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Partitioning soil respiration in two typical forests in semi-arid regions, North China

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ABSTRACT

This investigation examines the contributions of autotrophic respiration (R_A) and heterotrophic respiration (R_H) to total soil respiration (R_T) in two typical forests (*Armeniaca sibirica* Lam. (AS) and *Vitex negundo* Linn. var. *Heterophylla* (VN)) in semi-arid region of North China. The soil respiration components' responses to changing temperatures were also examined. A similar pattern was identified in the diurnal variation of R_T and R_H; R_A exhibited a different diurnal pattern with nighttime values being greater than daytime values. On the seasonal scale, the variations of R_T, R_H and R_A exhibited a similar and strong single-peak pattern with values peaking in early August for both forest sites. The seasonal variations of R_T, R_A and R_H were strongly affected by soil temperature and moisture, with soil temperature accounting for more variations in soil respiration components at both sites. The contributions of R_A to R_T (R_A/R_T ratio) exhibited remarkable diurnal and seasonal variations. Due to the lag time between photosynthesis and root respiration, diurnal variation of R_A/R_T was lower during the daytime than at night in both AS and VN sites. Meanwhile, under the influence of plant physiology, the seasonal variation of R_A/R_T presented a bimodal curve, with ratios peaking in April and August and bottoming out in October. In addition, due to having higher fine root biomass, VN had a significantly higher annual mean R_A/R_T ratio (24.44%) than AS (17.46%). Regardless of vegetation type, the responses of R_T, R_A and R_H to soil temperature were more sensitive during the dormant season than during the growing season, with their Q_{10} ranked as $R_A > R_T > R_H$. Our results indicate that R_A is more sensitive to temperature variation than R_H, and that the dormant season may have greater soil respiration potential than the growing season in our study areas in the context of increasing global temperatures. The response of R_T, R_A and R_H to soil temperature showed greater sensitivity for VN than for AS during the annual time scale. We can infer that soil respiration under VN may be more sensitive to temperature variations under global warming scenarios.

1. Introduction

Soil respiration (SR), one of the key components of carbon cycle in terrestrial ecosystems, is recognized as the second largest carbon flux from terrestrial ecosystems into the atmosphere (Peng et al., 2008; Bahn et al., 2009). Due to uncertainty (positive and negative) feedback mechanisms associated with the belowground carbon cycle in the process of global warming, there has been a recent increase in investigations into soil respiration (Giardina and Ryan, 2000; Moyano et al., 2007). Soil respiration releases 80.4 Pg C annually to the atmosphere, a volume which is about 10-fold greater than that of fossil fuel combustion and deforestation combined (Raich et al., 2002). Any changes therefore in soil respiration could have a profound influence on atmospheric CO_2 concentrations, and potentially aggravate climate warming induced by greenhouse gases (Kane et al., 2005; Song et al., 2013).

Soil respiration is usually comprised of auto- (R_A; root and rhizosphere) and heterotrophic (R_H; microbes and soil fauna) respiration components (Kuzyakov, 2006; Yi et al., 2007). The contribution of R_A to total soil respiration has been reported to have a wide range (10–90%) with mean values of 45–50% for forest ecosystems (Hanson et al., 2000). Autotrophic respiration is highly dependent on fine root biomass, plant primary productivity, photosynthesis and photosynthate allocation to roots, while heterotrophic respiration is mainly influenced by the carbon substrate availability such as belowground detritus, soil organic carbon and nutrient contents (Tang and Baldocchi, 2005;

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Wang et al., 2006). As different components of soil respiration contain various biological and ecological processes, the responses of each component to environmental changes are also different (Boone et al., 1998; Lee et al., 2003; Lee et al., 2010). Therefore, it is necessary to partition SR into its components, which is benefit to gain a mechanistic understanding of SR and its response to environmental changes, and determine carbon source or sink patterns in terrestrial ecosystems in relation to global climate change (Jia et al., 2006; Luo and Zhou, 2006).

Partitioning the heterotrophic and autotrophic components of SR in situ and determining its driving factors are difficult but very important (Li et al., 2010). Three main methods have been used to distinguish hetero- from autotrophic respiration in field studies, including component integration, root exclusion and isotopic approaches (Hanson et al., 2000; Subke et al., 2006). Among these methods, the trenching method is recognized as a simple but effective root exclusion approach. This method has been applied extensively due to it having little disturbance to remaining trees; being suitable for maintaining most field conditions; and being easy to implement under experimental conditions (Li et al., 2010; Shi et al., 2012). Through this method, Li et al. (2010) found that the R_A/R_T ratio in the growing season was 67.3% in a *Setaria italic* (L.) Beauv. cropland on the Loess Plateau, northern China. Larionova et al. (2006) reported that the R_A/R_T ratios in spring barley, corn and bulk wheat croplands were 37.6, 69.4 and 88.2% in the growing season, respectively. Yi et al. (2007) found that the R_A/R_T ratios in the rainy season and the dry season were in the range of 26.1–35.4 and 18.1–22.1% in subtropical forests, respectively.

Soil carbon storage in arid and semiarid regions is important for global carbon storage and easing atmospheric CO_2 concentration enrichment, therefore making these regions increasingly important in the global carbon cycle (Gaumont-Guay et al., 2006; Xu et al., 2011). Mount Taihang, located in the lithoid hilly area of North China, has a thin soil layer with high gravel content. Soil water content in this region is the main limiting factor for vegetation growth. Although some investigations have been conducted on environmental factors such as vegetation type, soil temperature and moisture effecting soil respiration in this area (Shen et al., 2014; Zeng et al., 2014), little research has been undertaken on soil respiration partitioning and their response to environment factors. Partitioning soil respiration components and studying their driving factors will deepen our understanding of soil respiration processes and their mechanisms, and it will also provide a reference for accurate evaluation of regional carbon sources and sinks in the view of global climate change.

