



Environmental control over seasonal variation in carbon fluxes of an urban temperate forest ecosystem



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HIGHLIGHTS

- The urban forest ecosystem acted as a local carbon sink in both years.
- High T_a increased ER more than GEP during the growing season.
- Low VWC decreased GEP more than ER during the growing season.
- Daytime NEP stopped increasing with PAR when T_a was highest in mid-summer days.

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ABSTRACT

Knowledge of surface-atmosphere CO_2 exchanges in urban forests is imperative. We measured net ecosystem CO_2 exchange of an urban forest in Beijing over a two-year period (2012–2013). The aim was to examine seasonal controls of environmental variables on ecosystem carbon (C) cycle assessed with eddy covariance technique. Net ecosystem production (NEP) was 30% less in 2012 ($200 \pm 27 \text{ g C m}^{-2}$) than in 2013 ($287 \pm 35 \text{ g C m}^{-2}$). Both years were warmer than the long-term average. Seasonal and annual ratios of ecosystem respiration (ER) to gross primary productivity (GEP) were higher in 2012 than in 2013. Dry conditions decreased GEP more than ER, while warm conditions increased ER more than GEP. Heat stress exerted controls over seasonal changes in NEP. Daytime NEP ceased to increase beyond $11 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ and $13 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ in 2012 and 2013, respectively, where mean photosynthetically active radiation was $>700 \mu\text{mol m}^{-2} \text{ s}^{-1}$ and air temperatures was greatest ($>27^\circ\text{C}$) in mid-summer days. The extremely strong precipitation day (176 mm) was recorded as having the greatest C discharge to the atmosphere (5.6 g C m^{-2}). Intermediate-size precipitation events ($>2 \text{ mm}$ and $\leq 15 \text{ mm}$) acted to increase C-sink strength. The results highlight the roles of environmental stresses and their alleviation in regulating C fixation in the face of warmer climate and increasing intensity of extreme precipitation events.

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1. Introduction

The carbon (C) balance of temperate forest ecosystems is particularly sensitive to climatic changes in spring and autumn, with spring and autumn temperatures over northern latitudes having risen by about 1.1°C and 0.8°C , respectively, over the past two

decades (Mitchell & Jones, 2005; Piao et al., 2008). Temperate forests (767 Mha) contributed $0.75 \pm 0.1 \text{ Pg C year}^{-1}$ (31%) to the global C sink for the past two decades (1990–2007; Pan et al., 2011). These forests are highly productive and particularly vulnerable to environmental variables, which alter seasonal C fluxes and ecosystem functions (Baldocchi, 2008; Stoy et al., 2008). It is important to understand the current roles of C-sink strength in both unmanaged-natural and protected-urban temperate forests (Chen et al., 2013). Urban temperate forests have been playing a more progressively important role in sequestering C (McHale, McPherson,

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& Burke, 2007). For example, Pan et al. (2011) suggested that there were extensive areas of managed young-to-immature forests with potential to continue sequestering C in the future in China. Xiao et al. (2013) reported that forest plantations potentially provided larger C-sequestration capacity than that of natural forests.

Photosynthesis (fixation of atmospheric CO₂ into organic C) and respiration (plant and microbial respiration converting organic C into atmospheric CO₂) differ between species and functional groupings within forest ecosystems (Law et al., 2002). Seasonal variation in net ecosystem productivity (NEP) is determined by variations in gross primary productivity (GEP) and ecosystem respiration (ER; Baldocchi, 2008). For example, in temperate coniferous forests, seasonal patterns of GEP and ER are in phase, causing NEP to peak whenever GEP and ER reach their highest values (Stoy et al., 2008). It is widely reported that GEP rates increase with photosynthetically active radiation and ER rates increase with soil temperature, when soil water is not limiting (Reichstein et al., 2005; Zha, Kellomäki, Wang, & Rouvinen, 2004). Furthermore, radiation, temperature, and leaf area can explain most of the variation in GEP and ER between forest ecosystems (Van Dijk, Dolman, & Schulze, 2005). Yet, there is still lack of consensus regarding the specific seasonal response in GEP and ER to warming and drought in forest ecosystems (Richardson, Hollinger, Aber, Ollinger, & Braswell, 2007). For example, Ciais et al. (2005) and Jassal, Black, Novak, Gaumont-Guay, and Nesic (2008) found that atmospheric warming led to reductions in both GEP and ER. In contrast, Kirschbaum (2000) and Reichstein, Tenhunen, and Ourcival (2002) postulated that both GEP and ER could increase with increases in air temperature (T_a). Additionally, Van Dijk et al. (2005) found that high T_a increased ER more than GEP. Yet, Noormets et al. (2008) reported that spring warming decreased GEP more than ER.

The response of GEP and ER to environmental factors of forest ecosystems are complex. It has been posed, which of the two fluxes (i.e., GEP and ER) is dominant in defining variation in NEP. For instance, warming and drought decrease annual NEP in forest ecosystems due to increases in ER more than in GEP, and stimulation of ER possibly offsets or negates the increases in GEP (Carrara et al., 2003; Flanagan & Johnson, 2005). Also, Bubier, Bhatia, Moore, Roulet, and Lafleur (2003) and Dunn, Barford, Wofsy, Goulden, and Daube (2007) found that annual ER was more variable than annual GEP; ER was the variable most responsible for the C balance in European forests. In contrast, temporal variation in GEP is greater than those in ER and, therefore, temporal variation in NEP is mostly controlled by variation in GEP (Noormets et al., 2008; Van Dijk et al., 2005; Zha et al., 2009). Conversely, Stoy et al. (2008) suggested that annual ER accounted for a larger degree of the variability in annual NEP for deciduous-broadleaved forests than did GEP, yet GEP was noted to define variation in NEP for adjacent needle leaf forests. Finally, Savage and Davidson (2001) showed that both GEP and ER had comparable ranges in annual variation and both sources of variation were considerably larger than that of NEP.

