cleistogenes chinensis*; 7, *Bothriochloa ischaemum*

diameter for PT and RP, and basal height diameter for AS, PG, and ZJ), and canopy area (CA) of each tree as well as canopy density. Within each plot of the six sites, three 1 m × 1 m subplots were established to determine dominant understory species. Site characteristics and understory vegetation composition of the six sites are summarized in Table 1.

During the growing season between June and September 2012, soil sampling was performed once a month. For this, we randomly dug three soil pits in each plot. In each pit, we collected 100 cm^3 soil columns at depth layers of 0–10, 10–20, 20–40 and 40–60 cm to determine soil bulk density. In addition, we sampled 500 g soil from each layer for laboratory analysis. The soil samples were air-dried and crushed before being passed through a 0.25 mm sieve prior to analyses. Soil organic carbon (SOC) was measured using Walkley-Black's method (Walkley and Black, 1934), soil total nitrogen (STN) was determined via the Semimicro-Kjeldahl method (Bremner and Mulvaney, 1982), and soil pH was measured with a pH meter as described by Lu (1999).

Within each plot, three polyvinyl chloride (PVC) collars (8 cm × 20 cm i.d.) were randomly installed for *SR* measurement. Soil respiration was measured twice a month from June 2012 to May 2013 (only one time in February), using an automated soil CO_2 flux system (Li-8100, Li-Cor Inc., Lincoln, NE, USA) equipped with a Li-Cor 8100-103 chamber. The PVC collars were inserted 3 cm deep into the soil and remained there throughout the measurement period. The plants within the collars were regularly clipped at ground level, and litter inside the collars was removed before measurement. Soil respiration was measured twice a month between 09:00 and 13:00 on each sampling day. Mean *SR* values for each collar is the average of three values generated from three continuous cycles at each collar. At the time of *SR* sampling, soil temperature (*ST*) at a depth of 10 cm and soil moisture (*SM*) at a depth of 5 cm were monitored simultaneously near each collar using a temperature sensor and a moisture sensor attached to the Li-8100, as per the method of Song et al. (2013).

Fine root biomass was determined according to the method described by Shi et al. (2009). The fine root (< 2 mm diameter) at four soil depths (0–10, 10–20, 20–40 and 40–60 cm) were sampled in the vicinity of the soil collars monthly from June to September 2012 using a soil auger (5 cm in diameter) with a sharpened edge. Twelve soil cores from the same soil layer in each plot were randomly collected and combined to form a composite soil sample. Soil samples were then placed into a metal screen with 0.1 mm mesh, soaked and washed with tap water. Fine roots were then carefully picked out using tweezers. Roots samples were oven dried at 65°C until a constant weight was recorded.

Three litter traps (1 m × 1 m) with 1 mm nylon mesh

were randomly arranged about 0.4 m above the soil surface in each plot except for the GR site. Litter samples were collected every month from June 2012 to May 2013 according to the method described by Yang et al. (2004).

Net photosynthetic rate was measured once every ten days between 10:00 and 12:00 from June to September 2012, using a portable gas exchange system (Li-6400, Li-Cor Inc., Lincoln, NE, USA). At each measurement time point, three healthy and fully expanded leaves were chosen in situ in each plot. Mean photosynthesis value for each leaf is the average of three values generated from three continuous records on each leaf.

2.3 Data analysis

Linear and nonlinear regression functions were used to describe the correlations of soil respiration with soil temperature and soil moisture:

$$SR = \alpha e^{\beta \cdot ST} \tag{1}$$

$$SR = m \cdot SM + n \tag{2}$$

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

where SR is the soil respiration rate ($\mu mol/(m^2 \cdot s)$), ST is the soil temperature at 10 cm depth (℃), SM is the soil moisture at 5 cm depth (%), and α, β, m, n, a, b and c are the regression coefficients.

The Q_{10} value was calculated according to the following equation:

$$Q_{10} = e^{10\beta} \tag{4}$$

The temporal and spatial variability in soil respiration were quantified by coefficient of variation (CV):

$$CV = \text{Standard deviation/mean} \times 100\% \tag{5}$$

Temporal variability in SR was based on the data of the whole experiment period (from June 2012 to May 2013) for each site, and spatial variability in SR among the six sites was based on the data at individual time points (23 collection dates from June 2012 to May 2013).

