Canadian Journal of Soil Science
Revue canadienne de la science du sol

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Journal:	<i>Canadian Journal of Soil Science</i>
Manuscript ID	CJSS-2016-0030.R2
Manuscript Type:	Article
Date Submitted by the Author:	01-Aug-2016
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Title: Extreme rainfall impacts on soil CO₂ efflux in an urban forest ecosystem in Beijing, China

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Abbreviations:

CO₂, carbon dioxide; Rs, soil respiration;

GPP, gross primary production;

PAR, photosynthetically active radiation;

Ts, soil temperature;

VWC, volumetric water content;

EC, eddy covariance;

NEE, net ecosystem CO₂ exchange.

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Abstract

Extreme rainfall events are infrequent disturbances that affect urban environments and soil respiration (Rs). Using data measured in an urban forest ecosystem in Beijing, China, we examined the link between gross primary production (GPP) and soil respiration on a diurnal scale during an extreme rainfall event (i.e., the '21 July 2012 event'), and examined diel and seasonal environmental controls on Rs. Over the seasonal cycle, Rs increased exponentially with soil temperature (Ts). In addition, Rs was hyperbolically related to soil volumetric water content (VWC), increasing with VWC below a threshold of $0.17 \text{ m}^3 \text{ m}^{-3}$, and then decreasing with further increases in VWC. Following the extreme rainfall event (177 mm), Rs showed an abrupt decrease and then maintained a low value of $\sim 0.3 \mu\text{mol m}^{-2} \text{ s}^{-1}$ for about 8 h as soil VWC reached the field capacity ($0.34 \text{ m}^3 \text{ m}^{-3}$). Rs became decoupled from Ts and increased very slowly, while GPP showed a greater increase. A bivariate Q_{10} -hyperbolic model, which incorporates both Ts and VWC effects, better fit Rs than the Q_{10} model in summer, but not for whole year.

Keywords: Extreme rainfall, Gross primary production, Soil respiration

Introduction

About half of the earth's terrestrial surface has been affected by human activities (Vitousek et al. 1997; Lambin 2003). On a global basis, cities contribute to more than 70% of fossil fuel related carbon dioxide (CO₂) emissions. Urban forest ecosystem, characterized by distinct vegetation composition and structure (semi-natural and artificial vegetation), have been increasing during the past decades in China due to the rapid expansion of urban areas. Currently, urban forest ecosystems cover approximately 28% of the total area in Beijing (Wang et al. 2013). It is well documented that urban forest ecosystems play an important role in carbon cycling and may contribute greatly to the terrestrial carbon sequestration (Piao et al. 2009; Xiao et al. 2009; Pan et al. 2011). In particular, soil respiration (Rs) typically accounts for 30% - 80% of total ecosystem respiration in urban forests (Davidson et al. 2000; Law et al. 2002; Davidson & Janssens 2006; Wang et al., 2008). Therefore, quantification and understanding of soil respiration in urban areas are essential to the assessment of global terrestrial carbon balance (Marland et al., 2006; Zhou et al., 2008). Increasing occurrence of large precipitation events and less frequent small precipitation events have been reported in many areas around the world (Shiu et al. 2012). In addition, global precipitation patterns are predicted to shift towards greater intra-annual variability and more rainfall extremes, especially in large cities (Jin et al. 2015). China is expected to undergo more extreme climate regimes characterized by an increasing amount of total precipitation and a higher frequency of extreme rainfall events in this century (IPCC 2014). These extreme rainfall events are more likely to occur in large cities and affect ecosystem processes therein. The increase in precipitation variability is expected to influence soil volumetric water content (VWC) and soil temperature (Ts) which needed by root growth and biological activity in the soil (Gupta & Singh, 1981; Chee-siong lee, 2008), thus affecting Rs increase (Sponseller, 2007) or

