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Seasonal variation in ecosystem water use efficiency in an urban-forest reserve affected by periodic drought

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The impact of extreme weather events on water-carbon coupling and ecosystem water use efficiency (WUE) in arid to semi-arid conditions is poorly understood. Evapotranspiration (ET) and gross ecosystem production (GEP) were based on continuously eddy-covariance measurements taken over an urban-forest reserve in Beijing, in a 3-year period (2012–2014) to calculate WUE (GEP:ET). Our objective was to investigate the seasonal response of WUE to changing environmental and drought conditions at different timescales. Annually, the forest produced new plant biomass at 2.6 ± 0.2 g C per kg of water loss. Within each season, interactions of surface conductance (g_c) and normalized difference vegetation index (NDVI; *i.e.*, $g_c \times$ NDVI) in spring, net radiation (R_n) and air temperature (T_a; *i.e.*, $R_n \times T_a$) in summer, and R_n and vapor pressure deficit (D; *i.e.*, $R_n \times$ D) in autumn were found as the significant variables explaining seasonal variation in WUE. Daily WUE correlated positively with T_a and NDVI during the growing season, but a negative relationship during excessively dry periods (*i.e.*, 2014). Daily WUE decreased during warm and dry days or remained nearly constant at low levels due to proportional decreases in GEP and ET. An extreme drought during the leaf expansion led to a greater decline in GEP than in ET, causing WUE to be lower in 2012 and 2014 than that in 2013. In contrast, an extreme drought during the leaf coloration led to a greater decline in ET than in GEP, causing higher WUE in 2013 and 2014 than that in 2012. We concluded that: (i) high soil water content (SWC) during leaf expansion was more important than high SWC in mid-summer or autumn for maintaining a high seasonal WUE; and that (ii) seasonal water availability combined with variable drought severity and duration during periods of changing T_a, caused seasonal ET and GEP to respond differently, introducing significant variation in seasonal WUE.

1. Introduction

Afforestation in China has been increasing since 1949, with levels of afforested areas expanding every year (Gao et al., 2014). As a consequence of global warming, local shortages of available water have been documented to occur more frequently, and its devastating impact is increasingly becoming apparent in Northeastern China (Zhai et al., 2010). Extreme warm and dry conditions of protected environments may locally counteract the positive effects of atmospheric CO_2 enrichment and plant fertilization, causing gross ecosystem production (GEP) and, thus, ecosystem water use efficiency (WUE) to decline (Huang et al., 2015). However, little is known about how ecosystem-level WUE of forest plantations respond to climate warming and extreme drought over extended

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periods (*e.g.*, several years) due to the complexity of ecosystem response behaviors.

Ecosystem WUE is considerably important in the investigation of forest carbon (C) assimilation relative to water vapor loss by evapotranspiration (ET; Kuglitsch et al., 2008; Yang et al., 2010). Ecosystem-level assessment of WUE is effective at determining the adaptability of protected urban-forest plantations to variable climate (Beer et al., 2009; Xie et al., 2014). Current thinking about ecosystem-WUE responses to incidences of warming and drying conditions, or extreme climate events, is mixed throughout the scientific literatures. For example, modeling studies suggest that ecosystem WUE may decrease under conditions of climate warming (De Boeck et al., 2006; Bell et al., 2010; Niu et al., 2011). Consistent with this view, Reichstein et al. (2007) detected a slight decrease in WUE for European forests during a severe heatwave in the summer of 2003. Also, Ponton et al. (2006), Tang et al. (2006), and Kuglitsch et al. (2008) found WUE to be lower when precipitation was low. In contrast, Ponce-Campos et al. (2013) and Xiao et al. (2013) found that WUE tended to increase when air temperature (T_a) was high. Krishnan et al. (2006), Li et al. (2008), Yu et al. (2008), and Beer et al. (2009) reported similar increases in WUE during periods of excessive dryness.

Literature dissensus stems, in part, from: (i) the different ways in which data were acquired (*e.g.*, stratified or non-stratified) and processed and/or the different timescales of integration (*e.g.*, hourly, daily, or annual timescales; Yang et al., 2010); (ii) water losses from the canopy and soil surface (*i.e.*, ET) are theorized to have different sensitivities to changes in T_a and precipitation (Ponton et al., 2006; Hu et al., 2008; Niu et al., 2011); and (iii) lack of consensus as to atmosphere-plant exchanges of C and water vapor under different environmental conditions. For example, Law et al. (2002), Ponton et al. (2006), and Yu et al. (2008) found that increases in ET occurred faster than increases in GEP under increasing T_a. Zhang et al. (2014) reported an opposite trend, which is largely explained by the positive effects of optimum temperature on plant photosynthesis.