All statistical analyses were performed using SPSS software (SPSS 16.0 for windows, SPSS Inc., Chicago, IL, USA). Before analysis, all variables were checked for normal distribution and homogeneity of variance. One-way ANOVA with Duncan's multiple range test was used to check the differences of SR, ST and SM

among different vegetation sites, and values for SR, ST and SM were derived from 23 collection dates twice a month from June 2012 to May 2013. Q_{10} values were estimated using yearly data sets for each vegetation site. A linear regression was further applied to model the relationships between SR and total annual litter, ST, SM, SOC, STN, pH, fine root biomass, net photosynthetic rate and bulk density among the six sites (Values for SR, ST, SM, SOC, STN, pH, fine root biomass, net photosynthetic rate and bulk density were monthly averaged values from June to September 2012). The significant level was set at $P < 0.05$. All graphs were plotted using Origin 8.5 software.

3 Results

3.1 Temporal variation in soil respiration within each site

As is shown in Fig. 2A, the temporal variation of SR showed a similar single-peak pattern for all six sites from June 2012 to May 2013. In the growing season, SR rates were significantly higher than that in the non-growing season; they peaked in August 2012 with the maximum rate of 5.74 $\mu mol/(m^2 \cdot s)$ in PT site; whereas lowest values were measured in early April 2013 with the minimum rate of 0.15 $\mu mol/(m^2 \cdot s)$ in RP site. We also observed single-peak patterns of ST throughout the observation period for the six sites. Soil temperature peaked in early July with the maximum value of 26.82℃ in GR site and was lowest in January with the minimum value of –6.17℃ occurring in RP site (Fig. 2B). However, seasonality of SM fluctuated frequently and showed multiple-peak patterns for the six sites during the observation period (Fig. 2C).

The temporal coefficient of variation (CV) of SR for the six sites ranged from 76.98% to 94.08%, with the maximum value occurring in PT site and the minimum value in AS site (Fig. 3A). The temporal CV values of SR in secondary forests (RP and PT) and grassland appeared to be greater than those in plantation sites (PG, ZJ, and AS), but CV was slightly lower in RP site than in PG site.

3.2 Temporal SR related to soil temperature and moisture

The seasonal SR exhibited a positive exponential correlation with ST at a depth of 10 cm for all the six sites,
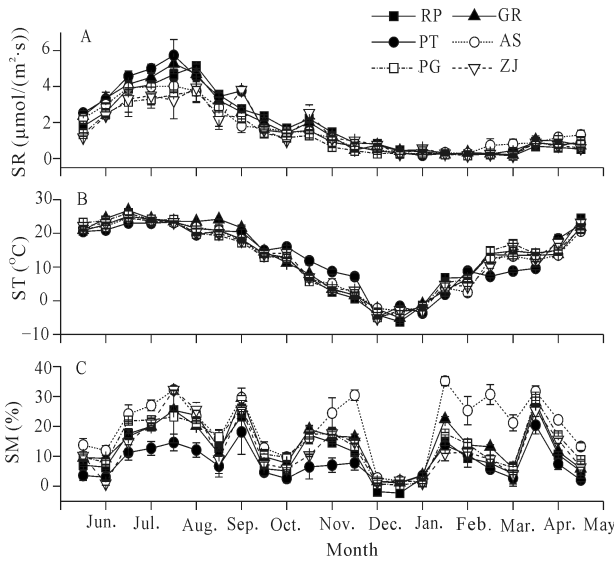
Fig. 2 Temporal dynamics of soil respiration (*SR*) (A), soil temperature (*ST*) (B) and soil moisture (*SM*) (C) for the six vegetation types. Error bars represent standard errors (*n* = 9). PT, *Populus tomentosa*; RP, *Robinia pseudoacacia*; PG, *Punica granatum*; ZJ, *Ziziphus jujube*; AS, *Armeniaca sibirica*; GR, Grassland
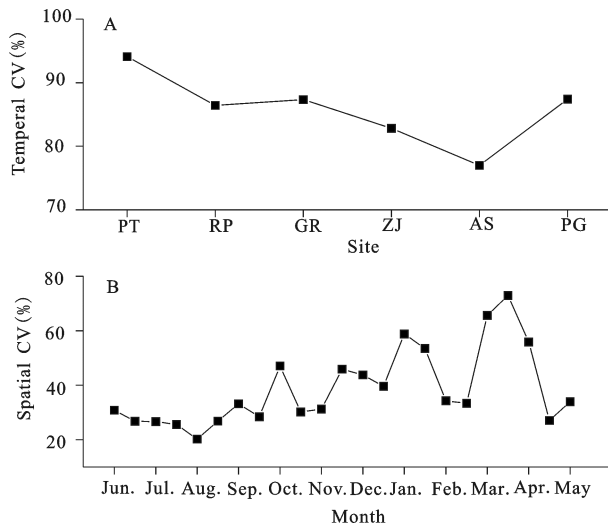