decrease (Davidson et al., 2000). However, how extreme precipitation pulses may influence soil CO₂ effluxes has not been well evaluated compared to other environmental variables, partly as a result of the limited opportunities to investigate these unexpected episodes (Li et al. 2007). Furthermore, hysteresis effects have been shown where Rs was decoupled from Ts (Gaumont-Guay et al. 2006; Carbone and Vargas 2008). Changes in soil VWC following extreme rainfall events triggered abrupt, yet unsynchronized, responses in photosynthesis and Rs in a humid cool-temperate oak-birch forest in central Japan (Kishimoto-Mo et al. 2015). A sudden pulse-like increase in soil VWC often enhances CO₂ efflux from soil under seasonally dry climates in response to rewetting after drought (Davidson et al. 2000), but this can also reduce soil gas transport due to the saturation of soil pores with water (Bauer et al. 2008). Studies on the dynamics of Rs *in situ* during extreme rainfall events in the growing season remain scarce (Barron-Gafford et al. 2011; Song et al. 2015). This suggests a lack of knowledge of the relative contribution of soil VWC to Rs. Further studies are needed to better quantify the responses of canopy photosynthesis and Rs to extreme rainfall events in urban forest ecosystems (Kuzyakov and Gavrichkova 2010; Han et al. 2014).

Auto-chamber and eddy-covariance (EC) measurements at a high temporal resolution enable us to evaluate the responses of Rs and canopy photosynthesis to transient climate dynamics (i.e., extreme rainfall events). We hypothesized that in the studied urban forest ecosystem: (1) Rs is highly limited by saturated soil VWC and less sensitive to Ts following an extreme rainfall event; and (2) radiation exerts a strong control on Rs through its effects on plant photosynthetic activity. The objectives of this study were: (1) to quantify the influence of soil VWC on the temperature sensitivity of Rs, (2) to explore the effects of soil VWC on the hysteretic relationship between Rs and Ts over the seasonal cycle, and (3) to assess the link between photosynthesis and Rs on the diurnal scale.

Materials and methods

Site description

The study site (40°01' N, 116°23' E, 51 m a.s.l.) was located in Beijing Olympic Forest Park, Chaoyang District, Beijing, China. The park, which covers an area of 680 ha and has a vegetation coverage of 95.6%, is the largest urban forest park in Asia. It was designed to integrate natural plant communities and artificial plantations. The site was located in a conservation area in the middle of the northeast part of the park. Tourists are restricted from entering the area and only few recreational facilities were established in order to minimize human disturbance.

The study area is characterized by a temperate and semi-humid continental monsoon climate. The mean annual air temperature is 12.5 °C and the frost-free season lasts for 190 days on average. The average annual rainfall in Beijing is about 420 - 660 mm, with a highly uneven seasonal distribution of precipitation (~ 80% of annual rainfall falls during June-August). Beijing is one of the regions having the highest annual rainfall amount in the North China Plain. Beijing usually experiences frequent heavy rainfall or storms in summer. During 1951-2012, it was struck by 22 rainfall events of larger than 100 mm, with the largest event having 318 mm of rainfall (Zhuang and Guitian 1994). The extreme rainfall on 21 July 2012 is the largest event in Beijing since 1961. These climatic data are based on records at the meteorological station of Chaoyang District, Beijing (39°55' N, 116°5' E) for the period 1961-2010. The soil is typically Luvisols (WRB, 1998 and 2006), having a bulk density of $1.62 \pm 0.06 \text{ g cm}^{-3}$ (mean $\pm$ standard deviation (SD), $n = 6$) in the upper 10 cm of the soil profile. The soils were generally shallow, well-drained and of silt loam texture. Soil porosity and pH were 40.33% and 7.8, respectively.

Plant species composition and stand biometric properties were investigated in 2011 in a

100 m × 100 m permanent plot centered on the EC tower. All trees with diameter at breast height (DBH) greater than 3 cm were tagged and identified to species. Most of the stand was dominated by plantations of *Pinus tabulaeformis* L. Other species include *Sophora japonica* L., *Platycladus orientalis*, *Fraxinus chinensis*, and *Ginkgo biloba*. The understory consisted mainly of *Iris tectorum* and *Dianthus chinensis*. The mean age of the dominant trees was ~20 years. The stand density was 210 trees ha⁻¹, with a mean tree height of 7.7 m and a mean tree diameter at breast height of 20.6 cm.