Temperate forests are sequestering C in urban forest parks and play an important role in local C cycles (Xiao et al., 2013). Yet, the exact magnitude of C uptake and the factors that control this apparent sink are still unclear due to the difficulty of C-flux measurements (Chen et al., 2013). Advances in the eddy covariance technique (EC) allow for direct and continuous measurement of ecosystem C exchanges on different time scales (Baldocchi, 2008). Reliable information about CO₂ exchange over a diverse range of urban landscapes (e.g., an urban forest park >500 ha) over different time scales is inadequate. The objective of this study were to: (a) quantify daily, monthly, and seasonal variation in NEP and its two component fluxes (i.e., GEP and ER) in an urban forest setting during a two-year period (2012–2013); and (b) understand the seasonal control of environmental variables on temporal variation in C fluxes.

2. Materials and methods

2.1. Study site

The study site is located in Beijing Olympic Forest Park (40.02°N, 116.38°E), Chaoyang District, Beijing, China. This park is the largest urban forest park in Asia, with an area of 680 ha and vegetation coverage of 90%. The site is in the middle of the northeast park, which is an ecological conservation and recovering area. Tourists are restricted from entering the park and few recreational facilities are available in order to reduce human disturbance.

The study area belongs to temperate and semi-humid continental monsoon climate, with mean annual air temperature (T_a) of 12.5 °C and an average of 190 frost-free days per year. Mean annual precipitation is 592 mm, of which 80% falls from June through August. The soil is mainly of the fluvo-aquic type. Soil porosity and pH are 40.3% and 7.8, respectively. Meteorological and environmental data of this study come from the meteorological station of Chaoyang District and summarized as averages over 50 years (1961–2010, inclusive).

The flux site is generally characterized by flat topography with slopes <5° and elevations of about 51 m a.s.l. Plant species composition and stand biometric properties were measured on a 100 m × 100 m permanent sample plot. Mean age of the dominant trees was ~20-year old. The park forest is dominated by *Pinus tabulaeformis* L. Other species include *Platycladus orientalis*, *Sophora japonica* L, *Fraxinus chinensis*, and *Ginkgo biloba*, with an understory of *Iris tectorum* and *Dianthus chinensis*. All trees were tagged and identified as to species, with diameter at breast height (1.37 m above ground; DBH) >3 cm being assessed annually. The stand density was 210 trees ha⁻¹, with a mean tree height of 7.7 m and a mean DBH of 20.6 cm in 2013. Ratio of trees to shrubs is about 7:3. The shrubs include *Prunus davidiana*, *Amygdalus triloba*, *Swida alba* Opiz, and *Syzygium aromaticum*, with a mean height of 2.8 m.

2.2. Flux, meteorological, and vegetation measurements

The 11.5-m-tall tower is surrounded in all directions by uniform plantation, extending to approximately 600 m of homogeneous fetch. The CO₂ and H₂O exchanges between the ecosystem and atmosphere are measured with EC equipment placed near the top of the tower. The EC system consists of a closed-path infrared gas analyzer [IRGA; model EC-155, Campbell Scientific, Inc. (CSI), Logan, UT, USA] and a sonic anemometer (CSAT3; CSI) placed at 11.5 m. The IRGA is calibrated every third month using 99.99% nitrogen gas (zero offset calibration) and 650 ppm CO₂ and a dew point generator (LI-610, LI-COR Inc., USA). Continuous high-frequency (10 Hz) data were archived and processed to calculate the corresponding fluxes at 30-minute intervals. The 30-minute mean flux values were calculated as the covariance of vertical wind speed, T_a , and CO₂/H₂O densities (Massman & Lee, 2002). Wind coordinates to mean streamline plane were rotated (Wilczak, Oncley, & Stage, 2001), which were calculated from mean wind data over an entire year. Sonic temperature was corrected for changes in atmospheric humidity and pressure (Schotanus, Nieuwstadt, & De Bruin, 1983). Net ecosystem CO₂ exchange (NEE, $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) was calculated as the sum of corrected CO₂ flux and CO₂ storage change in the canopy-air layer.

Above-canopy meteorological factors were reported as 30-minute means. Relative humidity (RH, %) and T_a (°C) were both measured with HMP-45C sensors (Vaisala Oyj, Helsinki, Finland) at 11.5 m. Photosynthetically active radiation (PAR, $\mu\text{mol m}^{-2} \text{ s}^{-1}$) was measured with PAR-LITE sensors (Kipp and Zonen, Delft, the Netherlands) and net radiation (R_n , W m^{-2}) with a CNR-4 sensor (Kipp and Zonen, Delft, the Netherlands) at 11.5 m. Soil heat flux (G , W m^{-2}) was measured at four locations using HFP-01 flux plates

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