Fig. 3 Temporal and spatial coefficient of variation (*CV*) of soil respiration. (A) Temporal *CV* of soil respiration for the six vegetation types; (B) Spatial *CV* of soil respiration among the six vegetation sites during the experimental period. PT, *Populus tomentosa*; RP, *Robinia pseudoacacia*; PG, *Punica granatum*; ZJ, *Ziziphus jujube*; AS, *Armeniaca sibirica*; GR, Grassland

with the highest coefficient in AS site (R^2 = 0.82) and the lowest in RP site (R^2 = 0.26) (Fig. 4). The apparent Q_{10} value against *ST* varied among different vegetation types (Table 2). In general, Q_{10} values in secondary forests (3.05 and 2.52 for PT and RP, respectively) and GR site (2.61) were higher than those in plantations (2.16,

1.73 and 1.89 for PG, ZJ and AS, respectively). Meanwhile, we observed a positive linear correlation between *SR* and *SM* in these vegetation sites, except in AS site (Fig. 5). The *SM* explained 4% to 36% of temporal variation of *SR* in the six sites, and the correlation of *SR* with *SM* was relatively weaker than that with *ST*. In addition, we used *ST* and *SM* as independent variables to express the effect of interaction of *ST* and *SM* on *SR* (fit Equation 3). However, no significant increases in R^2 were found as compared with those fitted by *ST*-based models for the six sites (Equation 1) (Table 3).

3.3   Spatial variation in soil respiration among different vegetation types

Based on *SR* rates, vegetation sites were grouped into two significantly different groups (Table 2). Annual mean *SR* values in PT, RP and GR sites were significantly higher than those in PG and ZJ sites. Annual mean *SR* was highest in PT (1.91 μmol/(m²·s)), which was 39% higher than the lowest value found in PG (1.37 μmol/(m²·s)). However, there were no significant differences in annual mean *ST* values among the six sites. Annual mean *ST* was highest in GR (13.29 °C) and lowest in AS (12.45 °C) throughout the observation period. Meanwhile, annual mean *SM* had a certain difference among the sites and values ranged from 7.86% to 19.89% across the six sites (Table 2).

The spatial *CV* of *SR* among the six sites averaged 38.78% across the 12-month measurement, with a distinct seasonal pattern which showed higher values in the non-growing season than in the growing season (Fig. 3B). The highest spatial *CV* among the sites was observed in April, with a maximum value of 72.97%, whereas the lowest *CV* was found in August, with a minimum value of 20.28%.