Soil respiration measurements

Half-hourly Rs was continuously measured throughout 2012 in a mixed stand of natural woodland reserve and artificial plantations using an automated soil respiration system (model LI-8100A fitted a LI-8150 multiplexer, LI-COR, Nebraska, USA). Six permanent PVC collars (20.3 cm in diameter, 10 cm in height and inserted into the soil to a depth of about 7 cm) were randomly installed on the soil surface. The vegetation within collars was carefully removed at the time of collar installation. Any regrowth was clipped regularly to prevent aboveground CO₂ fluxes from occurring in the collars. Litter fall in the park was removed in late autumn. The collars were divided into two groups (three collars each) to represent the spatial heterogeneity of soil respiration. The two groups were rotated every 10 days. The measurements were made every 30 minutes for each chamber. Each Rs measurement lasted for 3 min and 15 s, including a 30 s pre-purge, a 45 s post-purge, and a 2 min observation period. Rs values were automatically calculated from linear or exponential regression of CO₂ mole fraction vs. time. A minimum coefficient of determination (r^2) of 0.2 was required for a valid regression. Half-hourly Ts and soil VWC at 5 cm depth were measured simultaneously using 8150-203 soil temperature sensors and EC_{H2O} soil moisture sensors (LI-COR, Nebraska, USA), respectively. A temperature and a moisture sensor were attached to each LI-104

chamber.

Eddy covariance (EC) and meteorological measurements

Net ecosystem CO₂ exchange (NEE) was measured continuously in 2012 using an EC system mounted at 11.5 m above the soil surface. The EC system consisted of a three-axis sonic anemometer (CSAT-3, Campbell Scientific Inc., USA) and a closed-path infrared gas analyzer (IRGA; model EC-155, Campbell Scientific, Inc. (CSI), Logan, UT, USA). Raw EC data were recorded at 10 Hz by a data-logger (CR3000, Campbell Scientific Inc., USA). Downloaded raw data were then processed using the EddyPro 4.0.0 software (LI-COR Inc., USA) to determine half-hourly NEE values. Processing steps included spike removal, tilt correction (double axis rotation), correction for sensor separation, spectral correction, detrending (Reynolds averaging) and flux computation (Burba and Anderson, 2010). We used the following procedures to fill the missing and bad data resulting from instrument failures and data screening procedures: (1) Small gaps (shorter than 2 h) were filled by linear interpolation; (2) Large gaps (longer than 2 h) were filled based on nonlinear regressions treated separately for daytime and night-time data (Falge et al. 2001). The model used to describe the effects of temperature on night-time NEE (NEE_{night}, which equals nighttime ecosystem respiration) was

$$NEE_{\text{night}} = R_0 Q_{10}^{T_a/10} \quad (1)$$

where R_0 is night-time ecosystem respiration at an air temperature of 0 °C and Q_{10} is the factor by which the respiration increases for a rise of 10 °C in air temperature. Daytime ecosystem respiration was subsequently estimated based on this parameterization. Gross primary productivity (GPP) was then calculated as the balance between ecosystem respiration (Re) and NEE:

$$GPP = Re - NEE \quad (2)$$

Meteorological factors were measured simultaneously with sensors installed on the EC tower at 11.5 m above the ground. Air temperature (T_a) was measured with a thermohygrometer (HMP45C, Vaisala, Helsinki, Finland), photosynthetically active radiation (PAR) was measured with a quantum sensor (PAR-LITE, Kipp and Zonen, Delft, the Netherlands). Precipitation was measured with a tipping bucket rain gauge (TE-525, Texas Electronics, Texas, USA). T_s was measured at four locations within 10 m from the EC tower using (CS-109 probes (CSI) at a 10-cm depth. All meteorological data were measured every 10 s and then averaged to half-hourly values.

Data processing and statistical analysis

The missing values in T_s for analysis (measured at 5 cm depth) were filled using an empirical relationship to those measured at 10 cm depth by CS-109 probes mentioned above. After Yu et al. (2011), the out-of-normal-range (-5 – $20 \mu\text{mol m}^{-2} \text{s}^{-1}$) R_s values were considered spurious and were thus excluded from analysis. Afterwards, half-hourly R_s values were excluded when they departed by more than five times the standard deviation from the corresponding monthly mean (Wang et al., 2014). The mean half-hourly values of the three chambers were used for analysis. Instrument failure and quality control procedures resulted in only 1% missing data in 2012.

