Seasonal variations in the response of soil respiration to rainfall events in a riparian poplar plantation

Reference:

Zhu Mengxun, de Boeck Hans, Xu Hang, Chen Zuosinan, Lv Jiang, Zhang Zhiqiang.- Seasonal variations in the response of soil respiration to rainfall events in a riparian poplar plantation

The science of the total environment - ISSN 0048-9697 - 747(2020), 141222
Full text (Publisher's DOI): https://doi.org/10.1016/J.SCITOTENV.2020.141222
To cite this reference: https://hdl.handle.net/10067/1715820151162165141

Seasonal variations in the response of soil respiration to rainfall events in a riparian poplar plantation

Mengxun Zhu[1,2], Hans J De Boeck[3], Hang Xu[1,2], Zuosinan Chen[1,2],Jiang Lv[4], Zhiqiang, Zhang[1,2*]

1 Key Laboratory of Soil and Water Conservation and Desertification Combating, State Forestry and Grassland Administration, P. R. China

2 College of Soil and Water Conservation, Beijing Forestry University, Beijing 100083, PR China; zhumengxun@163.com(M.Z.); xuhang_bjfu@163.com (H.X.); zuosinan.chen@gmail.com(Z.C.);

3 Research group PLECO (Plants and Ecosystems), Universiteit Antwerpen, 2610 Wilrijk, Belgium; hans.deboeck@uantwerp.be

4 Gongqing Forest Farm, Beijing 101300, China; lvjianggongqing@163.com(J.L.)

* Correspondence: zhqzhang@bjfu.edu.cn; Tel.: 86-10-6233-8097

Abstract

Rainfall events have profound influence on the soil carbon release in different forest ecosystems. However, seasonal variations in soil respiration (RS) response to rainfall events and associated regulatory processes are not well documented in riparian forest ecosystems to date. We continuously measured soil respiration in a riparian plantation ecosystem from 2015 to 2018 to explore the relationships between soil respiration and rainfall events. Across the 4 years, 83 individual rainfall events were identified for spring, summer and autumn. We found that mean RS rate after rain (post-RS) was significantly higher than that before rain (pre-RS) (p<0.05) in spring, and the relative change in soil respiration (RSrc) increased against rainfall size due to the stimulation by the significant increases in soil moisture content (ΔSM). In contrast, mean post-RS was lower than pre-RS and RSrc was significantly decreased with the increasing rainfall size (p<0.01) in summer and autumn. Reduced changes in soil temperature (ΔTS) and increased soil moisture content after rain (post-SM) contributed to the decreased RS due to frequently occurring heavy rain events in summer. Increased ΔSM following rainfall events coupled with groundwater level increase suppressed RSrc in autumn, even though increased ΔTS could offset the negative effects of SM on RS to some extent. In addition, we found that higher post-SM after large rainfall events (>10mm day^{-1}) changed the response of RS to soil temperature (TS) by reducing the temperature sensitivity (Q_{10}) even in this riparian plantation ecosystem. Our study highlights the importance of integrating seasonal difference in soil respiration response to rainfall events and the impact of large rainfall events on soil C release for estimating forest soil carbon cycling at multiple scales.

Keywords

Carbon cycling; Riparian forest ecosystem; Rainfall regime; Soil moisture; Soil temperature

1. Introduction

Soil respiration (RS), the second largest terrestrial carbon efflux from ecosystems to the atmosphere, consists mainly of autotrophic and heterotrophic respiration (Raich et al., 2002; Shabaga et al., 2015; Vargas et al., 2008). Numerous studies have shown that there are significant seasonal patterns in different forest ecosystems (DeForest et al., 2006; Gong et al., 2012; Wu et al., 2015) and these are regulated by many abiotic (e.g., soil moisture, temperature and substrate availability) and biotic factors (e.g., microorganisms, fine roots, and photosynthesis) (Hanson et al., 2000; Liu et al., 2017; Ryan and Law, 2005). Among those factors, soil moisture (SM) and soil temperature (TS) are the main environmental factors that directly drive the seasonal variations of root and microbial activities (Shi et al., 2012; Yoon et al., 2014). However, the degree to which soil temperature and soil moisture affect RS depends on soil condition and seasonal climate (Afreen and Singh, 2019; Singh et al., 2017).

Most of the growing season rainfall in temperate monsoon climate regions is generated by discrete thunderstorm events (Chen et al., 2012; Xia et al., 2018), which can lead to rapid increase or decrease of RS (Deng et al., 2011; Niu et al., 2019). On one hand, rainfall events could alter SM and TS, which in turn affect RS(Afreen and Singh, 2019; Liu et al., 2019a). On the other hand, rainfall events may affect RS through physical degassing or absorption induced by changes in pressure gradient(Fa et al., 2015; Huxman et al., 2004). Therefore, episodic rainfall events may change the well-established response relationship between RS and TS on shorter timescales (Han et al., 2018) leading to the uncertainty and errors in quantifying soil carbon efflux(Drake et al., 2018; Ni et al., 2019; Yan et al., 2014). Due to a lack of understanding on the dynamic responses of RS to rainfall events, current process-based ecosystem models have not integrated the carbon cycling responses to the rainfall events (Liu et al., 2016). Often time, widely used empirical model of respiration and soil temperature does not fully incorporate the complexity of the soil processes, limiting its predictive ability, especially over short time scales (Curiel Yuste et al., 2005; Yan et al., 2019).

Previous field measurements and manipulation experiments have shown that, in most water-limited ecosystems, RS may be stimulated by rainfall events due to SM increase as this could lead to higher availability of substrates for microorganisms and enhanced ecosystem photosynthesis (Knapp et al., 2008; Afreen and Singh, 2019; Wang et al., 2019). However, in water-rich ecosystems, RS can be depressed by rainfall events as the increased SM may lead to limitations on the diffusion of oxygen and microbial activity (Han et al., 2018; Luo and Zhou, 2006; Wang et al., 2012). Although prior studies have explored RS responses to rainfall events for different ecosystems, seasonal variations of such responses are not explicitly considered (Liu et al., 2016, 2019a; Peng et al., 2013). With changes in phenology (Radville et al., 2016) and precipitation distribution variability under climate change (Beier et al., 2012; IPCC, 2014; Pfahl et al., 2017), the uncertainty regarding the impact of rainfall events on soil carbon efflux will increase further.

A recent meta-analysis found that increasing RS stimulated by rainfall events was consistently observed in regions where annual rainfall is lower than 800 mm (Ni et al., 2019). Nevertheless, SM of riparian ecosystems in semi-humid and semi-arid regions can be affected by both rainfall events and shallow groundwater (Perry et al., 2012; Smith et al., 2017). In addition, riparian forest ecosystems generally display higher biological activity and more gas diffusion compared with non-riparian ecosystems in semi-arid and semi-humid regions due to the seasonal hydrological fluctuation and frequent water infiltration (Chang et al., 2014; Poblador et al., 2017; Scott et al., 2004). In such systems, intra-annual switches between aerobic and anaerobic states are possible, which in turn affect the RS (Castelli et al., 2000; Han et al., 2018; Xu et al., 2018). Moreover, climate change is expected to have dramatic influence on the rainfall patterns and hydrological conditions such as changes in flow regime, groundwater supply, and plant-available water(Nilsson et al., 2013; Nunes et al., 2008). Such changes may also alter the species richness, disrupt nutritional and symbiotic interactions in dryland riparian ecosystems, and even widen /narrow the riparian zone(Perry et al., 2012; Stromberg et al., 2013). As a result, variations in carbon fluxes of riparian ecosystems are significant in global carbon cycling projections, especially as these systems are considered as early warning systems for climate change (Capon et al., 2013; Perry et al., 2012; Singh et al., 2017). Clearly, quantifying the impact of rainfall events on RS can improve our understanding of the biophysical changes in these ecosystems and enable our advances in model development for more accurate prediction of the role of riparian ecosystems in the global carbon cycle under changing rainfall patterns.