3.4   Factors impacting spatial variation

We performed linear regression analyses to investigate the relationships between spatial variability of *SR* and some possible driving variables. In all six sites, there was no significant correlations between *SR* and *ST* or *SM* (Fig. 6A, G), which were controlling factors of the temporal variation in *SR* in each site. However, *SR* was significant positively correlated with fine root biomass (R^2 = 0.78, *P* = 0.02), SOC (R^2 = 0.89, *P* = 0.01), photosynthesis (R^2 = 0.91, *P* = 0.00), and STN (R^2 = 0.98, *P* = 0.00) (Fig. 6B, D, E, F). No significant correlation was found between SR and annual litter input (R^2 =
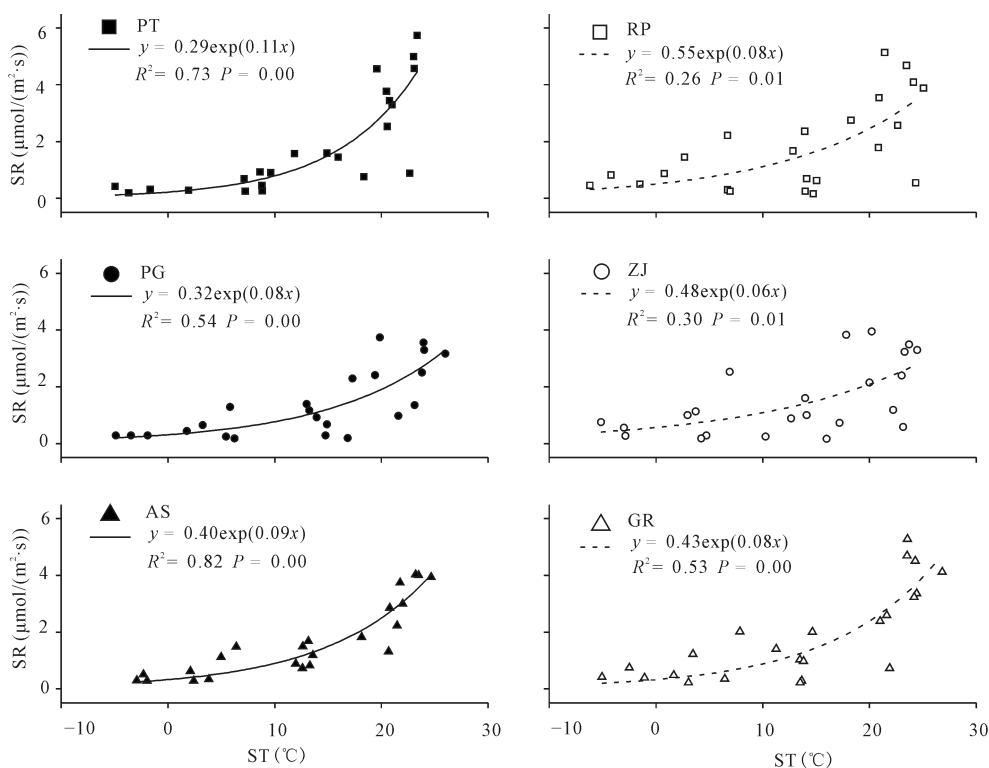
Fig. 4   Relationship between soil respiration (*SR*) and soil temperature (*ST*) at 10 cm depth for different vegetation sites. PT, *Populus tomentosa*; RP, *Robinia pseudoacacia*; PG, *Punica granatum*; ZJ, *Ziziphus jujube*; AS, *Armeniaca sibirica*; GR, Grassland

Fig. 5   Relationship between soil respiration (*SR*) and soil moisture (*SM*) at 5 cm depth for different vegetation types. PT, *Populus to-mentosa*; RP, *Robinia pseudoacacia*; PG, *Punica granatum*; ZJ, *Ziziphus jujube*; AS, *Armeniaca sibirica*; GR, Grassland
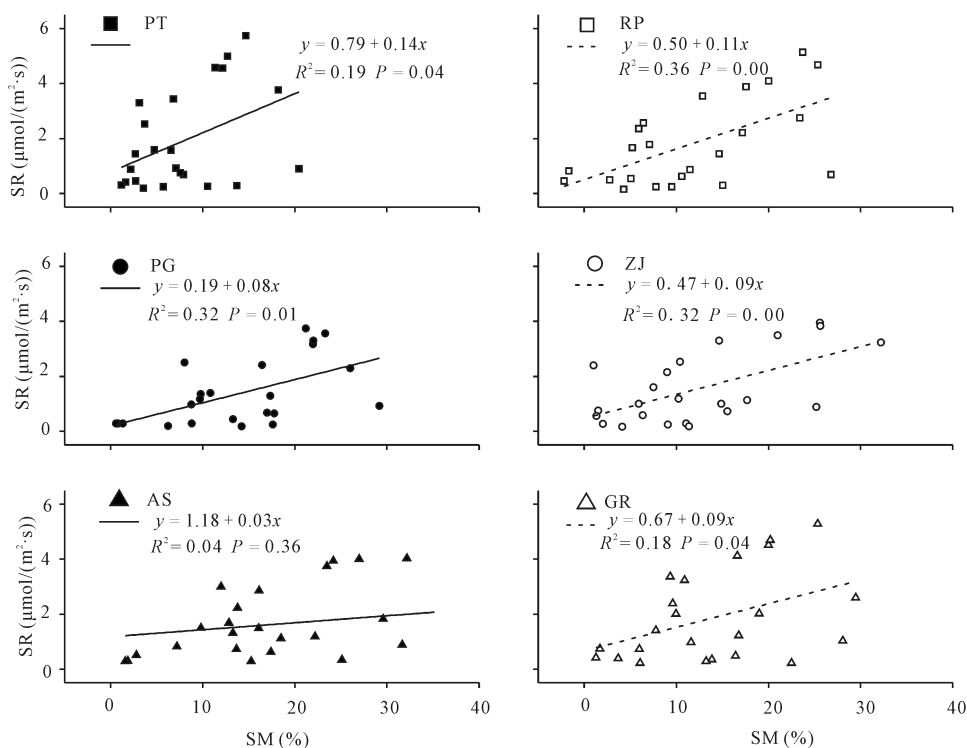
Table 2   Means of soil respiration rate (*SR*), soil temperature (*ST*), soil moisture (*SM*) and temperature sensitivity of *SR* (Q_{10}) in the six vegetation sites. Values for *SR*, *ST*, and *SM* were derived from 23 collection dates twice a month from June 2012 to May 2013. Q_{10} values were estimated using yearly data sets for each site