Two typical vegetation types were selected for our study (artificial plantation: *Armeniaca sibirica*; deciduous shrub: *Vitex negundo*) in the hilly region of Mount Taihang to separate soil respiration components using the trenching method. We aimed to (1) study the diurnal and seasonal variations of soil respiration components of different vegetation types; (2) quantify and compare the contribution of autotrophic respiration to total soil respiration at diurnal and seasonal scales; and (3) compare the responses of soil respiration and its components to environmental factors within and between vegetation types.

2. Materials and methods

2.1. Site description

This study was conducted at the Hilly Ecology Experimentation Station (114°13′–16′E, 37°53′–56′N, 350 m a.s.l) of the Chinese Academy of Sciences, which is located in the hilly region of Mount Taihang, China (Fig. 1). The area has a semi-arid continental climate with an annual average air temperature of 13.2 °C and a mean annual precipitation of 570 mm. The minimum mean air temperature is − 1.6 °C in January, and the maximum mean air temperature is 26.3 °C in July. The soil parent material is mainly granitic gneiss with relatively small amounts of shale and limestone. The soil is classified as Cinnamon soil in 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%; this soil is classified as a loam with a textural composition of 51.5% sand, 34.5% silt and 14.0% clay (Zhou and Zhang, 2012). Vegetation at the site is currently composed of secondary forest, artificial plantations, deciduous shrubs and herbs, these accounting for 10, 15, 45 and 20% of the study area, respectively. *Armeniaca sibirica* (AS) and *Vitex negundo* are two typical vegetation types in this area, which are representative of the artificial plantations and deciduous shrubs (VN), respectively. The stand characteristics and soil properties of the experimental sites are shown in Table 1.

2.2. Partitioning soil respiration

A trenching method was used to partition autotrophic respiration (R_A) and heterotrophic respiration (R_H) from total soil respiration (R_T). In October 2012, six 1 m × 1 m permanent plots were set up in each vegetation site (three plots for trenching and three plots as controls). The trenching plots were established adjacent to the control plots (Fig. 1). Trenches of 0.2 m wide and 0.8 m deep (approximately the bottom of the root zone) were excavated around the trenching plots. In order to prevent root growth into the trenched plots, we lined the trench with polyethylene nets of 0.037 mm mesh size, and then refilled the soil back into the trench according to its original soil profiles. A polyvinyl chloride (PVC) collar (20 cm inside diameter × 10 cm height) was inserted 3 cm deep into the soil in each plot for soil respiration measurement. The seeding and herbaceous vegetation within the plots were regularly clipped at ground level during the measurements. It was assumed that the CO_2 efflux measured in the trenching plot was composed of R_H, while that in the control plot was composed of R_H and R_A. Differences between the control plots and corresponding trenching plots were used to determine R_A.

2.3. Field measurements and laboratory analysis

An automated soil CO_2 flux system (LI-8100, LI-COR, USA) equipped with a portable chamber (Model 8100-103) was used to measure soil respiration from January to December, 2013. Soil respiration was measured twice a month during the growing season (May–September) and once a month during the dormant season (January–April and October–December). Measurements were made between 09:00 and 13:00 local time on each sampling day. Continuous measurements were made on July 25–28 and September 25–28 to monitor diurnal variation in total soil respiration and its components. These measurements were made every 2 h from 08:00 to 08:00 the next day. Soil temperature (ST) at 10 cm depth and soil moisture (SM) at 5 cm depth were monitored simultaneously near the PVC collars using a temperature sensor and a moisture sensor attached to a LI-8100, as per the method of Song et al. (2013).

Soil samples were collected once a month from July to October using 5-cm diameter tube auger at depth intervals of 0–10, 10–20, 20–40 and 40–60 cm depths near the PVC collars. Twelve soil samples from the same soil layer in each plot were combined to form a composite sample. After excluding gravel, roots and clutter, the soil samples were air-dried and crushed before being passed through a 0.25 mm soil sieve. Soil organic carbon (SOC) was measured by Walkley-Black's method (Walkley and Black, 1934), and soil total nitrogen (STN) was measured by the Semimicro-Kjeldahl method (Bremner and Mulvaney, 1982).

Fine root biomass was determined according to the method described by Shi et al. (2009). Soil samples were collected in the vicinity of the soil collars every month from July to October. A soil auger (5 cm in diameter) with a sharpened edge was used to collect the soil material for this analysis. 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 of 0.1 mm mesh size, soaked and washed with tap water. Fine roots were then