In this study, soil CO_2 fluxes were continuously measured in a riparian plantation ecosystem across four years (2015-2018). We hypothesized that the soil respiration responses to the rainfall events in the riparian plantation ecosystem have seasonal variations and governed by coupled interactions of rainfall regime and groundwater fluctuation. Specifically, our research objectives are to: (1) determine the seasonal variation in RS responses to rainfall events; (2) explore the regulatory mechanisms of RS response to rainfall events in different seasons, and (3) quantify the effects of rainfall size on RS.

2. Materials and methods

2.1 Site description

This study was conducted in a riparian poplar plantation along the Chaobai river in Gongqing Forest Park (40° 06′ 30″ N, 116° 42′ 30″ E, 9 m a.s.l.), located in Shunyi District, Beijing, China. The temperate continental monsoon climate is characterized by hot and humid summers, and cold and dry winters. Long-term observations (1985-2015) from the Shunyi Meteorological Station show that the average annual air temperature is 13.4°C, with a mean monthly temperature of -2.9°C in January and 26.8°C in July. Mean annual precipitation is 546 mm and about 94% falls between April and October, with over 67% occurring in summer (June-August) mainly resulted from locally intense convective storms. Study site is topographically flat and about 500 meters away from Chaobei River, where there was no over-bank flow occurred throughout the study period. The groundwater table depth was around 2m, with seasonal fluctuation of about ± 0.5 m.

The field experiment was setup in a poplar (*Populus euramericana*) plantation which was approximately 35 years-old. Fine roots (<2mm) are mainly distributed at 0-60 cm, and the fine root biomass decreases as the soil layer deepens. Stand density is 367 trees ha^{-1} with mean tree height of 17 ± 1.2 m (mean ± SD) and mean diameter at breast height of 26 ± 4.3 cm in 2016. The understory vegetation is dominated by *Swida alba* (L.) Opiz., Pinus *bungeana* Zucc. ex Endl., *Flos Caryophylli*, *Sabina vulgaris* Antoine, and *Gaillardia aristata* Pursh. The bulk density of the well-drained riparian sandy soil is 1.51 ± 0.05 g cm^{-3}. Soil texture was 92% sand, 2% silt, and 6% clay. Soil nutrient concentrations decrease with soil depth, and the average soil organic carbon and soil organic nitrogen at 0-30cm depth was 2.79 ± 0.23 g kg^{-1} and 0.13 ± 0.01 g kg^{-1}, respectively. More details about the soil characteristics can be found in the study by Zhu et al. (2019).

2.2 Soil respiration measurement

Soil respiration was measured during the growing season (April-October) for four consecutive years from 2015 to 2018, using a LI-8100 automated RS measurement system and LI-8150 multiplexer with four 8100-104 long-term chambers (Li-Cor Inc, Lincoln, NE, USA). Four soil collars (11.4 cm in height and 21.3 cm in diameter) were randomly distributed in the study site and inserted 3 cm into the soil one month before the first measurement. The soil collars were left in place throughout the study period, with measurements made at least once every 2 hours. Each measurement took 120 seconds and the linear increase of CO_2 concentration in the chamber was used to estimate RS. Hourly means were computed as the mean of the 4 chambers, and daily means were computed as the average of the hourly means. During the entire study period, all living plants inside the collars were carefully clipped regularly from the soil surface to exclude aboveground plant respiration.

2.3 Meteorological measurement

Precipitation was measured using an InteliMet Advantage Weather Station (Dynamax Inc., USA), which was located outside of the forest, about 200 m from the research site. Soil temperature and soil moisture were measured at depths of 10 cm and 5 cm by a LI-8150 system equipped with LI-8150-203 and LI-8150-202 sensors, respectively (Li-Cor Inc., Lincoln, NE, USA). Both TS and SM sensors were placed near the RS monitoring points. Furthermore, additional SM was measured by three soil moisture probes (CS616, Campbell Scientific Inc., USA) installed at depths of 25, 60, 100 cm, respectively, in the center of the measurement field from 2016 to 2018.

2.4 Data analyses

The growing season was defined as the period when average net ecosystem productivity (NEP) of three years (2015, 2016, and 2017) exceeded 1 g C m^{-2} d^{-1} (Richardson et al., 2010), which is from the day of the year (DOY) from 96 to 302. In addition, we divided the growing season into spring (DOY 96-151), summer (DOY 152-243), and autumn (DOY 244-302). When analyzing the response of RS to rainfall event during the growing season, we focused on discrete rainfall episodes, i.e. events lasting less than a day, while rainfall events spanning more than one day were excluded. The relative change of soil respiration rate (RSrc) after rainfall event was calculated by the difference between daily soil respiration rate on the day after rainfall (post-RS) and the day before the rain (pre-RS) divided by pre-RS [i.e. (post-RS - pre-RS) / pre-RS]. To explore the influence of rainfall events on SM and TS, we calculated changes of soil moisture (ΔSM) and soil temperature (ΔTS) between the day after rainfall and the day before the rain. In addition, according to the classification standard of precipitation intensity issued by China National Meteorological Administration, the cumulative rainfall within 24 hours a day was divided into three levels: light (< 10 mm), moderate (10-25 mm), and heavy (> 25 mm).

Prior to statistical analysis the data was tested for normal distribution and the non-normal data was log or reciprocal transformed. Paired t-tests were used to analyze the differences in daily RS, TS, and SM before and after rainfall in each season. However, soil temperature and moisture data among three seasons were still non-normally distributed after transformation. We therefore used non-parametric Kruskal-Wallis H test to conduct the analysis. One-way ANOVA was used to analyze the differences in daily mean RS among three seasons, before and after rainfall, and post hoc least significant differ (LSD) test if significant. Also, regression analysis was used to determine the effects of rainfall size on RSrc, ΔSM, and ΔTS. In order to understand the impacts of environmental variables on RSrc in different seasons, stepwise multiple regressions were performed, with RS as the dependent variable, and soil temperature before rain (pre-TS), soil temperature after rain (post-TS), soil moisture content before rain (pre-SM), soil moisture content after rain (post-SM), ΔSM, ΔTS as the independent variables. Furthermore, Spearman rank correlation analysis was applied to identify the relationships between daily RS and SM and TS following rainfall events. . The relationship between daily RS and TS before and after rainfall was fitted using a simple empirical exponential model: $RS = a \times e^{bTs}$,(TS is the soil temperature (°C), and a and b model parameters). After the exponential relationship was linearized, the difference of the regression relationship before and after rainfall was compared by covariance analysis. The temperature sensitivity (Q_{10}) was estimated from the classical equation: $Q_{10} = e^{10b}$. All analyses were performed using SPSS 19.0 for Windows (SPSS Inc., Chicago, IL).

3. Results

3.1 Environmental conditions and soil respiration in different seasons

The contribution of rainfall from June to August to the growing season total was relatively high in all four study years (Fig. 1). Eighty-three independent daily rainfall events were identified, with 22, 39, and 22 events occurring in spring, summer, and autumn, respectively (Fig. 2). The majority (75%) of rainfall events in spring amounted to less than 5 mm (Fig. 2). The variation of rainfall size in summer was the greatest, and more than 50% of the rainfall events exceeded 10 mm (Fig. 2). Although the mean and variation range of rainfall event size in autumn were larger than those in spring, more than 75% of rainfall events were light and less than 10mm (Fig. 2).