Vegetation type	Land use type	*SR* (μmol/(m²·s))	*ST* (℃)	*SM* (%)	Q_{10}
PT	Forest	1.91 (0.37) a	12.93 (1.88) a	7.86 (1.14) c	3.05
RP	Forest	1.81 (0.33) a	12.93 (2.03) a	11.68 (1.75) bc	2.52
PG	Plantation	1.37 (0.25) b	12.96 (2) a	13.99 (1.67) b	2.16
ZJ	Plantation	1.54 (0.27) b	12.76 (2) a	12.31 (1.84) bc	1.73
AS	Plantation	1.68 (0.27) ab	12.45 (1.91) a	19.89 (2.11) a	1.89
GR	Grassland	1.86 (0.12) a	13.29 (2.07) a	13.88 (1.67) b	2.61

Note: Numbers followed by same letters within a column for a parameter indicate no significant difference between sites at *P* < 0.05. Values in parentheses are standard errors. PT, *Populus tomentosa*; RP, *Robinia pseudoacacia*; PG, *Punica granatum*; ZJ, *Ziziphus jujube*; AS, *Armeniaca sibirica*; GR, Grassland
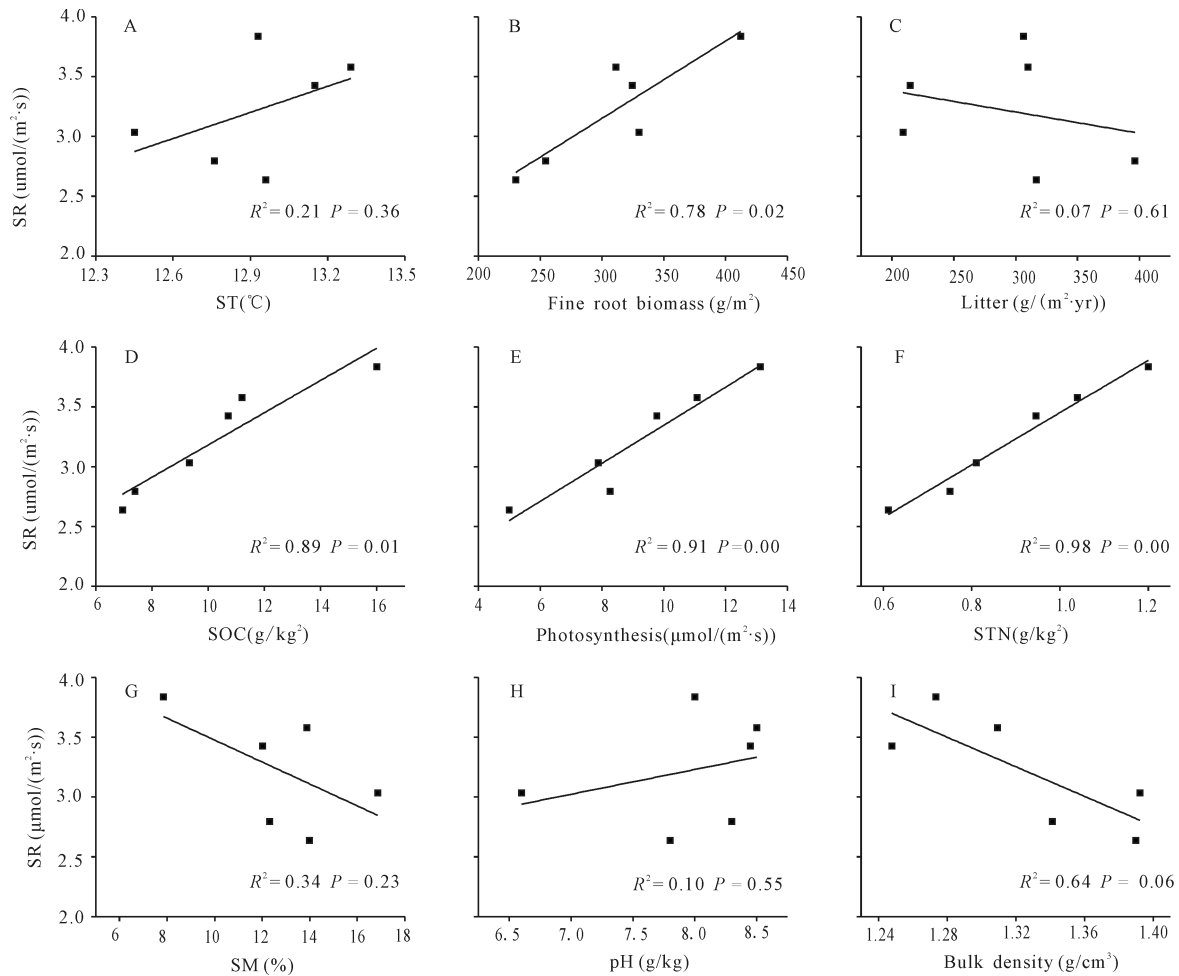
Fig. 6   Relationships between soil respiration (*SR*) and soil temperature at 10 cm depth (A), fine root biomass (B), annual litter input (C), soil organic carbon (*SOC*) (D), Photosynthesis (E), soil total nitrogen (*STN*) (F), soil moisture at 5 cm depth (G), pH (H), and soil bulk