Previous studies have shown that WUE is controlled by the interactions between the number of sites and biophysical variables (Kuglitsch et al., 2008). However, information about these controls, especially for protected urban forests during extreme environmental conditions, is lacking. Although the role of environmental variables in regulating ecosystem WUE in urban forests is complicated and challenging to investigate, improved understanding of ecosystem WUE is clearly central to assessing acclimatization of urban forests to extreme dry conditions, as reductions in regional precipitation intensify with climate change. Given the ongoing, extreme changes in the climate system, attaining a mechanistic understanding of the long-term dynamics of ecosystem WUE, including identification of its key controlling variables, is an important research objective.

In this study, we measured water vapor and C fluxes over a manmade nature reserve in Beijing, China (*i.e.*, Beijing Olympic Forest Park) during a three-year period (2012–2014). Flux measurements were acquired with the eddy covariance (EC) technique. This technique provides direct measurements of water vapor and C exchanges between forests and the atmosphere, providing a basis in examining forest WUE at the ecosystem level (Falge et al., 2001; Zha et al., 2013). The measurement period covers events with extreme annual total precipitation levels (from extremely low to very high) and annual mean T_a (high), compared to the past 50 years. The particular objectives of this study were to: (i) determine the environmental variables affecting ecosystem WUE in an urban forest over several timescales, and (ii) examine the seasonal response of WUE to climate extremes, particularly drought, common to Northeastern China.

2. Materials and methods

2.1. Study site

The study site is located in Beijing Olympic Forest Park (40.02°N, 116.38°E), Beijing, China. It is the largest manmade urban-forest park in Asia, with an area of 680 ha and vegetation coverage of about 90%. The forest-reserve is located in the middle of the northeastern section of the park, an area committed to ecological conservation and recovery. Tourists are restricted from entering the study area and recreational facilities are minimized in order to reduce human disturbance.

The area is classified as having a continental, semi-humid monsoon climate, with a mean annual T_a of 12.5 °C and frost-free period of about 190 days. Mean annual total precipitation is 592 mm, of which 80% falls between June and August. The soil is mainly of the fluvo-aquic type, with soil porosity of 40.3%, pH of 7.8, and an estimated field capacity and permanent wilting point of 26% and 10%, respectively. Historical climate data are from the Chaoyang District meteorological station nearby, and are summarized as averages over a 50-year period (1961–2010).

The flux site is characterized by flat topography with slopes <5° and elevations of 51 m above sea level (a.s.l.). Plant species composition and stand biometric properties were measured in a 1-ha permanent sampling plot. The young urban-plantation forest consisted of several tree species, with a shallow rooting depth of 0.08–0.40 m and mean age of 20 years, based on the age of overstory trees. The site is dominated by *Pinus tabulaeformis*; 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 by species, with diameter at breast height (DBH) >3 cm being assessed annually. Stand density in 2013 was 210 trees ha^{-1}, with a mean tree height of 7.7 m and a mean DBH of 0.2 m. Cover ratio of trees to shrubs was about 7:3. The shrubs included *Prunus davidiana*, *Amygdalus triloba*, *Swida alba*, and *Syzygium aromaticum*, with a mean height of 2.8 m. The growing season is defined as the period between the first and last occurrence of three consecutive days, when GEP is <5% of the summer maximum C uptake. We defined March through May as spring, June through August as summer, and September through November as autumn. Normally, tree leaf expansion and coloration stages begin in April and October, respectively. We defined duration and severity of 'drought' according to mean SWC <12.5% from spring to autumn; dry-soil periods during each year, are identified in Fig. 1a.

2.2. Flux, meteorological, and vegetation measurements

A 12-m-tall tower is surrounded by uniform forest cover with a homogeneous fetch of about 600 m in all directions. Carbon dioxide (CO_2) and water vapor (H_2O) exchanges are based on high-frequency measurements (at 10 Hz) obtained with EC equipment placed at the top of the tower (11.5-m height from ground). 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). The IRGA is calibrated quarterly using 99.99% nitrogen gas (zero offset calibration) and a standard CO_2 concentration of 650 ppm and a dew point generator (LI-610, LI-COR Inc., USA). Continuous data were collected and processed to calculate the corresponding fluxes at 30-min. intervals following the method described in Massman and Lee (2002). Sonic temperature was corrected for changes in atmospheric humidity and pressure (Schotanus et al., 1983). Net ecosystem CO_2 exchange (or negative net ecosystem production, NEP, μmol CO_2 m^{-2} s^{-1}) was calculated as the sum of the corrected CO_2 flux and the CO_2-storage change in the canopy-air layer. We adopted the sign convention