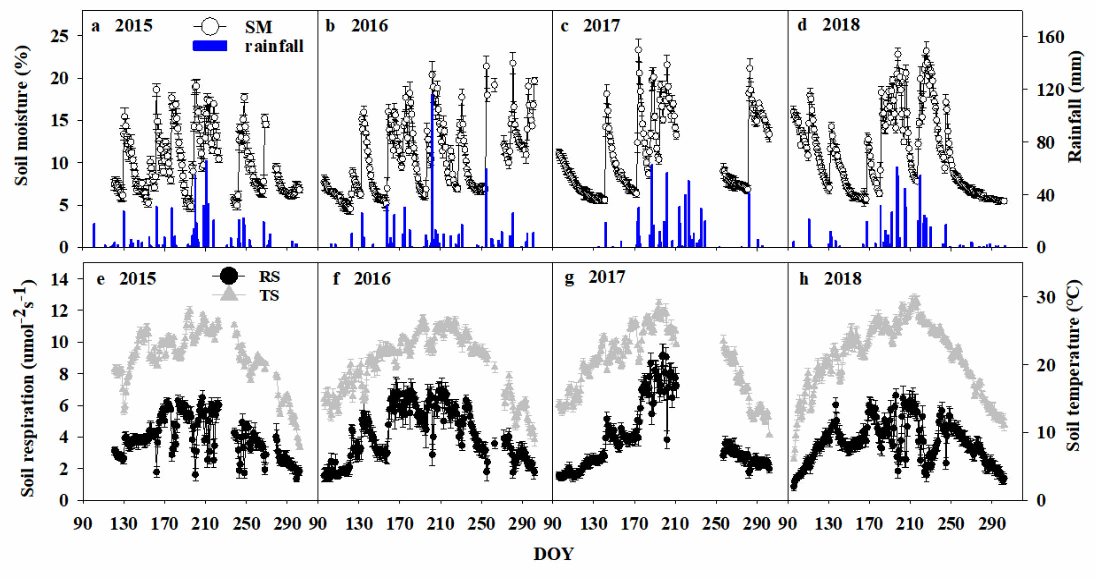

Fig. 1 Daily rainfall and soil moisture (upper panel a-d) and averaged daily soil respiration and soil temperature (lower panel e-h) from 2015 to 2018. Vertical bars represent the standard error of four soil chambers (lower panel). Breaks in the connecting line indicate missing data due to instrument failure.

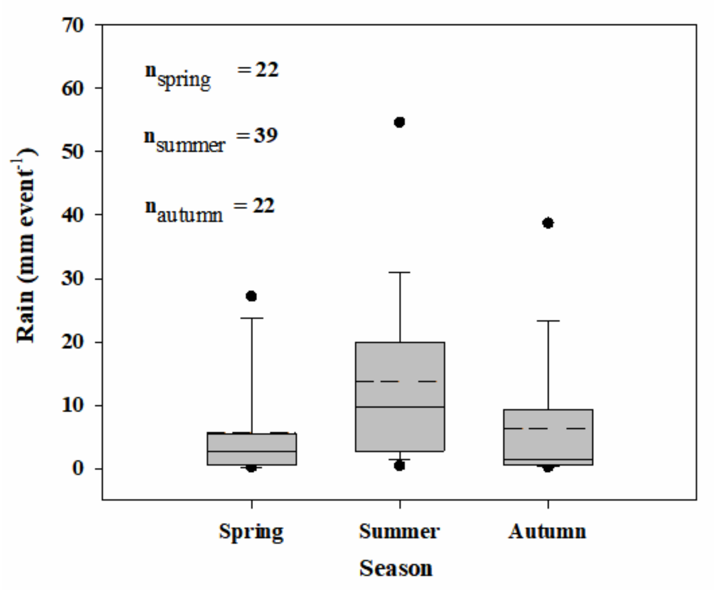

Fig. 2 Distribution of 83 individual daily rainfall events in different seasons across the four-year study period. The median, mean, 25th/75th percentile, 10th/90th percentile, and 5th/95th percentile are shown as solid line, dashed line, box, whiskers and dots, respectively. The letter n represents the number of rainfall events in each season.

Soil moisture at 5 cm depth was affected by rainfall events, with larger rainfall sizes leading to stronger increases in SM (Fig. 1 and Fig.S.1). The average post-SM was significantly higher than the average pre-SM in summer ($p < 0.01$, Fig. 3a). Although the averaged post-SM was also higher than pre-SM in spring and autumn, the difference was not significant (Fig. 3a) due to the small size of rainfall events (Figs. 1 and 2). In addition, the three-year (2016, 2017, and 2018) averaged daily SM at different soil depths (25cm, 60cm, and 100cm) showed obvious seasonal fluctuation (Fig. S.2) governed by the temperate monsoon climate.

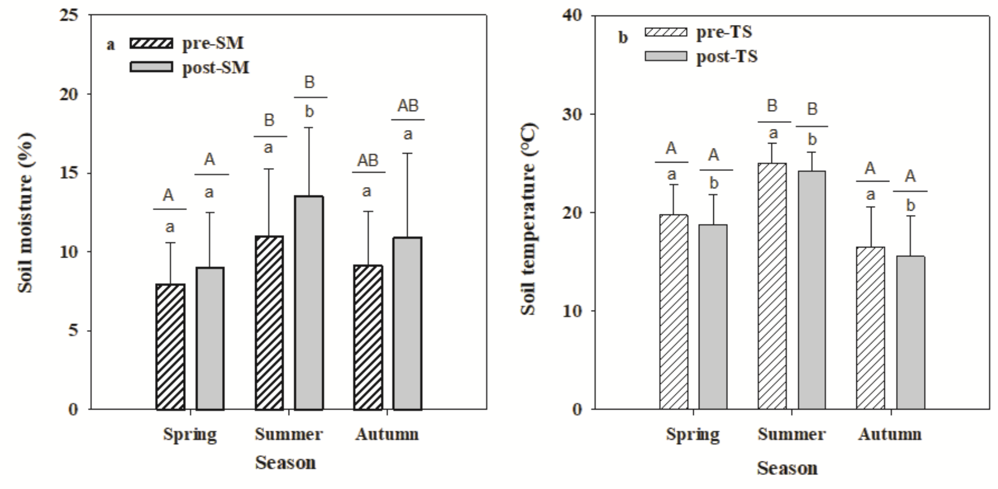

Fig. 3 Averaged soil volumetric moisture content (SM± SD) (a) and soil temperature (TS± SD) (b) before and after rainfall events in different seasons across the four years. Uppercase letters indicate significant differences between seasons (pre-RS and post-RS, respectively). Lowercase letters represent the differences between pre- and post-rain events within the same season. More information about the analyses can be found in Tables S.1 and S.2.

Mean post-TS was lower than mean pre-TS in all seasons (Fig. 3b) indicating that rainfall events had a significant effect on TS ($p < 0.05$, Fig. 2b and Fig. S.1d-f). In addition, among the three seasons, the lowest averaged TS was in autumn (Fig. 3b). The seasonal variations in RS were similar for each of the 4 years, increasing from spring, peaking in summer, and then decreasing gradually in autumn (Fig. 1).

3.2 Soil respiration response to rainfall events

Although the seasonal variations in RS were in general consistent with the seasonal changes in TS, there were distinct mismatched periods (many outliers of daily RS) when rainfall events (especially large sized ones) occurred (Fig. 1). The mean post-RS was significantly higher than the mean pre-RS in spring, while mean post-RS was significantly lower than mean pre-RS in autumn ($p < 0.05$, Fig. 4a). Although mean post-RS was also lower than mean pre-RS in summer, this difference was not statistically significant (Fig. 4a).