density (I) across the six vegetation types. Values for *SR*, *ST*, *SM*, *SOC*, *STN*, pH, fine root biomass, net photosynthetic rate, and bulk density were monthly averaged values from June to September 2012

Table 3 Values of regression coefficients (a, b and c) in models of soil respiration (SR) against soil temperature at 10 cm depth (ST) and soil moisture at 5 cm depth (SM) for the six vegetation types ($SR = a \exp (b \cdot ST) \times SM^c$). R^2 and P represent determination coefficient and P value, respectively. Values for SR, ST, and SM were derived from 23 collection dates twice a month from June 2012 to May 2013. PT, *Populus tomentosa*; RP, *Robinia pseudoacacia*; PG, *Punica granatum*; ZJ, *Ziziphus jujube*; AS, *Armeniaca sibirica*; GR, Grassland

Vegetation type	a	b	c	R^2	P
PT	0.25	0.10	0.11	0.74	0.00
RP	0.24	0.02	0.55	0.26	0.01
PG	0.26	0.07	0.14	0.55	0.00
ZJ	0.36	0.05	0.19	0.33	0.01
AS	0.46	0.09	−0.06	0.82	0.00
GR	0.39	0.05	0.04	0.53	0.00

0.07, $P = 0.61$), pH ($R^2 = 0.10$, $P = 0.55$), and soil bulk density ($R^2 = 0.64$, $P = 0.06$) (Fig. 6C, H, I).