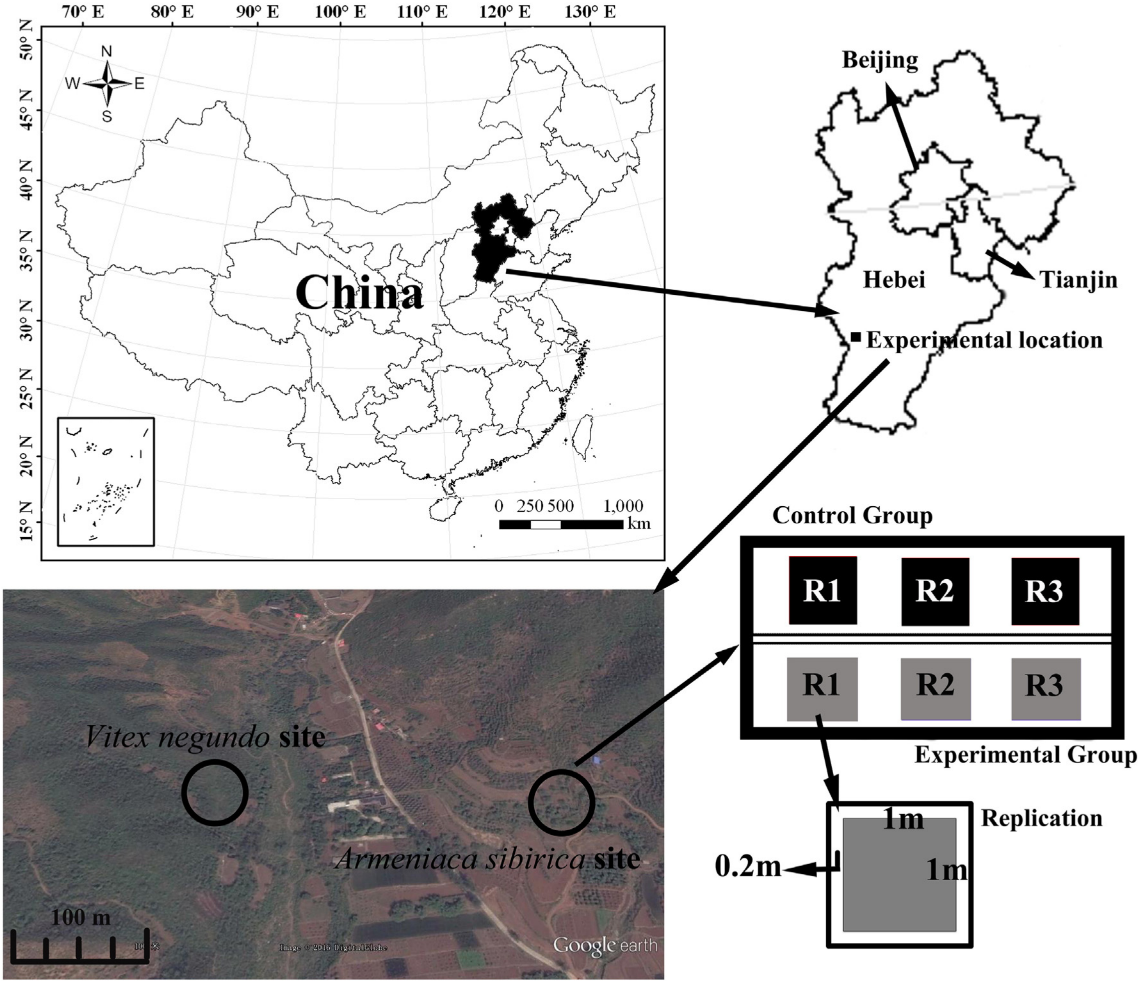

Fig. 1. Geographic location of the study area and experiment design in the study site.

carefully picked out using tweezers before being 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 the AS and VN sites. The litter samples were collected every month during the sampling year according to the method described by Yang et al. (2004). Litter samples were oven dried at 65 °C until a constant weight was recorded.

2.4. Data analysis

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

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

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

where SR is the soil respiration rate (μmol m^{-2} s^{-1}); ST is the soil temperature at 10 cm depth (°C); SM is volumetric soil moisture at 5 cm depth (%); α, β, m and n are the regression coefficients.

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

$$Q_{10} = e^{10\beta} \tag{3}$$

All statistical analyses were performed using 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 SOC, STN, fine root biomass and annual litterfall between the AS and VN sites. Paired *t*-test was conducted to compare the differences of soil temperature and soil moisture between the control plot and the corresponding trenching plot. Significance was defined at the 95% confidence level. All graphs were plotted in Origin 8.5 software.

Table 1
Stand characteristics and soil properties of experimental sites.

Vegetation type	DBAH (cm)	H (m)	Canopy density	SOC (g/kg)	STN (g/kg)	Annual litter input (g/m)	Fine root biomass (kg/m^3)
Armeniaca sibirica	8.5	4.5	0.95	9.33(0.7)^b	4.42(0.28)^b	209.05(24.67)^a	0.22(0.03)^b
Vitex negundo	1.4	1.3	0.85	13.28(0.94)^a	7.16(0.44)^a	120.5(13.52)^b	0.37(0.04)^a

Note: H is plant height and DBAH is diameter at base height. Same lowercase letters within a column indicate no significant difference between sites. Values in parentheses are standard deviations.

3. Results

3.1. Diurnal variations of soil respiration components

Diurnal soil temperature fluctuations, R_T, R_A and R_H on July 25–28 and September 25–28 for both sites are shown in Fig. 2 and Fig. 3. The diurnal variations of soil temperature in the control and trenching plots showed single-peak patterns for both sites. Results also indicate that ST peaked at both sites between 17:00–19:00 h in July and between 15:00–17:00 h in September. In July and September, the greatest diurnal variations in ST existed in the trenching plot under VN, and the temperature gaps between the control plot and the trenching plot for the VN site were larger than that at the AS site. The diurnal variations of R_T, R_A and R_H under VN and AS exhibited similar single-peak patterns in July and September. The peak values of R_T and R_H occurred between 13:00–15:00 h in July and September, which appeared relatively earlier than that of ST. Generally, R_H showed higher values than R_A during the 24 h sampling time for both sites (Fig. 2 and Fig. 3).

3.2. Seasonal variations of soil respiration components

No significant differences in mean temperature at 10 cm depth between the control site and the trenching site were observed in the study sites ($p > 0.05$) (Table 2). Soil temperature steadily increased from January until early summer, reaching a maximum in June, and then declined through autumn and winter until it reached the lowest value of 3 °C in the VN site in December. Annual average temperature in the trenching and control sites under AS were 16.49 and 15.79 °C, lower than those in the VN site (19.34 and 18.65 °C, respectively). There was a tendency that soil temperatures in the trenched plots were higher than that in the control plots for both sites (Fig. 4A).

Soil moisture at 5 cm depth ranged from 2 to 30.8% and 0.8 to 20.4%, with a mean of 14.34 and 7.27% in the AS and VN sites, respectively. Soil water content exhibited a multi-peak pattern throughout the observation period for the two sites; the AS site had higher SM values than the VN site (Fig. 4B). However, due to the absence of root water uptake, annual mean SM for both sites were higher but not significant in the trenched plots compared to those in the control plots (Table 2).

R_T, R_A and R_H showed strong seasonal variability in both sites. R_T, R_A and R_H ranged from 0.3 to 3.26, 0.01 to 0.91 and 0.25 to 2.35 μmol m^{-2} s^{-1} in the AS site and 0.14 to 3.07, 0.02 to 1.15 and 0.11 to 1.92 μmol m^{-2} s^{-1} in the VN site, respectively (Fig. 4C and D). R_T, R_A and R_H exhibited a significant single-peak pattern throughout the observation period for the two sites. R_T gradually increased from January, reaching peak values in early August, before decreasing consistently to its lowest levels in December. R_A and R_H, having similar seasonal trends as R_T, appeared to have smaller fluctuations. In addition, R_A had smaller seasonal variations and mean values than R_H for both sites.

