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Regulations of cloudiness on energy partitioning and water use strategy in a riparian poplar plantation

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ABSTRACT

Cloudiness is an important environmental variable that affects the total and proportion of diffuse radiation reaching the ground and thereby the rate of plant carbon assimilation. However, its regulations on ecosystem energy partitioning and water use strategy are not well understood, particularly for riparian ecosystems. We used the eddy covariance technique and micrometeorological sensors to measure the energy fluxes and environmental conditions for a poplar plantation adjacent to the Chaobai River in North China during the growing seasons (April–October) in 2014 and 2015. We found that canopy conductance (G_s) was the primary biophysical factor regulating the ecosystem energy partitioning, while vapor pressure deficit (VPD) did not impose significant effects on evaporative fraction (EF). Cloudiness suppressed EF primarily due to the stomatal closure caused by the decrease in direct radiation (R_{dir}). Furthermore, the ratio of stomatal sensitivity (m) and reference conductance (G_{sref}) was 0.36 and 0.48 mol m^{-2} s^{-1} $ln(kPa)^{-1}$ during clear sky and cloudy sky conditions, respectively. These results indicated that this poplar plantation with an anisohydric behavior weakened stomatal control on water loss under clear skies by avoiding leaf burn arising from higher direct sunlight and temperature. Finally, the mean Priestley–Taylor coefficient (α) and EF was 1.01 and 0.61 across two growth periods, respectively, and ecosystem evapotranspiration (ET) exceeded rainfall, even in rainy year, suggesting that a certain amount of groundwater might be consumed by this riparian poplar plantation, which would exacerbate regional drought.

1. Introduction

Increased concentration of airborne particulate matter and aerosols in many regions of the Northern Hemisphere has led to decreased direct radiation (R_{dir}) and increased diffuse radiation (R_{dif}), which will further complicate the energy partitioning and changes in the carbon and water cycles of terrestrial ecosystems (Lu et al., 2017; Steiner et al., 2013; Wang and Yang, 2014). Several studies have examined the regulations of cloudiness on ecosystem carbon and water cycling (Chu et al., 2014; Gu et al., 1999; Letts et al., 2005; Xu et al., 2017) and found that elevated R_{dif} could enhance gross primary productivity (GPP) and net ecosystem productivity (NEP) for those ecosystems with a high leaf area index (LAI > 2) (Kanniah et al., 2012; Still et al., 2009; Urban et al., 2007). Interestingly enough, there is no consensus on the impacts of cloudiness on ecosystem evapotranspiration (ET). Previous studies found that increased R_{dif} by cloudiness was conducive to stomatal openness and thus enhanced ET (Dengel and Grace, 2010; Wang et al., 2008). However, for sparse canopies, cloudiness reduced ecosystem ET largely because of the decrease in vapor pressure deficit (VPD) and temperature (Rocha et al., 2004). Therefore, cloudiness triggers ecosystem-dependent responses on water flux and energy partitioning.

Reduced radiation loading on canopy by cloudiness is often coupled with decreased air temperature (T_a), leaf temperature (T_l) and VPD (Steiner and Chameides, 2005) that may indirectly alter transpiration and energy partitioning (e.g., evaporative fraction, EF) (Knohl and Baldocchi, 2008; Wilson et al., 2000; Zenone et al., 2015). Generally, a combination of low radiation and low temperature will reduce EF (i.e., the ratio of LE to [LE + H]) by limiting vegetation transpiration and

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surface evaporation (Kanniah et al., 2013, 2012; Rocha et al., 2004; Zhang et al., 2010). As for VPD, its role in energy partitioning varies from a positive effect on transpiration to a negative effect on canopy conductance (G_s) (Gu et al., 2006; Jia et al., 2016). Clearly, sky conditions exert a complex and coupled influence on the surface energy budget and partitioning. Yet, quantitative exploration of the direct and indirect regulations of cloudiness on ecosystem energy partitioning has not been conducted to fill this knowledge gap.

Riparian ecosystems are highly susceptible to the changing environment, such as higher temperature and varying hydrological conditions (Capon et al., 2013; Chen et al., 1999; Nilsson et al., 2013), and are thus regarded as early warning systems for climate change (Johnson et al., 2006). Moreover, energy partitioning and water use strategies of these ecosystems are also vital for the long-term water use of plants and regional water budget (Serrat-Capdevila et al., 2011; Zenone et al., 2015; Zhang et al., 2014). Poplar trees are extensively used in semi-humid and semi-arid areas for timber and bioenergy production, windbreak shelterbelt, urban greening, and riparian restoration due to their fast growing nature (González et al., 2016; Martín-García et al., 2013). However, the high ET of poplar plantations associated with their fast growth may trigger a decline in the groundwater table and aggravate regional drought (Kang et al., 2015; Migliavacca et al., 2009; Wilske et al., 2009). Physiologically, poplar trees with better cavitation-resistant xylem have two contrasting hydraulic behaviors (i.e., isohydric behavior and anisohydric behavior) that reflect the different responses of stomata to atmospheric demand (i.e., VPD) (Domec and Johnson, 2012; Hinckley et al., 1994). The stomatal control of isohydric poplar (*Populus nigra* × *P. maximowiczii*) was tied to maintain minimum leaf water potential (Ψ_{leaf}) (Schmidt-Walter et al., 2014). On the contrary, a multi-genotype poplar plantation (*Populus deltoids* × *P. maximowiczii* × *P. trichocarpa*) with anisohydric behavior allows plant Ψ_{leaf} to decrease with increasing VPD for sustaining longer periods of transpiration and photosynthesis even under water stress while this behavior may put plants at greater risk of xylem dysfunction (Zenone et al., 2015). More importantly, these hydraulic behaviors and water use strategies within the same species could vary with environment (Domec and Johnson, 2012; Franks et al., 2007). For example, the water use strategy of hybrid poplar (*Populus trichocarpa* × *P. deltoides*) could change with light (Hinckley et al., 1994). Grape (*Vitis vinifera* L.), a typical anisohydric species, can switch from an anisohydric-like behavior with increasing VPD to isohydric-like behavior during low transpiration periods (Zhang et al., 2012). Unfortunately, the variable response of stomata to VPD under non-water stress condition remains unclear, especially in different sky conditions (Lovisolo et al., 2010).