4   Discussion

4.1   Temporal variability of soil respiration

Regardless of vegetation type, SR exhibited a similar and strong single-peak pattern in annual variation for the six sites, with significantly higher values in the growing season than in the non-growing season. Higher SR values in the growing season might attribute to significantly better hydrothermal coupling conditions. Because the semi-arid continental climate in our study area features high summer precipitation (over 65% of the annual precipitation occurs in July to September) and temperatures, adequate water and heat for root and microbial metabolism are supplied. In contrast, low soil moisture and temperature values in the non-growing season might negatively impact dissolved substance diffusion and inhibit root and soil microbial community respiration. Temporal coefficient of variation (CV) of SR for the six sites ranged from 76.98% to 94.08%, with higher values in the secondary forests (RP and PT) and grassland than in the plantations. This result indicates that an appropriate selection of the measuring time point is important when estimating annual soil respiration efflux.

Soil temperature is the main control factor of SR temporal variation at ecosystem level (Sheng et al., 2010; Luo et al., 2012). In our study, we observed a significant strong exponential correlation between SR and soil temperature in each site, and 30% to 82% of the temporal variation of SR was explained by soil temperature alone for the six sites. Such strong relationships between SR and ST have been reported in previous studies on temperate ecosystems (Zhang et al., 2012; Oishi et al., 2013). These results indicate that soil temperature is the main driving force to the variation of temporal SR in each site. That may be the major reason why many researchers use Q_{10} functions to estimate SR. In our study, Q_{10} values ranged from 1.73 to 3.05 across the six sites, with a mean value of 2.26, which was slightly lower than that reported for other regions. For example, Janssens and Pilegaard (2003) reported Q_{10} values in the range from 2.0 to 23.1, with an average of 4.3 in a beech forest in Denmark. Davidson et al. (1998), working in a temperate mixed hardwood forest, calculated Q_{10} values in the range from 3.4 to 5.6, with an average of 3.9.

Apart from ST, SM is another widely studied factor affecting temporal variability of SR at the ecosystem level (Saize et al., 2006; Liu et al., 2011). In this study, we observed a significant linear relationship between seasonal SR and SM in each site except AS. However, this relationship was not as strong as that between SR and ST, which is in agreement with the results previously reported from other temperate regions (Wang et al., 2006; Wang et al., 2013). However, the relationship between SR and SM in our study area was stronger than that in subtropical areas. Because of the semi-arid continental climate (e.g., uneven rainfall and precipitation far lower than evaporation) of our study area, the soil underwent seasonal drought, possibly limiting microbial activities and photosynthesis in some months (Drake et al., 2012). Meanwhile, the response of root respiration to seasonal variation of SM may be stronger in our study area than in subtropical regions, where soils are rarely subject to prolonged droughts (Tang et al., 2006; Sheng et al., 2010). The regression model based on ST and SM (Equation 3) did not explain more variation in SR than the model based on ST only (Equation 1) in the present study. This indicates that the interaction between ST and SM has very little effect on temporal variability of SR in this area (Table 3). In addition, there are many other factors, such as microbial populations, fine root biomass, organic matter input and the allocation pattern of photosynthetic products, which may exert strong effects on seasonal variation of SR in this study area.

4.2   Spatial variability of soil respiration

Vegetation types strongly affect root biomass, quantity and quality of detritus production, soil microclimate and structure, stand photosynthesis, and biomass (Pregitzer et al., 1998; Wang et al., 2006; Luo et al., 2012; Wang et al., 2013), hence influencing *SR*. Among the six sites in this study, secondary forests and grassland exhibited significantly higher annual *SR* rates than plantations. This result reveals that trend of decreasing *SR* values after conversion of secondary forests and grassland to plantations. Values of *SR* were reduced by 8% to 39% with conversion from secondary forests to plantations and by 11% to 36% from grassland to plantations. Similarly, Sheng et al. (2010) reported that *SR* decreased by 20% to 44% after conversation from secondary forests to plantations in subtropical China. Smith and Johnson (2004) found that *SR* values under grassland were 38% higher than values under woodland in a juniper woodland-grassland pair in Kansas, USA. This might be due to the fact that grassland and secondary forests tend to allocate larger proportions of their photosynthetic products to belowground (Smith and Johnson, 2004). Meanwhile, SOC and STN contents in grassland and secondary forests were also higher than those in plantations in our study area, indicating that substrate availability strongly limits soil microbial activities, significantly influencing *SR* in this area. Temperature sensitivity of *SR* (Q_{10}) in secondary forests and grassland ranged from 2.52 to 3.05, and that in plantations ranged from 1.73 to 2.16, indicating that the conversion of natural ecosystems to man-made ecosystems may reduce temperature sensitivity of *SR*. Such reduction of Q_{10} could be explained by decreased photosynthesis rates, and lower topsoil organic carbon and nitrogen contents, which indirectly and directly affect the supply of respiratory substrate and thus influence the response of soil microbial respiration to temperature (Tang et al., 2005; Mahecha et al., 2010). Spatial *CV* values of *SR* among the six sites averaged 38.78% across the 12-month measurement and were higher than the value of 25% reported by Wang et al. (2006) for six temperate forest types. The factors leading to spatial variability of *SR* are complex. Comparing the factors influencing temporal variation of *SR*, we found that neither *ST* nor *SM* had a significant effect on spatial variation of *SR* in the six sites. This is possibly related to the fact that differences in *ST* between the six sites were not significant