3.3. Contribution of autotrophic respiration to total soil respiration at diurnal and seasonal scales

By using R_T and R_H values from the same time period, we can obtain the contribution of autotrophic respiration to total soil respiration (R_A/R_T). Table 3 shows that the diurnal variation of R_A/R_T under AS and VN sites exhibited a single-peak pattern, with values lower in the daytime than at night. The maximum R_A/R_T ratios appeared between 21:00–01:00 h with the minimum ratios occurring between 11:00–13:00 h for both sites. In July and September, the daily mean R_A/R_T ratios in the VN site were 32.34 and 29.81%, these results being higher than those recorded at the AS site (28.57 and 27.65%, respectively). The daily mean R_A/R_T ratios in July were also recorded to be higher than those in September for both sites.

Fig. 5 shows the values of R_A/R_T for different periods during the observation experiment for the two sites. The seasonal variation of R_A/R_T for AS and VN are similar, both sites showing strong seasonal patterns with two peaks throughout the whole year (one in April and another in August). The R_A/R_T ratio in the AS and VN sites were in the range of 1.82–42.85 and 7.69–48.28%, with a mean of 17.46 ± 11.95 and 24.44 ± 12.09% (mean ± SD), respectively. Annual R_A/R_T ratios in the

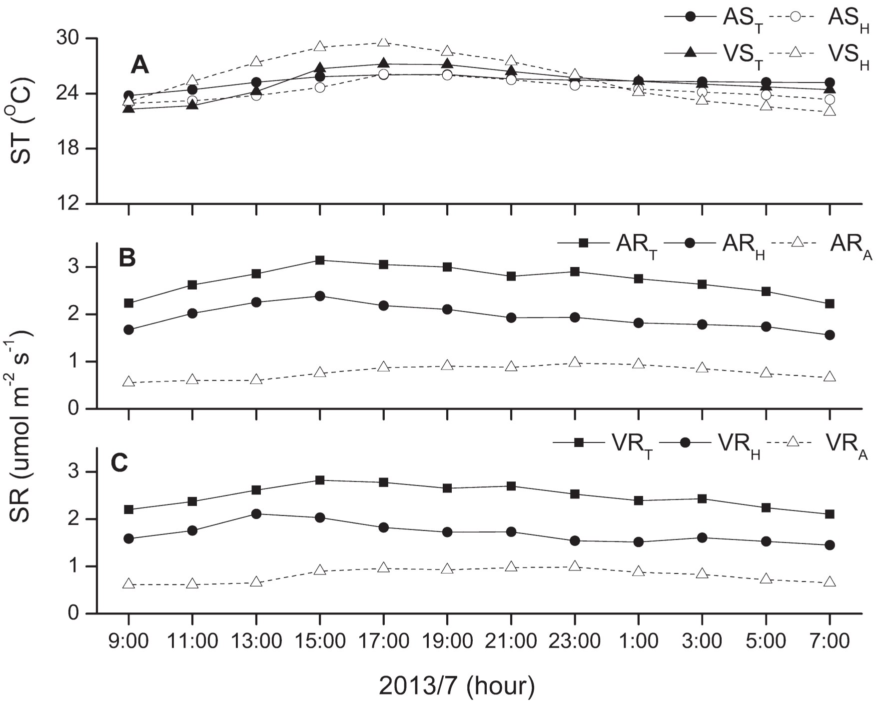

Fig. 2. (A) Diurnal variations in soil temperature at 10 cm depths in the control and trenched plots of *Armeniaca sibirica* (AS_T and AS_H) and *Vitex negundo* (VS_T and VS_H) on July 25–28, 2013. (B) Diurnal variations in total soil respiration (AR_T), autotrophic respiration (AR_A), and heterotrophic respiration (AR_H) in the *Armeniaca sibirica* site. (C) Diurnal variations in total soil respiration (VR_T), autotrophic respiration (VR_A), and heterotrophic respiration (VR_H) in the *Vitex negundo* site (n = 12).

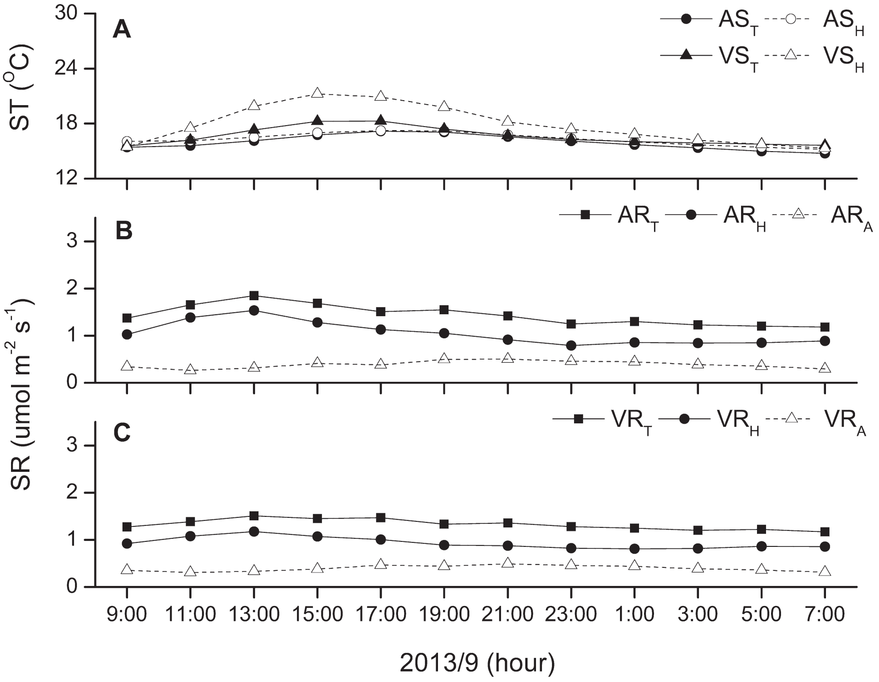

Fig. 3. Diurnal variations in soil temperature (A), soil respiration of *Armeniaca sibirica* (B) and *Vitex negundo* (C) in the control and trenched plots on September 25–28, 2013. Data are presented as explained for Fig. 2.