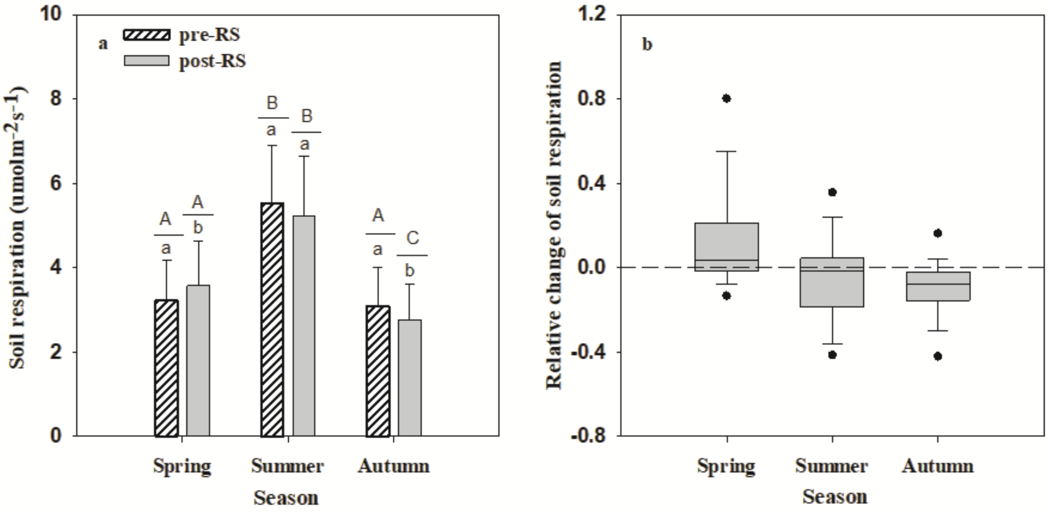

Fig. 4 Averaged daily soil respiration (a) and the relative change of soil respiration (RSrc) (b) in different seasons. Uppercase letters indicate significant differences between seasons（pre-RS, post-RS, respectively, lowercase letters refer to significant differences between pre- and post-rain events within the same season ($p < 0.05$). The median, 25th/75th percentile, 10th/90th percentile, and 5th/95th percentile are shown as solid line, box, whiskers and dots, respectively. Black short dash line at RSrc = 0. More information about the analyses can be found in Tables S.1 and S.3.

3.3 Effect of soil moisture and soil temperature on soil respiration following rainfall events in different seasons

There was a significant positive correlation between RS and SM following rainfall events in spring (Table 1 and Fig. 5a-c). However, the relationship between RS and TS was decoupled (Fig. 5a-c and Table 1). The change in SM after rainfall (ΔSM) explained 82% of the variation in RSrc in spring, with the relationship between them being positive ($p < 0.01$, Table 2). In contrast to spring, RS significantly decreased as soil was wetter following rainfall in summer and autumn (Fig.5d-i and Table 1,). TS was not significantly correlated with RS after rainfall in summer (like in spring), though the lack of a significant relationship may have been caused by the small temperature range (unlike in spring) (Table 1 and Fig. 5). Indeed, when considering ΔTS, we find a positive effect of temperature (Table 2). Taken together, ΔTS (positive effect) and post-SM (negative impact) together explained 33% of changes in RSrc in summer ($p < 0.01$). Finally, in autumn, we found a significant negative relationship between SM and RS after rain, and a significant positive relationship between TS and RS (Table 1). Together, 64% of the variance in RSrc could be accounted for by ΔSM (negative effect, $R^2 = 0.53$, $p < 0.01$) and ΔTS (positive effect, $R^2=0.11$, $p < 0 .05$) (Table 2).

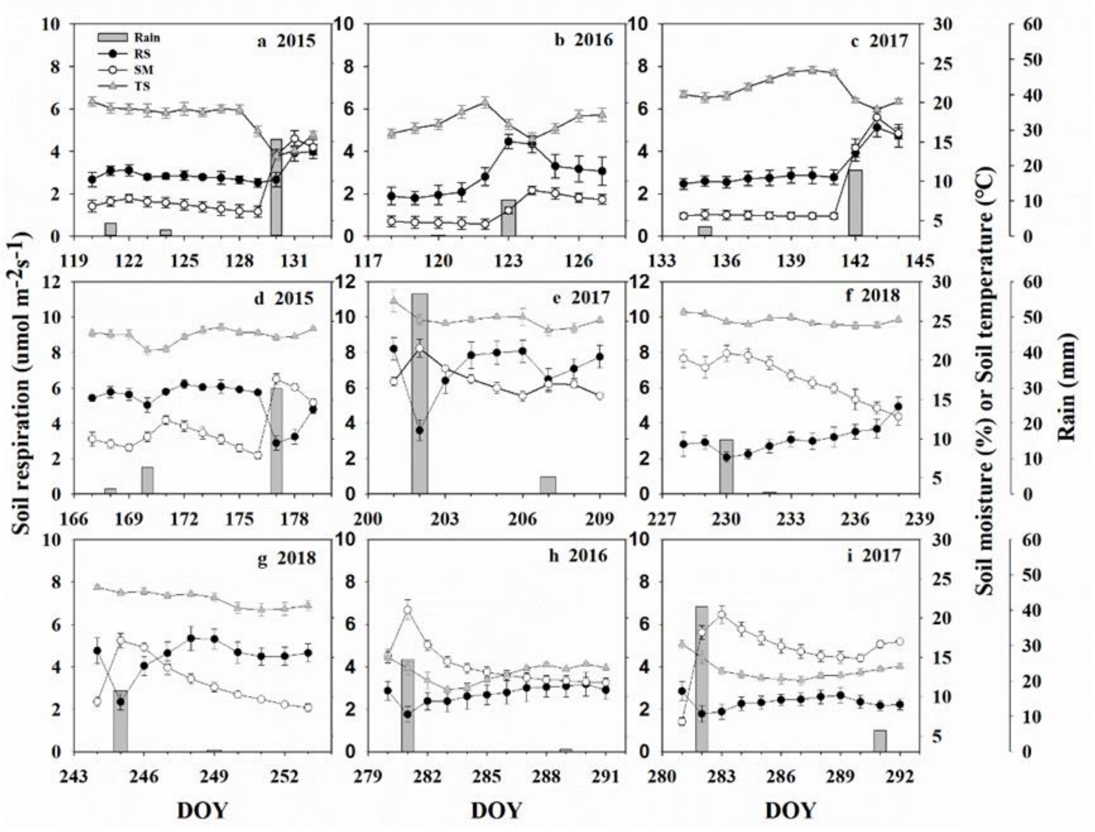

Fig. 5 Soil respiration, soil moisture, soil temperature and daily rainfall amount during the sampling periods for the four years and spring (a-c), summer(d-f), autumn (g-i). Error bars represent the standard error of four soil chambers. Our sampling periods generally contains more than two rainfall sizes including light (< 10 mm), moderate (10-25 mm), and heavy (> 25 mm). However, there were no distinct rainfall events >10mm occurring in the spring of 2018 and only three years of data are presented here.

3.4 Effects of rainfall event size on soil respiration in different seasons

Soil respiration had different responses to the size of rainfall event in the three different seasons (Fig. 6 and Fig. 5). RSrc was stimulated more if the size of precipitation events was larger in spring (Fig. 6a). In contrast, the correlation between

RSrc and rainfall size was generally negative in summer and autumn (Fig. 6). In summer, these suppressive effects especially occurred after heavy rainfall (> 25 mm) events (inserted panels in Fig. 6b, c and Fig. 5 d, e, h, i).

Rare heavy rain events in spring and autumn made it impossible to perform meaningful analysis on the seasonal difference in relationships between RS and TS per rainfall class. Therefore, we pooled data over the three seasons for subsequent analysis. Reflecting minor and insignificant difference in ΔSM, the temperature sensitivity (Q_{10}) of RS before and after light rainfall (< 10 mm) was similar (Fig. 7a). However, more intense rain events led to a significant increase in SM ($p < 0.05$) (insets in Fig. 7a-c), and this was mirrored by a lower influence of temperature on RS (lower Q_{10}) especially after heavy rainfall (> 25 mm) (Fig. 7 b and c).

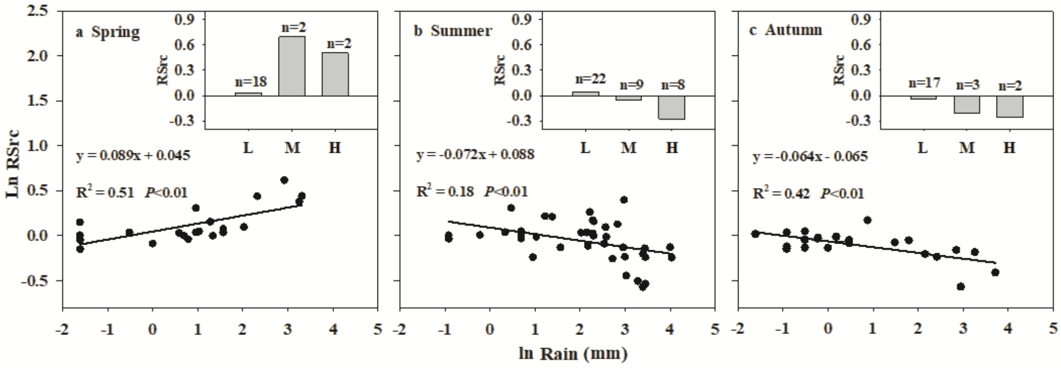

Fig. 6 Relationship between the relative change in soil respiration (RSrc) and the rainfall event size. The insert panel shows the mean relative change in soil respiration for three rainfall size classes L: light (< 10 mm), M: moderate (10-25 mm), H: heavy (> 25 mm) in each season. The letter n represents the number of samples of rainfall events in each rainfall size class. Rain and

RSrc were log transformed (Ln) before regression analysis.