Three commonly used models (Table 2) were used to analyze the response of R_s to T_s . Seasonal changes in the dependence of R_s on T_s at 5 cm depth provided temperature sensitivity parameters (Q_{10}), and were analyzed using the Q_{10} function:

$$R_s = R_{s10} \times Q_{10}^{(T_s - 10)/10} \quad (3)$$

Four different bivariate models with T_s and VWC as independent variables were used to represent the combined effects of both variables (Table 3). The diel variation in R_s in response to T_s and VWC were using three-day periods with contrasting VWC and calculated

the diel variation for each period. The Q_{10} -hyperbolic model used to describe R_s and a combination of T_s and VWC was:

$$R_s = R_{s10} \times Q_{10}^{(T_s - 10)/10} \times (a + b \times VWC + c / VWC) \quad (4)$$

where R_{s10} is the basal soil respiration rate at a soil temperature of 10 °C; Q_{10} is the temperature sensitivity of soil respiration (the factor by which soil respiration rate increases for a 10 °C increase in temperature), and T_s is measured soil temperature measured at 5 cm depth. VWC is soil volumetric water content for the top 5 cm layer. Model parameters (a , b and c) were estimated using the Levenberg-Marquardt method. Root mean square error (RMSE) and the coefficient of determination (r^2) were used to evaluate model performance. RMSE and r^2 were compared among models using a bootstrap approach in which the dataset was sampled 2000 times, followed by one-way analysis of variance (ANOVA).

Observations during rainfall were excluded to minimize the rain pulse effects. The mean diel cycles of R_s and T_s were computed from May to October by averaging the hourly means for each hour of day. Cross-correlation analysis was used to detect hysteresis between R_s and T_s at both seasonal and diel time scales. In the case of seasonal hysteresis, analysis of covariance (ANCOVA) was used to examine the difference in R_s among months from May to October, with T_s as the covariate. All statistical analyses were done using Matlab 7.11.0 (R2010b, The Mathworks Inc., Natick, MA, USA).

Results

Seasonal patterns of soil temperature, moisture, soil respiration and gross primary production

Daily mean values of T_s showed a typical seasonal pattern with a broad peak from June to September (Fig. 1a). The annual mean T_s for 2012 was 10.7 °C. Daily maximum and minimum were 24.5 °C, -7.7 °C, respectively. Annual precipitation was 738 mm in 2012, with

79% falling in summer. An extreme rainfall event (177 mm) occurred on 21 July 2012, which lasted for 18 hours (Fig. 1b). VWC varied from 0.03 to $0.34 \text{ m}^3 \text{ m}^{-3}$, with maximum value occurring during the extreme rainfall event on 21 July 2012. Small VWC values were observed during low precipitation periods in spring and winter (Fig. 1b). The daily mean R_s showed strong seasonal variations (Fig. 1c), varying from 0.17 to $3.75 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$. The seasonal pattern of R_s was similar to that of T_s , except for in summer when R_s fluctuated following frequent precipitation pulses. The variability of GPP was much higher than that of R_s in midsummer. The amplitude of variation in GPP was 67.4 g C m^{-2} and 23.3 g C m^{-2} in June-July and July-August, respectively, compared to the values of 2.2 g C m^{-2} and 1.0 g C m^{-2} for R_s (Table 1).

Immediate effects of extreme rainfall event on soil respiration and gross primary production

The extreme rainfall event on 21 July 2012 was the largest rainfall during 1952–2012 with the peak intensity being 32.5 mm h^{-1} (Fig. 2c). Soil pores were saturated with water after about 6 hours of heavy rainfall. T_s decreased sharply from $23.3 \text{ }^\circ\text{C}$ to $20 \text{ }^\circ\text{C}$, and then maintained a low value of $19.2 \text{ }^\circ\text{C}$ during the rest of the rainfall event (Fig. 2b). Due to the intense rainfall, R_s maintained a constant low value of $\sim 0.3 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ for about 8 h as soil VWC reach the field capacity of $0.34 \text{ m}^3 \text{ m}^{-3}$. In addition, an increase in R_s was observed corresponding to a decrease in soil VWC, resulting in a hysteretic relationship between R_s and T_s on 22 July (Fig. 2).