VN site were always higher than those in the AS site during the study period (Fig. 5).

3.4. Response of seasonal variations in soil respiration components to soil temperature and soil moisture

Regardless of the vegetation types, seasonal R_T, R_A and R_H exhibited an exponential response to soil temperature at 10 cm depth ($R^2 = 0.88$, 0.50 and 0.87 for AS, and $R^2 = 0.73$, 0.66 and 0.72 for VN, respectively) (Fig. 6). In addition, linear regression analyses showed that R_T, R_A and R_H were significantly affected by soil moisture at 5 cm depth for the two sites. Soil moisture accounted for 65, 32 and 52% of variation in R_T, R_A and R_H in the AS site, and 42, 29 and 64% of variation in the VN site, respectively (Fig. 7). Overall, soil temperature had a greater effect on seasonal variation in soil respiration compared to soil moisture at both sites.

3.5. Seasonal variation in Q_{10}

At the seasonal scale, R_T and R_H were significantly correlated with soil temperature at 10 cm depth. The annual Q_{10} of R_A was higher than that of R_H and R_T in both sites. At the same time, annual Q_{10} of R_T, R_A and R_H were all higher in the VN site than those in the AS site (Fig. 8A).

To identify the differences in responses of R_T, R_A and R_H to soil temperature at different periods, the data was separated into growing and dormant periods. In both growing and dormant seasons, the Q_{10} values were in the rank of $R_A > R_T > R_H$ for both vegetation sites. The Q_{10} of R_T, R_A and R_H in the dormant season were all higher than those in the growing season and for the whole year. During the growing period, the Q_{10} of R_T and R_H was higher in the AS site, while that of R_A was higher in the VN site. However, in the dormant season, the Q_{10} values of R_T, R_A and R_H were all higher in the VN site than those in the AS site (Fig. 8B and C).

Table 2
Mean soil temperature (ST) and soil moisture (SM) at control and trenched plots of two vegetation types (mean ± *SD*).

	Armeniaca sibirica		*Vitex negundo*	
Plot type	ST (°C)	SM (%)	ST (°C)	SM (%)
Control	15.79 (8.75)^a	14.34 (8.29)^a	18.65 (9.50)^a	7.41 (5.18)^a
Trenched plot	16.49 (9.05)^a	14.52 (7.30)^a	19.34 (9.45)^a	7.62 (5.40)^a

Note: Different letters in a column indicate significant differences between control and trenched plots ($p < 0.05$).

4. Discussion

4.1. Diurnal variation of soil respiration components

In this study, R_T and R_H exhibited similar diurnal variations in both sites, with peak values appearing between 13:00–15:00 h in July and September. R_T and R_H had a similar diurnal variation which may be attributed to the fact that R_H accounted for a relative high proportion of R_T. The diurnal R_H/R_T ratios in the AS and VN sites were 71.5–73 and 76.5–70.3%, respectively. The variation patterns of R_T and R_H were generally accorded with soil temperature, with the peak-value time about 2 h earlier than that of soil temperature. R_A showed a completely different diurnal variation compared with R_H, and the influence of soil temperature was less than for R_H. R_A had a different diurnal variation pattern to R_H which may be associated with the different responses to environment factors such as soil temperature, soil moisture, photosynthetic activity, fine root biomass, etc. Evidence suggests that diurnal R_T and R_H are mainly influenced by soil temperature while R_A tends to be more affected by photosynthesis (Wang et al., 2006). In this study, the diurnal patterns of R_A under AS and VN were not in accordance with that of photosynthesis, with R_A values higher during the nighttime than in the daytime. Tang and Baldocchi (2005) estimated that there was about 7–12 h time lag between photosynthesis and R_A, and the different lag times may predominantly be attributed to the height of the plants. Bahn et al. (2009), investigating a mountain meadow system in Austria, found that freshly plant-assimilated C was rapidly transferred belowground and respired there, and photosynthates of the previous days were a predominant respiratory substrate during the nighttime and early morning hours.

In July and September, the diurnal average R_T and R_H were higher in the AS site, while diurnal average R_A was higher in the VN site. These