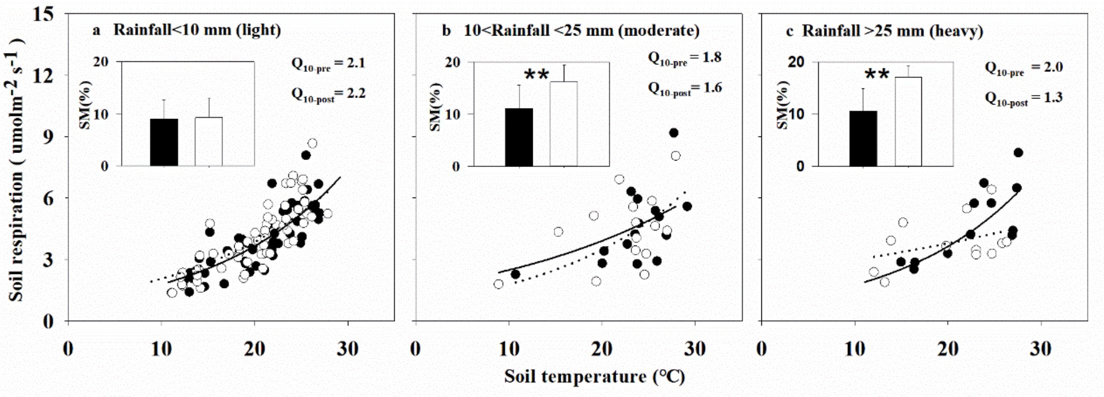

Fig. 7 Comparison of relationships between soil respiration and soil temperature at 10 cm depth before rainfall (pre-rain) (black circle) and after rainfall (post-rain) (white circle) in different rainfall size level (a-c) for the four years. The equation $y = ae^{bx}$ was used to describe the relationship between soil temperature and soil respiration. $Q_{10} = e^{10b}$. The inset shows the mean soil moisture with pre-rain (black column) and post-rain (white column), ** indicates significant differences ($p < 0.01$).

4. Discussion

4.1 Seasonality of soil respiration response to rainfall event

Soil respiration response to rainfall event varies due to the difference in ecosystem types, climatic variability and soil biophysical properties (Han et al., 2018; Liu et al., 2016; Niu et al., 2019). Our results indicated that the response of RS to rainfall events was characterized by strong seasonality. RS was stimulated by rainfall events in spring, but was generally reduced in summer and autumn, especially when the rainfall events were large. Liu et al.(2019a) also suggested that there are seasonal changes in the impact of rainfall events on RS in a non-riparian ecosystem. Yet they found that rainfall events stimulated RS throughout the growing season, with only the degree of stimulation differing throughout the year (Liu et al., 2019a). The influence of rainfall events on RS mainly depends on the abiotic factors such as post-TS and pre-SM in the same ecosystem(Han et al., 2018; Yoon et al., 2014). In the present study, there were different the relative changes in RS following rainfall events due to the variations in the dominate role of ΔSM, post-SM and ΔTS in different seasons. Such factors are strongly regulated by rainfall events, and substantial change occurred when rainfall size increased. The ΔSM, representing rapid changes in soil moisture or wetting intensity(Lado-Monserrat et al., 2014; Rey et al., 2017), plays an important role in driving the RS response to rainfall events in spring and autumn. The negative effects of SM on RS in summer and autumn were seemingly amended by a direct stimulation of biological activity under higher TS.

Regardless of seasonality, positive effects of rainfall events on RS have been found both in field studies and rainfall manipulation experiments conducted in a variety of ecosystems, even in humid and semi-humid areas (Peng et al., 2013; Liu et al., 2017b; Wang et al., 2019). In our study, RS was significantly increased by rainfall events and there was a significant positive correlation between RS and SM following rainfall events only in spring. This associated with a number of abiotic and biotic mechanisms. First, compared with other seasons, rainfall events in spring were relatively small, the interval between events was longer, and the mean season pre-SM of surface soils in spring was lowest of the three seasons. Although there is a relatively low groundwater tables in the riparian ecosystems, deep SM cannot be effectively replenished due to the size and frequency of rainfall events during spring (Fig.S.2). Low SM can inhibit soil microbial activity (Almagro et al., 2009), and increased available SM following rainfall events would induce RS through improved diffusion of substrates (Lado-Monserrat et al., 2014). Secondly, lower rainfall frequency in spring may increase the amount of CO_2 accumulated in soil pores (Liu et al., 2019b); with the occurrence of rainfall events, the CO_2 in the pores could be replaced by soil moisture, pushing the CO_2 out (Huxman et al., 2004). Thirdly, re-activated root growth in spring could imply higher sensitivity to SM (Schwinning et al., 2005), with increased SM after rainfall quickly stimulating root growth and induce RS (Liu et al., 2019a).

Conversely, RS decreased with increasing rainfall size in summer and autumn. Previous studies have shown that RS was inhibited when rainfall events occurred in a wet soil environment (McLain and Martens, 2006; Wang et al., 2012; Han et al., 2018). Increases in SM caused by rainfall events can reduce the soil oxygen concentration when the soil pore spaces are filled with water (Van Straaten et al., 2010). The ensuing anoxic stress would inhibit the activity of aerobic microorganisms and even suppress the metabolism of plants and aerobic respiration of roots, thus reducing RS production (Lado-Monserrat et al., 2014;Singh et al., 2017). Notably, riparian ecosystems are usually characterized by sandy soils in dryland regions, and the macropore space allows diffusion of atmospheric gases and even provides sufficient oxygen for aerobic microorganisms in the deep soil (McLain and Martens, 2006; Schjønning et al., 2003). Also, coarse-textured soils have lower water holding capacity and higher permeability rate(Gao et al., 2018). Rainfall events are therefore more likely to cause anoxic conditions and inhibit decomposition and respiration in the riparian ecosystem. Furthermore, heavy (> 25mm) rainfall events occurred more frequently in summer than in spring and autumn, which resulted in high post-SM even if the pre-SM was low (Fig.5).On the other hand, the rainfall amount in summer accounts for a large proportion of the annual total, and the SM level in summer was relatively high, reaching 51-65% of the water holding capacity. The threshold value of SM at which RS begins to decline is near 60% of the field capacity(Shi et al., 2011). Taken together, this implies that the potential for suppression of RS by high SM values was highest in summer in our study system. Moreover, compared with silt and clay, the stability of sandy soil protective aggregates is poor, and heavy rainfall could therefore easily cause dissolved organic carbon leaching from the surface, thus reducing CO_2 efflux (Knapp et al., 2008).