Diurnal variations in soil respiration, gross primary production, and soil temperature during the extreme rainfall event

The diurnal courses of GPP, R_s and T_s from 20–29 July 2012 are presented in Fig. 3. The diurnal variation in GPP showed a symmetrical pattern (i.e., a bell shape), peaking at noon. The diurnal pattern of R_s corresponded with that of GPP (Fig.3). On a diurnal scale,

GPP lagged Rs but preceded Ts (Fig. 3). Both Ts and Rs showed little fluctuation at night, and there was not obvious correlation between them. GPP decreased following the decreasing trend of Rs in the afternoon (13:00-21:00), (Fig. 3). The peak in GPP lagged that of Rs by about 3 hours. At daytime, Rs accounted for about 13.4 % of GPP.

Seasonal and diel variations of soil respiration in response to soil temperature and soil volumetric water content

The fitted curves in Fig. 4a are shown for significant relationships between Rs and Ts ($P < 0.05$). Daily-integrated Rs showed a significantly exponential relationship with Ts in spring (March–May) and late autumn (October–November) ($P < 0.05$, $r^2 = 0.54, 0.32, 0.20, 0.88$ and 0.27 , respectively) but not in summer and early autumn (June–September) (Fig. 4a). Rs increased with soil moisture up to a VWC threshold of $0.17 \text{ m}^3 \text{ m}^{-3}$ (Fig. 4b), thereafter decreased with further decreases in VWC. Overall, VWC significantly affected Rs only during the summer (June–September). The Rs–VWC relationship was hyperbolic, with a maximum Rs at VWC of $0.17 \text{ m}^3 \text{ m}^{-3}$ (Fig. 4b, $\text{Rs} = 9.91 - 20.82 \text{ VWC} - 0.57/\text{VWC}$, $P < 0.05$, $r^2 = 0.54$).

Half-hourly Rs significantly increased with Ts in 2012 ($P < 0.05$, Table 3). Half-hourly Ts explained 52% of the variation in half-hourly Rs. Empirical models taking both Ts and VWC as independent variables were fit to the dataset, when Ts was greater than zero (Table 3). The Q_{10} -hyperbolic bivariate equation ($\text{Rs}_{\text{observed}} = 1.05\text{Rs}_{\text{predicted}} - 0.04$, $P < 0.01$, $r^2 = 0.65$) fit the measured values better than the Ts-only models ($\text{Rs}_{\text{observed}} = 1.04\text{Rs}_{\text{predicted}} - 0.07$, $P < 0.01$, $r^2 = 0.52$) during the growing season. The predicted Rs values from Ts-only Q_{10} model were higher than those predicted by bivariate models, probably due to the influences of summer rainy season on Rs (Table 3). Because VWC values measured by sensors were not reliable under frozen soil conditions in winter, we used the

Ts-only Q_{10} model to estimate the annual sum of R_s .

Over the diel cycle, hourly R_s was out-of-phase with T_s at 5 cm depths, as seen in the hysteresis in the R_s – T_s relationship (Fig. 5). The mean time lag between R_s and T_s was 3 h during May and October, with T_s peaking earlier than R_s , but fluctuated irregularly during June–September. R_s were positively related to T_s almost without hysteresis when VWC was smaller ($0.05 < \text{VWC} < 0.17 \text{ m}^3 \text{ m}^{-3}$, Fig. 6a). However, the correlation between R_s and T_s became weak, and even switched to negative when soil VWC was higher than $0.17 \text{ m}^3 \text{ m}^{-3}$ (Fig. 6b).

Discussion

Time lag between gross primary production and soil respiration on a diurnal scale following the extreme rainfall event

The diel hysteresis between R_s and T_s has been reported to result from a lag time of several hours between photosynthetic assimilation of carbohydrates and their respiratory release in the rhizosphere (Tang et al. 2005; Davidson and Holbrook, 2009; Vargas et al. 2011a; Han et al. 2014). In general, diurnal R_s lagged plant photosynthetic activity on hourly scales (Bahn et al. 2008). Recently, a time lag of about 0–3 h between R_s and plant photosynthetic activity was found in a steppe ecosystem (Yan et al. 2011). However, the lack of such hysteretic relationships between R_s and GPP during the extreme rainfall event on 21 July 2012 (Fig.2 and Fig.3) is not consistent with previous findings. As water from the heavy rainfall infiltrated into the soil, T_s decreased while soil VWC rapidly increased until the soil pores became saturated with water. At that time, soil CO_2 efflux was inhibited due to the waterlogged conditions. After the rain stopped, diel R_s was decoupled from T_s . R_s was stimulated at the night following the rainfall, despite a decrease in T_s (Fig. 3). These results are consistent with previously findings of fast transport of recent photosynthates from canopy