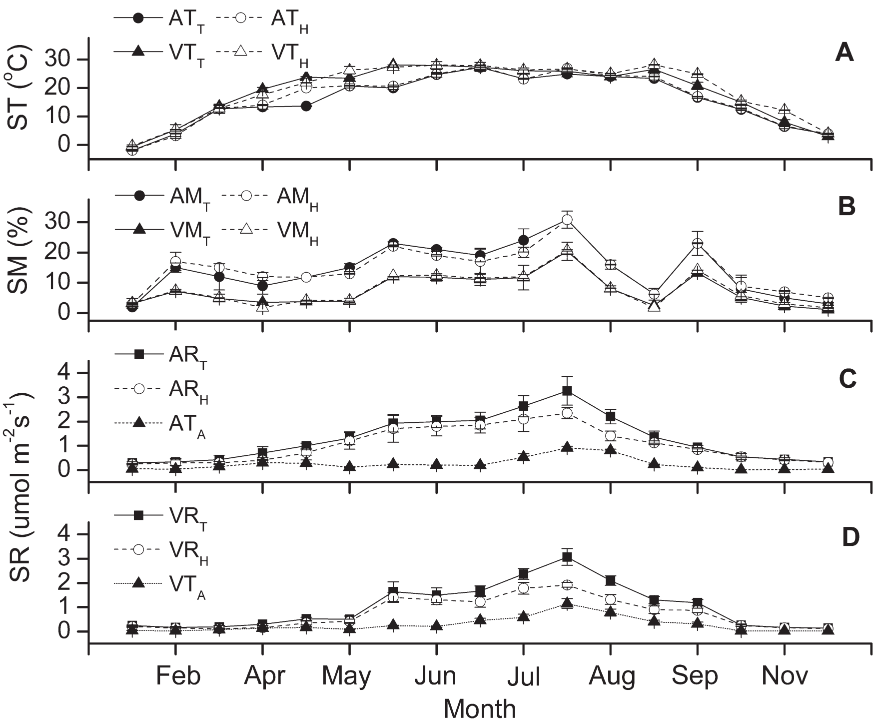

Fig. 4. (A) Soil temperature at 10 cm depth in the control and trenched plots of *Armeniaca sibirica* (AT_T and AT_H) and *Vitex negundo* (VT_T and VT_H) from January to December 2013. (B) Soil moisture at 5 cm depth in the control and trenched plots of *Armeniaca sibirica* (AM_T and AM_H) and *Vitex negundo* (VM_T and VM_H) from January to December 2013. (C) Variations of total soil respiration (AR_T), autotrophic respiration (AR_A) and heterotrophic respiration (AR_H) in the *Armeniaca sibirica* site from January to December 2013. (D) Variations of total soil respiration (VR_T), autotrophic respiration (VR_A) and heterotrophic respiration (VR_H) in the *Vitex negundo* site from January to December 2013.

could be attributed to the significantly higher annual average litter production and obviously lower fine root biomass and STN content in the AS site than those in the VN site. Subke et al. (2006) and Sheng et al. (2010) suggest that root respiration is closely linked to fine root biomass and soil nitrogen levels, and that heterotrophic respiration is positively correlated with annual litter production. The quantity and quality of litter fall will therefore influence soil physicochemical properties and microbial activity. In addition, fresh litter fall has a priming effect on soil respiration (Kuzyakov, 2010). Prevost-Boure et al. (2010) found that doubling or removing fresh litter fall would significantly increase or decrease soil respiration in temperate coniferous forests, and the treatment of doubling fresh litter fall contributed 32% of total respiration.

Table 3

Diurnal variations in the contribution of root respiration to total soil respiration (R_A/R_T ratio) of *Armeniaca sibirica* and *Vitex negundo* on July and September 2013.

	R_A/R_T (%)			
	Armeniaca sibirica		*Vitex negundo*	
Time	Jul. 25–26	Sep. 25–26	Jul. 27–28	Sep. 27–28
9:00	25.14	24.80	28.08	27.72
11:00	23.12	16.17	26.02	22.18
13:00	21.01	17.10	24.95	22.00
15:00	24.02	24.27	30.75	25.96
17:00	28.46	25.02	34.38	31.71
19:00	30.21	32.21	35.02	33.08
21:00	31.23	35.42	35.91	35.9
23:00	33.24	36.81	39.09	35.86
1:00	34.07	34.32	36.72	35.06
3:00	32.31	31.50	33.88	32.02
5:00	30.30	29.17	32.13	29.18
7:00	29.75	25.08	31.17	27.05

4.2. Seasonal variation of soil respiration components

Regardless of vegetation types, the seasonal variations of R_T, R_H and R_A exhibited a similar and strong single-peak pattern from January to December in the two study sites. The rates of R_T, R_H and R_A were much higher in the growing season than those in the non-growing season. R_T, R_H and R_A peaked in early August might be attributed to the relatively high soil temperature, soil water content and photosynthesis. With the study area experiencing a semi-arid continental climate with high summer precipitation (over 65% of the annual precipitation occurs in July to September), this provides a comparatively good hydrothermal

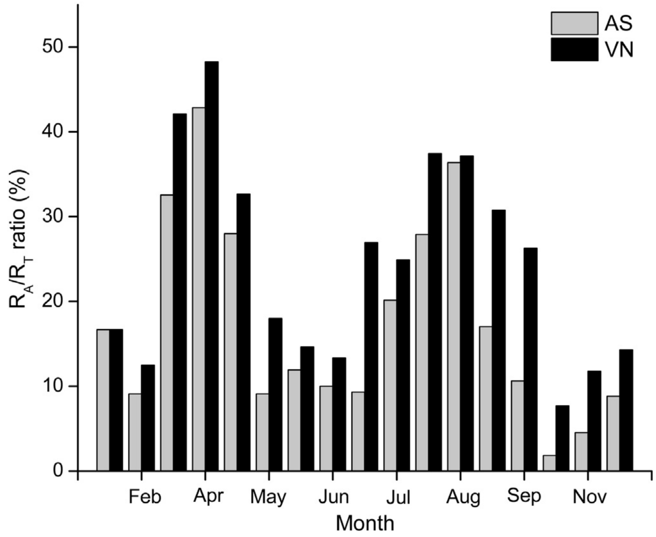

Fig. 5. Contribution of autotrophic respiration to total respiration (R_A/R_T ratio) of *Armeniaca sibirica* and *Vitex negundo* from January to December 2013.

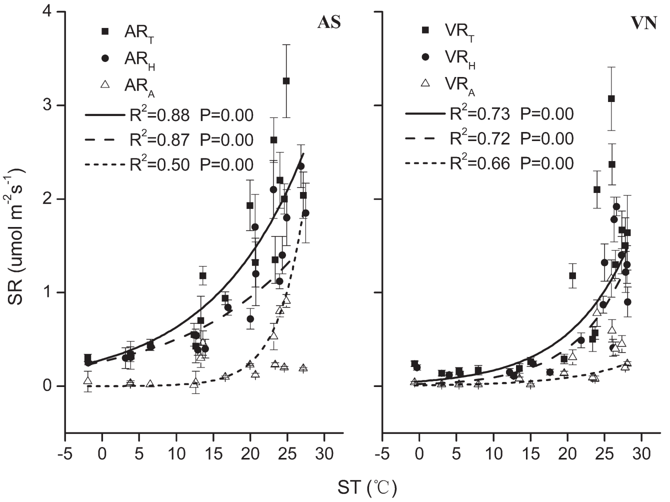

Fig. 6. Total soil respiration (R_T, closed square), heterotrophic respiration (R_H, closed circle) and autotrophic respiration (R_A, open triangle) plotted against soil temperature (ST) at 10 cm depth in the *Armeniaca sibirica* site (a) and *Vitex negundo* site (b) during periods of January to December 2013. The solid line, dashed line and dotted line indicated the regression curves of R_T, R_H and R_A with ST in the *Armeniaca sibirica* and *Vitex negundo* sites, respectively. Error bars represent standard deviations of the efflux means (n = 17).