Surprisingly, we found that RS was more easily suppressed by rainfall in autumn, although the seasonal mean SM of surface was lower than in summer, both before and after rainfall events. After the replenishment of frequent heavy rain events in the late summer, the groundwater level of the riparian ecosystem was increased, resulting in relatively high values of SM in the deep soil layers in autumn (Fig. S.2). In addition, poplar trees have high water consumption and root system with strong SM absorption capacity that can take up SM both from surface and deep soil layers (Liu et al., 2020; Lu et al., 2009). When deep SM supply is sufficient, on one hand, capillary rising water will supplement the SM of upper dry soil and fill the fine pore spaces (Han et al., 2018; Smith et al., 2017). On the other hand, hydraulic lift (i.e., upward redistribution of water by plant roots) increases water availability in the dry top soil, which would help maintain the activity of microbial communities and fine roots near the soil surface (Almeida-Rodriguez et al., 2011; Bauerle et al., 2008). Thus, additional water from rainfall events could suppress RS also in autumn, especially under more intense rainfall. Nevertheless, the deciduous poplar plantation could provide more fast-degradable carbon sources for microbial activity in autumn. However, relatively low TS and the reduction in the number of microbes following rainfall could negatively affect the decomposition of substrates immediately and inhibit RS (Lado-Monserrat et al., 2014; Peng et al., 2013; Rey et al., 2017). Our results indicate that the influence of rainfall on RS in this riparian forest ecosystems was not only related to the short-term effects of rainfall, but also to the interplay between longer term, rain-associated seasonal fluctuations in groundwater levels and immediate rain events.

4.2 Impact of rainfall size

While initial SM conditions, both at the surface and in the deeper layers, are important in affecting RS response, rainfall size was important as well (Table 2). Especially in spring and autumn, the ΔSM (which depended on the rainfall size) was a major driver of soil carbon emissions. Other studies have also reported on the importance of rainfall size on RS (Rey et al., 2017; Zeppel et al., 2014). Furthermore, the size of rainfall events could also determine the magnitude of RS responses in different months (Niu et al., 2019). In our study, rainfall size seemed to mostly reinforce the seasonal trends: increased RS when rainfall was moderate or high in spring, decreased RS after moderate or high intensity events in summer and autumn. Light rainfall had only minor or insignificant effects. Moreover, our results also demonstrate that the sensitivity of soil respiration to soil temperature (Q_{10}) can be decreased if daily precipitation intensity is higher. The water status of the riparian ecosystem is thought to in turn influence such effects (Suseela et al., 2012; Yu et al., 2020). In the last 50 years, the number of extreme rainfall events in China has increased in the period April-July, and slightly decreased in the late summer and autumn (Fu et al., 2013). As we have shown that rainfall size and seasonal factors can both influence RS, changes in rainfall patterns expected under climate change in China and elsewhere in the world (IPCC, 2014) may significantly alter soil respiration. Regional and global carbon budget assessments would thus benefit from more accurate quantification of the impact of different rainfall sizes on RS.

---

5. Conclusions

Seasonal differences in response of soil respiration of a riparian poplar plantation ecosystem to individual rainfall events were found over the four years study period. In spring, characterized by dry background soil conditions, soil respiration was more significantly coupled with soil moisture than soil temperature. As a result, rainfall events generally stimulated RS during this season. In contrast, RS was reduced in summer and autumn after rainfall. Higher overall soil moisture levels in these seasons, including a higher water table in autumn, led to faster water saturation of the soil, especially when daily rainfall exceeded 25 mm. Regardless of season, heavy rainfall tended to decrease the sensitivity of RS to soil temperature. This suggests that changes in the seasonal distribution of rainfall or rainfall sizes will increase the uncertainty for evaluating terrestrial ecosystem carbon emission by current empirical and processes based models at multiple scales.

Acknowledgements

This study was financially supported by the National Natural Science Foundation of China [grant number 31872711]. We also gratefully acknowledge the Beijing Municipal Education Commission for their financial support through Innovative Trans-disciplinary Program of Ecological Restoration Engineering and to the first author by Postgraduate Training Project (No.BLCXY2016) .The support of National

Forestry Welfare Research Program “Forest Management Affecting the Coupling of Ecosystem Carbon and Water Exchange with Atmosphere” (No.201704102) is also greatly acknowledged.

References

Afreen, T., Singh, H., 2019. Does change in precipitation magnitude affect the soil respiration response? A study on constructed invaded and uninvaded tropical grassland ecosystem. Ecol. Indic. 102, 84–94. https://doi.org/10.1016/j.ecolind.2019.02.022

Almagro, M., Lopez, J., Querejeta, J., M.Martínez-Mena, 2009. Temperature dependence of soil CO_2 efflux is strongly modulated by seasonal patterns of moisture availability in a Mediterranean ecosystem. Soil Biol. Biochem. 41, 594–605. https://doi.org/10.1016/j.soilbio.2008.12.021

Almeida-Rodriguez, A.M., Hacke, U.G., Laur, J., 2011. Influence of evaporative demand on aquaporin expression and root hydraulics of hybrid poplar. Plant, Cell Environ. https://doi.org/10.1111/j.1365-3040.2011.02331.x

Bauerle, T.L., Richards, J.H., Smart, D.R., Eissenstat, D.M., 2008. Importance of internal hydraulic redistribution for prolonging the lifespan of roots in dry soil. Plant, Cell Environ. https://doi.org/10.1111/j.1365-3040.2007.01749.x

Beier, C., Beierkuhnlein, C., Wohlgemuth, T., Penuelas, J., Emmett, B., Körner, C., de Boeck, H., Christensen, J.H., Leuzinger, S., Janssens, I.A., Hansen, K., 2012. Precipitation manipulation experiments - challenges and recommendations for the future. Ecol. Lett. 15, 899–911. https://doi.org/10.1111/j.1461-0248.2012.01793.x

Capon, S.J., Chambers, L.E., Mac Nally, R., Naiman, R.J., Davies, P., Marshall, N., Pittock, J., Reid, M., Capon, T., Douglas, M., Catford, J., Baldwin, D.S., Stewardson, M., Roberts, J., Parsons, M., Williams, S.E., 2013. Riparian Ecosystems in the 21st Century: Hotspots for Climate Change Adaptation? Ecosystems 16, 359–381. https://doi.org/10.1007/s10021-013-9656-1

Castelli, R.M., Chambers, J.C., Tausch, R.J., 2000. Soil-plant relations along a soil-water gradient in great basin riparian meadows. Wetlands 20, 251–266. https://doi.org/10.1672/0277-5212(2000)020[0251:SPRAAS]2.0.CO;2

Chang, C.-T., Sabaté, S., Sperlich, D., Poblador, S., Sabater, F., Gracia, C., 2014. Does soil moisture overrule temperature dependency of soil respiration in Mediterranean riparian forests? Biogeosciences Discuss. 11, 7991–8022. https://doi.org/10.5194/bgd-11-7991-2014

Chen, M., Wang, Y., Gao, F., Xiao, X., 2012. Diurnal variations in convective storm activity over contiguous North China during the warm season based on radar mosaic climatology. J. Geophys. Res. Atmos. 117, 1–14. https://doi.org/10.1029/2012JD018158

DeForest, J.L., Noormets, A., McNulty, S.G., Sun, G., Tenney, G., Chen, J.,

2006. Phenophases alter the soil respiration-temperature relationship in an oak-dominated forest. Int. J. Biometeorol. 51, 135–144. https://doi.org/10.1007/s00484-006-0046-7

Deng, Q., Zhou, G., Liu, S., Chu, G., Zhang, D., 2011. Responses of soil CO 2 efflux to precipitation pulses in two subtropical forests in Southern China. Environ. Manage. 48, 1182–1188. https://doi.org/10.1007/s00267-011-9732-2

Drake, J.E., Macdonald, C.A., Tjoelker, M.G., Reich, P.B., Singh, B.K., Anderson, I.C., Ellsworth, D.S., 2018. Three years of soil respiration in a mature eucalypt woodland exposed to atmospheric CO2 enrichment. Biogeochemistry 139, 85–101. https://doi.org/10.1007/s10533-018-0457-7

Fa, K.Y., Liu, J. Bin, Zhang, Y.Q., Wu, B., Qin, S.G., Feng, W., Lai, Z.R., 2015. CO2 absorption of sandy soil induced by rainfall pulses in a desert ecosystem. Hydrol. Process. https://doi.org/10.1002/hyp.10350

Fu, G., Yu, J., Yu, X., Ouyang, R., Zhang, Y., Wang, P., Liu, W., Min, L., 2013. Temporal variation of extreme rainfall events in China, 1961-2009. J. Hydrol. 487, 48–59. https://doi.org/10.1016/j.jhydrol.2013.02.021