in this area (Table 2, *P* > 0.05), resulting in only a slight, insignificant influence of *ST* on spatial variation of *SR*. Although *SM* values significantly differed among the six sites, they contributed less to spatial variation of *SR*. Meanwhile, STN, SOC, photosynthesis rate, and fine root biomass significantly contributed to the spatial variation of *SR*. Soil respiration is usually comprised of autotrophic and heterotrophic respiration (Davidson et al., 2006; Peng et al., 2008). Autotrophic respiration is tightly related to fresh photosynthetic products and fine root biomass (Hogberg et al., 2001; Sheng et al., 2010). High photosynthetic activity increases C substrate input into the soil, leading to high root respiration (Bahn et al., 2009; Schindlbacher et al., 2009). Autotrophic respiration was significantly correlated to fine root biomass, possibly because finer roots contain higher nitrogen concentration (Pregitzer et al., 1998), which is of great importance for plant growth and root activities (Luo et al., 2012). In addition, higher SOC contents will also accelerate heterotrophic respiration (Wan and Luo, 2003), which is a result of SOC mineralization and basically depends on the supply of C substrates (Fang et al., 2005; Reichstein et al., 2005a; Luan et al., 2011). Our study suggests that STN is the major contributing factor for spatial variation of *SR*, which is consistent with the studies of Luo et al. (2012) and Wang et al. (2013). Higher STN contents in secondary forests and grassland accelerate plant photosynthesis, thus providing more substrate for roots and soil microbes (Luo and Zhou, 2006), consequently increasing *SR* rates. Similar studies have shown that *SR* rates were negatively correlated with pH (Luo et al., 2012) and soil bulk density (Chen et al., 2010), and positively correlated with annual litter amounts (Sheng et al., 2010). However, we did not find significant correlations between *SR* and annual litter input, pH and bulk density. Low soil bulk density results in highly porous soil, thus leading to high soil oxygen availability which facilitates aerobic microbial activities (Chen et al., 2010). However, our study area is part of the rocky mountain area of northern China, with high gravel contents and soil porosity. The relatively high soil oxygen availability in this region has no limiting effect on microbial activities, leading to a poor relationship between soil bulk density and *SR*. Due to the biological difference of the vegetation types, quality and quantity of litter varied among vegetation types, leading to various litter decomposition and humi-

fication rates, and hence resulting in different organic matter and nutrient return rates to the soil (Davidson et al., 2006; Song et al., 2013). Therefore, we found no significant correlation between *SR* and annual litter input among different vegetation sites.

5 Conclusions

We investigated the spatio-temporal variation of *SR* and its controlling factors in different vegetation types in semi-arid regions, North China. Our results indicate that *SR* shows distinct seasonal patterns, with higher values in the growing season for all six vegetation types. Annual average *SR* and Q_{10} values tended to decrease from secondary forests and grassland to plantations. Due to the high spatio-temporal variation of *SR* in this area, care should be taken when converting natural ecosystems to man-made ecosystems from the point view of accurately quantifying *SR* emissions at a regional scale. Our results indicate that *ST* and *SM* were the controlling factors of temporal variation of *SR*, while STN, SOC, photosynthesis rate, and fine root biomass significantly contributed to the spatial variation of *SR*. Quantifying the spatio-temporal variation of *SR* and distinguishing its controlling factors is crucial to improve the precision of carbon budget estimations at regional scales.

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