to rhizosphere (Högberg et al. 2008; Bahn et al. 2009; Vargas et al. 2011a). High transport rates of recent assimilates from leaves into roots and the subsequent loss of photosynthates through root respiration have been demonstrated by previous laboratory experiments (Gregory and Atwell, 1991; Kuzyakov et al. 2001). The decoupling between R_s and T_s indicates that temperature might be inadequate to account for the diurnal variation of soil respiration (Tang et al. 2005; Liu et al. 2006; Yan et al. 2011). Radiation not only influences R_s via its effects on temperature, but also via its effects on photosynthesis. In the growing season, autotrophic respiration may dominate soil respiration on the diurnal scale during the extreme rainfall event (Vargas et al. 2011a).

Seasonal variations in soil respiration in relation to soil temperature and moisture

The seasonal variation in R_s was dependent on both T_s (Fig. 4a) and soil VWC (Fig. 4b). T_s explained 66% of the variation in R_s for the VWC range of 0.05–0.17 $\text{m}^3 \text{m}^{-3}$, compared to 52% for $\text{VWC} > 0.17 \text{ m}^3 \text{m}^{-3}$ (Table 2). The suppression of R_s in spring compared to autumn may be related to: (1) water stress in spring, which may reduce the contact between the substrates and the extracellular enzymes; (2) the previous findings that soil microbial activities are less stimulated in spring than in autumn. The soil VWC threshold of 0.17 $\text{m}^3 \text{m}^{-3}$, above which R_s decreased with increasing soil VWC (Fig. 4b), was the same as it was in 2011 (Chen et al., 2013). The reduction in R_s with increasing VWC most likely resulted from a restriction in CO_2 transport out of the soil and an inhibition of microbial activity due to a lack of oxygen, leading to decreases in root and heterotrophic respiration (Riveros-Iregui et al. 2007). However, many previous studies have reported an opposite pattern. For example, Palmroth et al. (2005) found that R_s depended on both T_s and VWC in a forest ecosystem when the soil was dry ($\text{VWC} < 0.20 \text{ m}^3 \text{m}^{-3}$), but depended on T_s alone when the soil was moist ($\text{VWC} > 0.20 \text{ m}^3 \text{m}^{-3}$). Jassal et al. (2008) reported for a forest ecosystem that R_s

became decoupled from T_s when VWC dropped below a threshold value of $0.11 \text{ m}^3 \text{ m}^{-3}$.

We found that bivariate R_s models, which consider both T_s and VWC as independent variables, outperformed models with a single independent variable of T_s (Table 3). This highlights the need to incorporate soil moisture effects on R_s into mechanistic models for predicting carbon cycling in urban forest ecosystems. Among bivariate models, the Q_{10} -hyperbolic model performed best, as indicated by highest r^2 and lowest RMSE. This result suggests the important effects of soil moisture on R_s in this urban forest ecosystem. A bivariate logistic-power model was found to perform best in predicting R_s in a temperate forest stand (Yu et al. 2011). The bivariate model with VWC and T_s as independent variables made a reasonable interpretation that R_s decreased with the increasing T_s after soil VWC reached a threshold in midsummer. This was in line with the result that hysteresis between R_s and T_s was negatively affected by VWC. As such, the role of soil VWC in controlling the relationship between soil CO_2 and T_s should be considered when modeling the dynamics of carbon cycling in ecosystems with strong seasonality in soil water content. However, the bivariate model was not suitable for the estimation of annual R_s due to water stress in spring and frozen soil conditions in winter. Therefore, a seasonally varying, environmentally controlled Q_{10} or Q_{10} -hyperbolic model should be used for modeling short-term R_s , as was suggested by Jia et al. (2013).