Gao, W., Huang, Z., Ye, G., Yue, X., Chen, Z., 2018. Effects of forest cover types and environmental factors on soil respiration dynamics in a coastal sand dune of subtropical China Effects of forest cover types and environmental factors on soil respiration dynamics in a coastal sand dune of subtropical Chi. J. For. Res. 29, 1645–1655. https://doi.org/10.1007/s11676-017-0565-6

Gong, J., Ge, Z., An, R., Duan, Q., You, X., Huang, Y., 2012. Soil respiration in poplar plantations in northern China at different forest ages. Plant Soil 360, 109–122. https://doi.org/10.1007/s11104-011-1121-3

Han, G., Sun, B., Chu, X., Xing, Q., Song, W., Xia, J., 2018. Precipitation events reduce soil respiration in a coastal wetland based on four-year continuous field measurements. Agric. For. Meteorol. 256–257, 292–303. https://doi.org/10.1016/j.agrformet.2018.03.018

Hanson, P.., Edwards, N.., Garten, C.., Andrews, J.., 2000. Separating root and soil microbial contributions to soil respiration: A review ofmethods and observations. Biogeochemistry 48, 115–146. https://doi.org/10.1023/A:1006244819642

Huxman, T.E., Snyder, K.A., Tissue, D., Leffler, A.J., Ogle, K., Pockman, W.T., Sandquist, D.R., Potts, D.L., 2004. Precipitation pulses and carbon fluxes in semiarid and arid ecosystems. Oecologia 254–268. https://doi.org/10.1007/s00442-004-1682-4

IPCC, 2014. Climate change 2014: Impacts, adaptation, and vulnerability. Part B: Regional aspects.In V. R. Barros, C. B. Field, D. J. Dokken, M.D. Mastrandrea, K. J. Mach, T. E. Bilir, L. L. White (Eds.), in: Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK: Cambridge University Press., pp. 64–65.

Knapp, A.K., Beier, C., Briske, D.D., Classen, A.T., Luo, Y., Reichstein, M., Smith, M.D., Smith, S.D., Bell, J.E., Fay, P.A., Heisler, J.L., Leavitt, S.W., Sherry, R., Smith, B., Weng, E., 2008. Consequences of More Extreme Precipitation Regimes for Terrestrial Ecosystems. Bioscience 58, 811–821. https://doi.org/10.1641/b580908

Lado-Monserrat, L., Lull, C., Bautista, I., Lidón, A., Herrera, R., 2014. Soil moisture increment as a controlling variable of the “Birch effect”. Interactions with the pre-wetting soil moisture and litter addition. Plant Soil 379, 21–34. https://doi.org/10.1007/s11104-014-2037-5

Liu, L., Wang, X., Lajeunesse, M.J., Miao, G., Piao, S., Wan, S., Wu, Y., Wang, Z., Yang, S., Li, P., Deng, M., 2016. A cross-biome synthesis of soil respiration and its determinants under simulated precipitation changes. Glob. Chang. Biol. 22, 1394–1405. https://doi.org/10.1111/gcb.13156

Liu, Y., Liu, S., Miao, R., Liu, Y., Wang, D., Zhao, C., 2019a. Seasonal variations in the response of soil CO_2 efflux to precipitation pulse under mild drought in a temperate oak (Quercus variabilis) forest. Agric. For. Meteorol. 271, 240–250. https://doi.org/10.1016/j.agrformet.2019.03.009

Liu, Y., Liu, S., Wan, S., Wang, J., Wang, H., Liu, K., 2017a. Effects of experimental throughfall reduction and soil warming on fine root biomass and its decomposition in a warm temperate oak forest. Sci. Total Environ. 574, 1448–1455. https://doi.org/10.1016/j.scitotenv.2016.08.116

Liu, Y., Shang, Q., Wang, Z., Zhang, K., Zhao, C., 2017b. Spatial

Heterogeneity of Soil Respiration Response to Precipitation Pulse in A Temperate Mixed Forest in Central China. J. Plant Anim. Ecol. 17, 1863. https://doi.org/10.14302

Liu, Y., Zhao, C., Shang, Q., Su, L., Wang, L., 2019b. Responses of soil respiration to spring drought and precipitation pulse in a temperate oak forest. Agric. For. Meteorol. 268, 289–298. https://doi.org/10.1016/j.agrformet.2019.01.029

Liu, Z., Jia, G., Yu, X., 2020. Variation of water uptake in degradation agroforestry shelterbelts on the North China Plain. Agric. Ecosyst. Environ. 287, 106697. https://doi.org/10.1016/j.agee.2019.106697

Lu, N., Wilske, B., Lu, N., Wei, L., Chen, S., Zha, T., Liu, C., Xu, W., 2009. Poplar plantation has the potential to alter water balance in semiarid Inner Poplar plantation has the potential to alter the water balance in semiarid Inner Mongolia. J. Environ. Manage. 90, 2762–2770. https://doi.org/10.1016/j.jenvman.2009.03.004

Luo, Y., Zhou, X., 2006. Soil Respiration and the Environment, Soil Respiration and the Environment. https://doi.org/10.1016/B978-0-12-088782-8.X5000-1

McLain, J.E.T., Martens, D.A., 2006. Moisture Controls on Trace Gas Fluxes in Semiarid Riparian Soils. Soil Sci. Soc. Am. J. 70, 367–377. https://doi.org/10.2136/sssaj2005.0105

Ni, X., Liao, S., Wu, F., Groffman, P.M., 2019. Short-term precipitation pulses stimulate soil CO_2 emission but do not alter CH 4 and N 2 O fluxes in a northern hardwood forest. Soil Biol. Biochem. 130, 8–11. https://doi.org/10.1016/j.soilbio.2018.11.021

Nilsson, C., Jansson, R., Kuglerová, L., Lind, L., Ström, L., 2013. Boreal Riparian Vegetation Under Climate Change. Ecosystems. https://doi.org/10.1007/s10021-012-9622-3

Niu, F., Chen, J., Xiong, P., Wang, Z., Zhang, H., Xu, B., 2019. Responses of soil respiration to rainfall pulses in a natural grassland community on the semi-arid Loess Plateau of China. Catena 178, 199–208. https://doi.org/10.1016/j.catena.2019.03.020

Nunes, J.P., Seixas, J., Pacheco, N.R., 2008. Vulnerability of water resources, vegetation productivity and soil erosion to climate change in Mediterranean watersheds. Hydrol. Process. https://doi.org/10.1002/hyp.6897

Peng, S., Piao, S., Shen, Z., Ciais, P., Sun, Z., Chen, S., Bacour, C., Peylin, P., Chen, A., 2013. Precipitation amount, seasonality and frequency regulate carbon cycling of a semi-arid grassland ecosystem in Inner Mongolia, China: A modeling analysis. Agric. For. Meteorol. 178–179, 46–55. https://doi.org/10.1016/j.agrformet.2013.02.002

Perry, L.G., Andersen, D.C., Reynolds, L. V., Nelson, S.M., Shafroth, P.B., 2012. Vulnerability of riparian ecosystems to elevated CO_2 and climate change in arid and semiarid western North America. Glob. Chang. Biol. 18, 821–842. https://doi.org/10.1111/j.1365-2486.2011.02588.x

Pfahl, S., O’Gorman, P.A., Fischer, E.M., 2017. Understanding the regional pattern of projected future changes in extreme precipitation. Nat. Clim. Chang. 7, 423–427. https://doi.org/10.1038/nclimate3287

Poblador, S., Lupon, A., Sabaté, S., Sabater, F., 2017. Soil water content drives spatiotemporal patterns of CO_2 and N_2O emissions from a Mediterranean riparian forest soil. Biogeosciences 14, 4195–4208. https://doi.org/10.5194/bg-14-4195-2017

Radville, L., McCormack, M.L., Post, E., Eissenstat, D.M., 2016. Root phenology in a changing climate. J. Exp. Bot. 67, 3617–3628. https://doi.org/10.1093/jxb/erw062