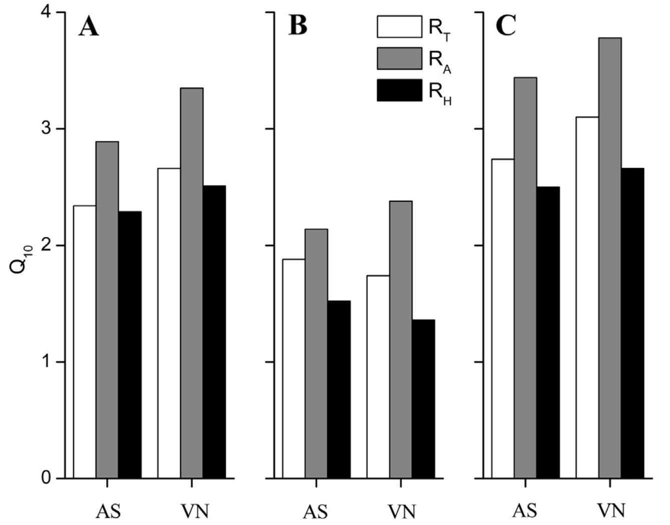

Fig. 8. Model parameters of Q_{10} function showing the seasonality of temperature sensitivities for total soil respiration (R_T), autotrophic respiration (R_A) and heterotrophic respiration (R_H). These were estimated separately for (A): annual (January–December 2013; n = 17), (B): growing (May–September 2013; n = 10), and (C): dormant (January–April and October–December 2013; n = 7) periods. All regressions were significant at $p < 0.05$.

condition for root and microbial metabolism in August (Zeng et al., 2014). In our study, R_T, R_A and R_H were significantly affected by soil temperature and soil moisture at both sites. This phenomenon is due to the reason that R_A and R_H each contain different biotic and abiotic processes, and each process is influenced by hydrothermal conditions (Boone et al., 1998; Lee et al., 2003). Ryan and Law (2005) and Wang et al. (2006) have shown that R_H is primarily driven by soil temperature, moisture and substrate availability, while R_A is largely affected by fine root biomass and plant photosynthesis.

The annual average R_T and R_H in the AS site were significantly higher than those in the VN site, while annual average R_A in the VN site was higher, but not significant, than that in the AS site. This may also be attributed to the fact that the annual average litter production in the AS site was significantly higher than that in the VN site, while the fine root biomass and STN content were significantly lower than those in the VN site. In this study, the annual mean R_T, R_A and R_H (μmol m^{-2} s^{-1}) were 1.28, 0.25 and 1.03 in the AS site and 1.07, 0.28 and 0.74 in the VN site, lower than those reported in other regions. For example, Shi et al. (2012) recorded R_T, R_A and R_H values of 3.68, 1.06 and 3.26 in an oak forest and 2.76, 0.87 and 2.23 in a black locust plantation on the semi-arid Loess Plateau of China; Rey et al. (2002) recorded values of 2.90, 0.61 and 2.31 in a coppice oak forest in Central Italy. This could be attributed to the different climate, vegetation and edaphic conditions. Vegetation types would influence the kind of plant detritus in the litter layers, and thus alter the quality and quantity of plant-derived organic carbon inputs to the soil (Song et al., 2013). The study area has relatively lower SOC content and annual litterfall than the above mentioned areas. Relatively low SOC content will result in a low mineralization rate of soil organic matter, and the mineralization processes are much less evident with a 10 °C increase in temperature at regions with lower SOC reserves (Muñoz et al., 2013).

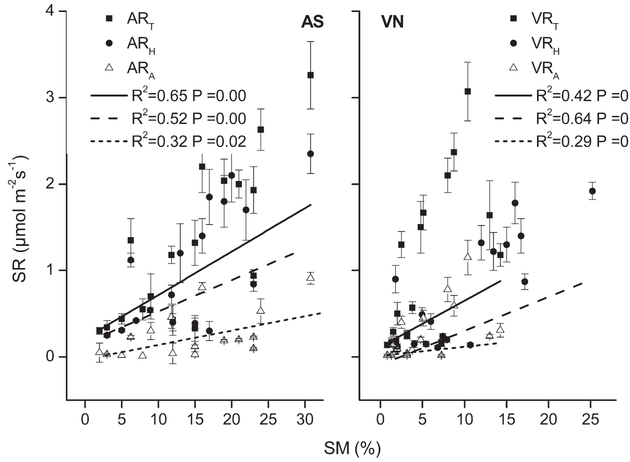

Fig. 7. Total soil respiration (R_T, closed square), heterotrophic respiration (R_H, closed circle) and autotrophic respiration (R_A, open triangle) plotted against soil moisture (SM) at 5 cm depth in the *Armeniaca sibirica* site (a) and *Vitex negundo* site (b) during periods of January to December 2013. The solid line, dashed line and dotted line indicated the regression curves of R_T, R_H and R_A with SM in the *Armeniaca sibirica* and *Vitex negundo* sites, respectively. Error bars represent standard deviations of the efflux means (n = 17).