Seasonal variations in soil respiration and gross primary production

The estimated cumulative R_s for the whole year of 2012 using the Q_{10} model were $394 \pm 4 \text{ g C m}^{-2}$, which was 17% lower than that for the previous year (Chen et al. 2013). The suppression of R_s by the extreme rainfall in 2012 contrasts with previous studies in which a pulse-like increase in R_s was observed following rainfall in arid and semi-arid ecosystems (Escobar et al., 2015). The model overestimated R_s at high T_s and high soil VWC and

underestimated R_s at low T_s . Smaller R_s values at the urban forest site than at natural forest sites may be ascribed to the following causes. First, water-saturated soil caused by the extreme rainfall strongly affected the seasonal response of R_s to T_s in the studied urban forest ecosystem; Second, the removal of the litter fall may have led to a thinner organic layer and thus less substrate supply to R_s than in nature forests, resulting in a reduction of R_s .

R_s accounted for 30.4% of annual GPP ($1295.5 \text{ g C m}^{-2}$). GPP reached its respective maximum 266.5 g C m^{-2} in July. This peak in GPP coincided with rapid leaf expansion and maturation, the period of high photosynthetic capacity (Muraoka and Koizumi 2005). Despite increases in GPP, R_s kept almost the same magnitude in June, July and August. Therefore, the large summer rainfall events obviously had positive effects on C uptake and negative effects on soil C release. The dynamics of precipitation and soil water availability were likely a key source of summertime day-to-day variations in C balance. Recent studies showed that the shifting precipitation regime is already affecting ecosystem C-exchange, even in temperate areas where ecosystems are not typically considered drought-prone (Mackay and Noormets 2008).

Conclusions

In summary, this study reports on continuous measurements of soil respiration (R_s) in an urban forest ecosystem in Beijing, China. We examined the temporal variations in R_s in relation to soil temperature (T_s) and moisture during an extreme rainfall event. As influenced by the extreme rainfall, T_s and R_s showed small amplitudes of fluctuation and their diel cycles were decoupled. R_s even showed higher values at night when T_s was low, and the response of diel R_s to T_s was regulated by soil volumetric water content (VWC). There also was a negative correlation between diel hysteresis and VWC. Over the seasonal cycle, the control of T_s on R_s was modified by VWC, especially after an extreme rainfall event. R_s

became decoupled from T_s when VWC was above $0.17 \text{ m}^3 \text{ m}^{-3}$. There was hysteresis in the relationship between T_s at 5-cm depth and R_s from spring to autumn, reflecting the confounding effects of soil temperature at deeper layer and other biophysical mechanisms that may regulate the diel pattern of R_s . A combined T_s -VWC model substantially improved the modeling of R_s in the growing season but not in winter or for the whole year.

Acknowledgements

This research was supported by China Postdoctoral Science Foundation funded project (2016M591092), National Natural Science Foundation of China (NSFC; 31361130340, 31270755) and the Fundamental Research Funds for the Central Universities (No: 2015ZCQ-SB-02). This work is related to the ongoing Finnish-Chinese research collaboration project EXTREME, between Beijing Forestry University (BJFU) and University of Eastern Finland (UEF). This work was also promoted by the U.S.–China Carbon Consortium (USCCC). We thank Dr. H. Li for providing help comments and suggestions on the manuscript in terms of both science and language. We thank C. Ren, P. Liu and J.Y. Ma for their assistance with field measurements and instrument maintenance.

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Table 1 Monthly mean soil temperature (Ts, °C), and monthly total precipitation (mm), soil respiration (Rs, g C m⁻²), and gross primary production (GPP, g C m⁻²) in 2012.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rs	12.4	10.8	15.3	23.7	30.6	57.6	59.8	58.8	42.7	31.1	8.2	5.7
GPP	0.0	0.6	1.9	98.3	199.3	199.1	266.5	243.2	166.1	105.3	13.6	1.6
Ts	-3.5	-2.5	4.0	14.4	17.6	20.8	22.4	21.6	16.9	11.2	2.7	-1.6
Precipitation	0.1	0.0	14.3	33.6	12.0	99.3	364.0	40.1	80.8	16.4	70.6	7.1

Table 2 Regression parameters (a, b, c) from temperature-only models of soil respiration, based on the analysis of half-hourly values. r^2 and RMSE refer to the coefficient of determination and the root mean square error, respectively.