Raich, J.W., Potter, C.S., Bhagawati, D., 2002. Interannual variability in global soil respiration, 1980-94. Glob. Chang. Biol. 8, 800–812. https://doi.org/10.1046/j.1365-2486.2002.00511.x

Rey, A., Oyonarte, C., Morán-López, T., Raimundo, J., Pegoraro, E., 2017. Changes in soil moisture predict soil carbon losses upon rewetting in a perennial semiarid steppe in SE Spain. Geoderma 287, 135–146. https://doi.org/10.1016/j.geoderma.2016.06.025

Richardson, A.D., Black, T.A., Ciais, P., Delbart, N., Friedl, M.A., Gobron, N., Hollinger, D.Y., Kutsch, W.L., Longdoz, B., Luyssaert, S., Migliavacca, M., Montagnani, L., Munger, J.W., Moors, E., Piao, S., Rebmann, C., Reichstein, M., Saigusa, N., Tomelleri, E., Vargas, R., Varlagin, A., 2010. Influence of spring and autumn phenological transitions on forest ecosystem productivity. Philos. Trans. R. Soc. B Biol. Sci. 365, 3227–3246. https://doi.org/10.1098/rstb.2010.0102

Ryan, M.G., Law, B.E., 2005. Interpreting, measuring, and modeling soil respiration. Biogeochemistry 73, 3–27. https://doi.org/10.1007/s10533-004-5167-7

Schjønning, P., Thomsen, I.K., Moldrup, P., Christensen, B.T., 2003. Linking soil microbial activity to water- and air-phase contents and diffusivities. Soil Sci. Soc. Am. J. 67, 156–165. https://doi.org/10.2136/sssaj2003.1560

Schwinning, S., Starr, B.I., Ehleringer, J.R., 2005. Summer and winter drought in a cold desert ecosystem (Colorado Plateau) part I: Effects on soil water and plant water uptake. J. Arid Environ. 60, 547–566. https://doi.org/10.1016/j.jaridenv.2004.07.003

Scott, R.L., Edwards, E.A., Shuttleworth, W.J., Huxman, T.E., Watts, C., Goodrich, D.C., 2004. Interannual and seasonal variation in fluxes of water and carbon dioxide from a riparian woodland ecosystem. Agric. For. Meteorol. 122, 65–84. https://doi.org/10.1016/j.agrformet.2003.09.001

Shabaga, J., Basiliko, N., Caspersen, J.P., Jones, T.A., 2015. Seasonal controls on patterns of soil respiration and temperature sensitivity in a northern mixed deciduous forest following partial-harvesting Seasonal controls on patterns of soil respiration and temperature sensitivity in a northern mixed deciduous for. For. Ecol. Manage. https://doi.org/10.1016/j.foreco.2015.03.022

Shi, W., Tateno, R., Zhang, J.G., Wang, Y.L., Yamanaka, N., Du, S., 2011. Response of soil respiration to precipitation during the dry season in two typical forest stands in the forest-grassland transition zone of the Loess Plateau. Agric. For. Meteorol. 151, 854–863. https://doi.org/10.1016/j.agrformet.2011.02.003

Shi, W.Y., Zhang, J.G., Yan, M.J., Yamanaka, N., Du, S., 2012. Seasonal and diurnal dynamics of soil respiration fluxes in two typical forests on the semiarid Loess Plateau of China: Temperature sensitivities of autotrophs and heterotrophs and analyses of integrated driving factors. Soil Biol. Biochem. 52, 99–107. https://doi.org/10.1016/j.soilbio.2012.04.020

Singh, R., Singh, H., Singh, S., Afreen, T., Upadhyay, S., Singh, A.K., Srivastava, P., Bhadouria, R., Raghubanshi, A.S., 2017. Riparian land uses affect the dry season soil CO_2 efflux under dry tropical ecosystems. Ecol. Eng. 100, 291–300. https://doi.org/10.1016/j.ecoleng.2017.01.002

Smith, A.P., Bond-Lamberty, B., Benscoter, B.W., Tfaily, M.M., Hinkle, C.R., Liu, C., Bailey, V.L., 2017. Shifts in pore connectivity from precipitation versus groundwater rewetting increases soil carbon loss after drought. Nat. Commun. 8, 1–11. https://doi.org/10.1038/s41467-017-01320-x

Stromberg, J.C., Mccluney, K.E., Dixon, M.D., Meixner, T., 2013. Dryland

Riparian Ecosystems in the American Southwest: Sensitivity and Resilience to Climatic Extremes. Ecosystems. https://doi.org/10.1007/s10021-012-9606-3

Suseela, V., Conant, R.T., Wallenstein, M.D., Dukes, J.S., 2012. Effects of soil moisture on the temperature sensitivity of heterotrophic respiration vary seasonally in an old-field climate change experiment. Glob. Chang. Biol. 18, 336–348. https://doi.org/10.1111/j.1365-2486.2011.02516.x

Van Straaten, O., Veldkamp, E., Köhler, M., Anas, I., 2010. Spatial and temporal effects of drought on soil CO_2 efflux in a cacao agroforestry system in Sulawesi, Indonesia. Biogeosciences. https://doi.org/10.5194/bg-7-1223-2010

Vargas, R., Allen, M.F., Allen, E., 2008. Environmental controls and the Influence of vegetation type , fine roots and rhizomorphs on diel and seasonal variation in soil respiration. New Phytol. 179, 460–471. https://doi.org/10.1111/j.1469-8137.2008.02481

Wang, Y., Li, X., Zhang, C., Wu, X., Du, E., Wu, H., Yang, X., Wang, P., Bai, Y., Wu, Y., Huang, Y., 2019. Responses of soil respiration to rainfall addition in a desert ecosystem: Linking physiological activities and rainfall pattern. Sci. Total Environ. 650, 3007–3016. https://doi.org/10.1016/j.scitotenv.2018.10.057

Wang, Y., Wang, Z.L., Wang, H., Guo, C., Bao, W., 2012. Rainfall pulse primarily drives litterfall respiration and its contribution to soil respiration in a young exotic pine plantation in subtropical China. Can. J. For. Res.

https://doi.org/10.1139/X2012-017

Wu, X., Yuan, J., Ma, S., Feng, S., Zhang, X., Hu, D., 2015. Seasonal spatial pattern of soil respiration in a temperate urban forest in Beijing. Urban For. Urban Green. 14, 1122–1130. https://doi.org/10.1016/j.ufug.2015.10.009

Xia, R., Zhang, D.L., Zhang, C., Wang, Y., 2018. Synoptic control of convective rainfall rates and cloud-to-ground lightning frequencies in warm-season mesoscale convective systems over North China. Mon. Weather Rev. 146, 813–831. https://doi.org/10.1175/MWR-D-17-0172.1

Yan, L., Chen, S., Xia, J., Luo, Y., 2014. Precipitation regime shift enhanced the rain pulse effect on soil respiration in a semi-arid steppe. PLoS One 9. https://doi.org/10.1371/journal.pone.0104217

Yoon, T.K., Noh, N.J., Han, S., Lee, J., Son, Y., 2014. Soil moisture effects on leaf litter decomposition and soil carbon dioxide efflux in wetland and upland forests. Soil Sci. Soc. Am. J. 78, 1804–1816. https://doi.org/10.2136/sssaj2014.03.0094

Yu, S., Mo, Q., Chen, Y., Li, Y., Li, Y., Zou, B., Xia, H., Jun, W., Li, Z., Wang, F., 2020. Effects of seasonal precipitation change on soil respiration processes in a seasonally dry tropical forest. Ecol. Evol. 10, 467–479. https://doi.org/10.1002/ece3.5912

Zeppel, M.J.B., Wilks, J. V., Lewis, J.D., 2014. Impacts of extreme precipitation and seasonal changes in precipitation on plants. Biogeosciences 11, 3083–3093. https://doi.org/10.5194/bg-11-3083-2014

Zhu, M., Xue, W., Xu, H., Gao, Y., Chen, S., Li, B., Zhang, Z., 2019. Diurnal and seasonal variations in soil respiration of four plantation forests in an urban park. Forests 10, 1–15. https://doi.org/10.3390/f10060513