Therefore, we examined the regulatory mechanisms of biophysical factors on energy partitioning and water use strategies in a riparian poplar plantation. Based on the measurements of energy fluxes and micrometeorological variables during the growing seasons (April – October) of 2014 and 2015, we set our study objectives to: (1) explore the annual and seasonal dynamics of energy balance components and bulk surface parameters, (2) quantify the biophysical controls on canopy conductance and energy partitioning in mid-growing seasons (i.e., June–August), and (3) assess the water use strategies of the poplar plantation under clear and cloudy skies. We hypothesized that cloudiness directly and indirectly affects ecophysiological processes and biophysical factors that intensively regulated the ecosystem energy partitioning. We further hypothesized that the associated water use strategy of the plantation ecosystem would be significantly altered by cloudy sky conditions.

2. Methods and materials

2.1. Study site

Our study was conducted in a poplar plantation forest located in the Shunyi Forest Farm (116°42′41″E, 40°06′27″N) in Beijing, China. The site is characterized by flat topography at an average elevation of 30 m above sea level. It is situated in a riparian area on a fluvial plain of the Chaobai River with a stable water level during the study period. The 178 ha forest consists of a 21-year old plantation dominated by poplar (*Populus* × *euramericana*, > 95%), with a planting density of 4 m × 3 m. By the end of 2015, the average height of the trees was 17.1 ± 1.3 m (mean ± SD) and the mean diameter at breast height (DBH) was 24.4 ± 1.9 cm. Understory shrubs mainly include *Swida alba Opiz.*, *Sorbaria sorbifolia (L.) A. Br.*, *Forsythia suspense* and *Sabina vulgaris*, and had been maintained at low densities since the initial establishment of the plantation.

The study site is characterized by a warm temperate sub-humid continental monsoon climate, with a mean annual temperature of 11.5 °C, a mean annual relative humidity (RH) of 50%, and average annual potential ET of approximately 1150 mm. Annual mean precipitation is 576 mm, with over 95% falling during the growing season (Shunyi Weather Station, 1990–2010). The soil is classified as a sandy parent material with a field moisture capacity (−10 kPa) of 18% and an organic matter content of 14 g kg^{-1} determined by the dichromate oxidation method (Walkley and Black, 1934). The fine root mass (ca. 70%) is mainly distributed in the 20–50 cm soil layer. The groundwater table is around 2 m and does not exhibit significant seasonal variations.

2.2. Fluxes and meteorological measurements

An eddy-covariance (EC) flux tower was established in 2013 with an open-path gas analyzer (EC150, Campbell Scientific Inc., Logan, Utah, USA) and a three-dimensional sonic anemometer (CSAT3, CSI) installed at 26 m above the ground. These two instruments measured the exchange of carbon, sensible heat (H) and latent heat (LE) fluxes between the poplar plantation and the atmosphere. Eight CO_2/H_2O profile systems (AP200, CSI) were installed at 0.5 m, 1.5 m, 5 m, 10 m, 15 m, 20 m, 25 m and 30 m above the ground for calculating the heat storage (S) in the air column below the EC sensors (Kang et al., 2015; Oliphant et al., 2004).

Other observation instruments and their configurations have been described in detail by Xu et al. (2017). In short, T_a and RH were measured at five heights with temperature and humidity probes (HC2S3, CSI), which were also used to calculate VPD. The net radiation (R_n) was recorded with a four-component radiometer (CNR1, Kipp and Zonen B.V., Delft, Netherlands) at the top of the tower (30 m). At the same height, a pyranometer (LI-200x, LI−COR Inc., Lincoln, Nebraska, USA) and a quantum sensor (LI–190SB, LI−COR Inc.) were installed for measuring the global shortwave solar radiation (R_g) and photosynthetically active radiation (PAR), respectively. Soil volumetric water content (VWC) was measured by five soil moisture probes (CS616, CSI) at 5–150 cm depth. Soil temperature probes (TCAV107, CSI) and heat flux plates (HFT3, CSI) were used to measure soil temperature (T_s) and soil heat flux (G) of a soil layer of 5 cm and 25 cm. The EC flux and micrometeorological data were recorded by CR3000 and CR1000 (CSI), respectively. The leaf area index (LAI) was measured at 16:30-18:00 h twice per month using the plant canopy analyzer (LAI-2200, LI−COR Inc.) and monitored in 12 sample plots with 6 replicates per plot, covering the double rows and the space between two adjacent double rows. LAI values were corrected by subtracting the woody canopy area index obtained during leafless periods.

2.3. Flux data processing

We followed the conventional procedure to process raw flux data, including spike filtering, detrending operation (block average), tilt correction (planar-fit method), WPL corrections and flux calculation (Burba and Anderson, 2010; Foken et al., 2012; Webb, 1982) by using Eddypro software (version 6.2.0, LI−COR Bioscience). The resulting half-hourly data were filtered out using the following criteria: (1) more than 10% for the sum of the data of removed spikes, missing records