4.3. Contribution of root respiration to total soil respiration

Due to the different responses of R_A and R_H to environmental factors, the R_A/R_T ratios exhibited remarkable diurnal and seasonal variations. In this study, diurnal variation of R_A/R_T for both sites was lower during the daytime and higher at night. Part of the reason for this occurrence could be due to the time lag between photosynthesis and root respiration; it takes about 7 to 12 h for the daytime photosynthate to transfer to the roots (Tang and Baldocchi, 2005). In addition, total soil respiration was greatly affected by soil temperature which led to total soil respiration being relatively small during the night. This also made R_A/R_T ratios higher in the nighttime than in the daytime. The AS site having lower daily mean R_A/R_T ratios in July and September than the VN site might be associated with the significantly smaller amount of fine root biomass (Table 1). Furthermore, higher daily mean soil moisture levels may have led to higher R_H in the AS site (Table 2). Evidence suggested that root respiration is closely related with fine root biomass, while heterotrophic respiration is strongly linked to soil temperature (Raich and Tufekciogul, 2000; Tang and Baldocchi, 2005).

The seasonal variations of R_A/R_T for the two vegetation sites were rather similar. The R_A/R_T ratios peaked in April and August, and bottomed in October. This occurrence may due to the fact that the plants were in a period of turning green in March and April, therefore having frequent root activities which resulted in relatively higher R_A/R_T ratios.

In May and June, the plants were in the phase of rapid growth. During this stage, although physiological activity was stronger (Li et al., 2010), root respiration might be restricted by the relatively lower root biomass, while R_H rapidly increased due to increasing soil temperature. Therefore, the R_A/R_T ratios were relatively smaller in this period. After June, with the end of the fast growth period, R_A sharply increased with a rate much larger than R_H and reached its peak in August. Furthermore, high root respiration due to strong photosynthesis and high fine root biomass also contributed to large R_A/R_T ratios in August. It was reported that root respiration was strongly correlated with fresh photosynthetic products and fine root biomass (Hogberg et al., 2001; Sheng et al., 2010), and high photosynthetic activity would add the allocation of assimilates into roots, ultimately leading to high root respiration (Bahn et al., 2009; Schindlbacher et al., 2009). By October, the R_A/R_T ratios were rather small. Part of the reason for this was that R_A decreased gradually due to the languishing plant root activity. Another reason was that R_H occupied a leading position in total soil respiration due to a greater amount of litter and stronger effects of soil microorganism and soil animals at this stage. Because R_A is mainly driven by root, while R_H is controlled by the processes of soil microorganism and soil animals decomposing overground litterfall, underground humus and soil organic matter (Hanson et al., 2000). A similar result was identified by Li et al. (2002) for the seasonal variation of R_A/R_T for a grazed grassland in the Xilin River Basin. Results from this study showed a bimodal curve, with R_A/R_T ratios peaking in June and August. However, a different phenomenon was observed by other researchers. Li et al. (2010) found that the R_A/R_T ratios for *Setaria italic* cropland on the Loess Plateau during the growing season showed a single peak curve, with ratios increased from 22.3% in July to 86.8% in October. Yi et al. (2007) found that the R_A/R_T ratios in Dinghushan Biosphere Reserve, subtropical China, ranged from 18.1 to 35.4%, with higher values being recorded in the rainy season and lower values in the dry season. Different seasonal patterns might be associated with various vegetation types, plant growth stages, soil types and environmental conditions (Larionova et al., 2003; Chen et al., 2006).

Due to the different soil carbon allocation patterns, litter inputs and understory microclimate conditions resulting from stand structures, the contribution of root respiration to total soil respiration varied with vegetation types (Chen et al., 2006; Song et al., 2013). In our study, the annual average R_A/R_T ratio for AS was 19.53%, this being significantly lower than that in the VN site (27.45%). The reason for this difference was that the fine root biomass in the VN site was significantly higher than that in the AS site, as fine root biomass was positively correlated with root respiration (Wang et al., 2006). The annual average R_A/R_T ratios in the AS and VN sites were lower than those at the diurnal scale in the growing season, a result which could also be attributed to the relatively lower fine root biomass at the seasonal scale. Raich and Tufekciogul (2000) found that the R_A/R_T ratios for forest, grassland, cropland and arctic tundra ranged from 33–89, 17–40, 12–38 and 50–93%, respectively. Hanson et al. (2000) summarized about 50 investigations and found that the R_A/R_T ratios ranged from 30 to 80%, with the mean ratio of 48% for forest and 60% for non-forest ecosystems. In our study, the R_A/R_T ratios for both vegetation sites were lower than the above mentioned results of forest ecosystems. One possible reason may be that the study area is located in a semidry continental climate zone with high evapotranspiration and low soil water holding capacity. Due to the weaker vegetation growth status compared to other subtropics and tropics regions, less photosynthate will allocate to roots which will therefore result in smaller R_A/R_T ratios in this study area.

5. Conclusions

Because different components of soil respiration contain different biotic and abiotic processes, R_A and R_H respond differently to environmental factors and exhibit significantly diurnal and seasonal variations. The diurnal variation patterns of R_H were generally accorded with soil temperature, while the diurnal patterns of R_A lagged behind the variations of soil temperature, with values higher being recorded in the nighttime than that in the daytime at both sites. In our study, the seasonal variations of R_T, R_A and R_H were significantly affected by soil temperature and soil moisture, with soil temperature having a stronger effect on the seasonal variations than soil moisture.

R_A/R_T ratios at both sites recorded large diurnal variations, with values high during the nighttime and low in the daytime. Under the influence of plant physiology, the seasonal variation in R_A/R_T ratio presented a bimodal curve, with values peaking in April and August and bottoming out in October. Due to the significantly higher fine root biomass, the VN site has higher R_A/R_T ratios than the AS site throughout the year, with a mean of 27.45% significantly higher than that in the AS site (19.53%).

The responses of R_T, R_A and R_H to temperature were more sensitive during the dormant season than during the growing season, with the temperature sensitivity of different soil respiration components in the rank of $R_A > R_T > R_H$ in both sites. This implies that R_A is more sensitive to the variation of temperature than R_H, and the dormant season may also have greater soil respiration potential than the growing season in our study area in the context of increasing global temperature. The response of R_T, R_A and R_H to soil temperature showed greater sensitivity for VN than for AS during the annual time scale. Our results indicate that soil respiration under VN may be more sensitive to the variation of temperature under global warming scenarios.

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