0.05 < VWC < 0.17		a	b	c	r^2	RMSE
Q ₁₀ model	$y=ab^{(x-10)/10}$	0.78	1.92		0.66	0.4634
Quadratic	$y=a+bx+cx^2$	0.36	0.02	0.002	0.65	0.4586
Logistic	$y=a/(1+\exp(b(c-x)))$	3.217	0.1052	20.54	0.66	0.4583
VWC > 0.17						
Q ₁₀ model	$y=ab^{(x-10)/10}$	0.67	2.07		0.52	0.6153
Quadratic	$y=a+bx+cx^2$	0.03	0.06	0.001	0.51	0.607
Logistic	$y=a/(1+\exp(b(c-x)))$	2.557	0.15	17.36	0.52	0.618
Total data						
Q ₁₀ model	$y=ab^{(x-10)/10}$	0.78	1.94		0.71	0.4376
Quadratic	$y=a+bx+cx^2$	0.363	0.022	0.002	0.69	0.4325
Logistic	$y=a/(1+\exp(b(c-x)))$	3.485	0.103	21.78	0.70	0.4327

y, x refers to soil respiration and soil temperature, respectively. ^a, ^b, ^c are parameters.

Table 3 Comparison of combined two-variable model of soil respiration with Q10 model. r^2 and RMSE refer to the coefficient of determination and the root mean square error, respectively. The integrated values of predicted R_s are accumulated over the period with simultaneous measurements of R_s , T_s and VWC, for comparison with the observed total R_s of 324 g C m⁻².

Name	Equation	a	b	c	d	r^2	RMSE	Predicted R_s (g C m ⁻²)
Q ₁₀ model	$y=ab^{(x-10)/10}$	0.82	1.99			0.52	0.5333	355
Asymptote	$y=[ab^{(x-10)/10}][z/(z+c)]$	0.74	2.04	-0.013		0.53	0.5300	346
Polynomial	$y=ab^{(x-10)/10}-(z-c)^2$	1.48	1.61	-0.631		0.57	0.5074	345
Logistic-power	$y=[a/(1+\exp(b(c-x)))] [z^d]$	2.32	0.14	17.35	-0.13	0.55	0.5175	344
Q ₁₀ -hyperbolic	$y=[b^{(x-10)/10}][(a+c*z+d/z)]$	2.87	2.14	-5.627	-0.16	0.65	0.4588	336

* y, x, z refers to soil respiration (R_s), soil temperature (T_s) and soil water content (VWC), respectively.

^a, ^b, ^c, ^d are parameters.

Figure captions:

Fig.1. Daily mean soil temperature (Ts) at 5 cm depth (a), soil water content (VWC) at 5 cm depth (left axis) and precipitation (right axis) (b), and soil respiration (Rs) (c) in 2012.

Fig.2. Immediate effect of an extreme rainfall event (the '12 July 2012 event') on (a) soil respiration (Rs) and gross primary productivity (GPP); (b) soil temperature (Ts) at 5 cm depth and soil volumetric water content (VWC); (c) photosynthetically active radiation (PAR) and precipitation. Time is in hours from 20 July 00:00 to 30 July 00:00 of 2012.

Fig.3. Mean diurnal variations in soil respiration (Rs, solid circles with solid lines), gross primary production (GPP, solid circles with dashed lines), and soil temperature (Ts) at 5 cm depth (empty circle with solid lines) during 20 July to 30 July of 2012 in an urban forest ecosystem. Lag times between the peak of Rs and that of GPP are indicated by grey lines.

Fig.4. Seasonal relationships between daily mean soil respiration (Rs) and soil temperature (Ts) at 5 cm depth for each month over the measurement period (a) and soil water content (VWC) for June–September (b). Data points are daily mean values. Points are plotted when the regression relationship is significant at the 0.05 level. Solid line in panel (b) indicated the VWC threshold of Rs.

Fig.5. Mean monthly diel cycles of soil respiration (Rs) and soil temperature (Ts). Each point is the monthly mean at a particular time of day.

Fig.6. Hourly soil respiration (Rs) and soil temperature (Ts) over three consecutive days under low ($0.05\text{--}0.17\text{ m}^3\text{ m}^{-3}$) and high ($0.17\text{--}0.34\text{ m}^3\text{ m}^{-3}$) soil volumetric water content (VWC) conditions.

Fig.1.

Fig.2.

Fig.3.

Fig.4.

Fig.5.

Fig.6.