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Ecosystem water use efficiency in a warm-temperate mixed plantation in the North China

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SUMMARY

Water use efficiency (WUE) at the ecosystem level is an important ecophysiological index reflecting the coupling relationship between water and carbon cycles. CO_2 and water vapor fluxes were measured by the eddy covariance method during the period 2006–2010 over a warm-temperate mixed plantation in the North China. The seasonal and interannual variations of gross primary productivity (GPP), evapotranspiration (ET) and ecosystem WUE were analyzed, and the impacts of climatic variables and soil moisture on GPP, ET and WUE were discussed. At the monthly scale, GPP and ET had similar relations with solar radiation, air temperature, vapor pressure deficit (VPD) and precipitation. It is suggested that photosynthesis and evapotranspiration were driven by climatic variables at the approximately equal strength. During the growing season, WUE decreased significantly with the increase of VPD and solar radiation. Cloudiness can improve photosynthesis and enhance WUE. GPP was 9–39% greater but ET was 8–26% lower under cloudy sky conditions than that under sunny sky conditions. Therefore, WUE was 29–72% higher under cloudy skies in comparison with that under sunny skies. Annual average WUE ranged from 1.76 to 2.41 g C kg^{-1} H_2O. The major driver of interannual variability in WUE was soil water content in May.

1. Introduction

Under climate change, the occurrence frequency and strength on drought will intensify in the arid and semi-arid regions (IPCC, 2007). The effects of drought on terrestrial water and carbon cycles have been one of focus issues in the study of global change. Water use efficiency (WUE) at the ecosystem level is an important ecophysiological index reflecting the coupling relationship between ecosystem water and carbon cycles (Yu et al., 2004, 2008). The variability of WUE indicated the difference in the coupling between carbon and water cycles (Yu et al., 2008). At the ecosystem level, WUE is defined as the ratio of gross primary productivity (GPP) to evapotranspiration (ET) (Law et al., 2002; Ponton et al., 2006; Reichstein et al., 2007; Yu et al., 2008; Jassal et al., 2009; Brümmer et al., 2012). WUE can indicate the strategy of water use by the plants under different living environments (Donovan and Ehleringer, 1991). Moreover, WUE can be used to evaluate the impact of water resource on the carbon sink/source function for the terrestrial ecosystems.

The eddy covariance system plays a useful tool to directly measure water vapor and carbon fluxes over forest ecosystems (Baldocchi, 2003; Yu et al., 2008). In the FluxNet stations, the eddy method is used to study the variability and the response of WUE on climatic and soil variables at the ecosystem level (Law et al., 2002; Reichstein et al., 2002; Scanlon and Albertson, 2004; Ponton et al., 2006; Yu et al., 2008; Jassal et al., 2009; Zhu et al., 2013). The seasonal variability of ecosystem WUE were obvious for Mediterranean evergreen forest (Reichstein et al., 2002), temperate broad-leaved Korean pine mixed forest (Yu et al., 2008; Zhu et al., 2013), but unobvious for Dugalas-fir stand (Ponton et al., 2006; Jassal et al., 2009). Seasonal and interannual climate variability as well as interactive effects of plant nutrients and soil water supply might impact WUE through their influences on energy partitioning and canopy conductance (Jassal et al., 2009). Climatic and soil variables impacting ecosystem WUE include vapor pressure deficit (VPD), air temperature, precipitation and soil water content (SWC). For example, WUE decreased with increasing

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VPD for rain forest, evergreen forests and deciduous broadleaf forests (Law et al., 2002) and Douglas-fir stand (Ponton et al., 2006). Yu et al. (2008) pointed out that mean annual air temperature and annual precipitation were the main factors controlling the spatial pattern of both vegetative seasonal and annual WUE for the forest ecosystems in eastern China, especially in the vegetative season. At the Mediterranean evergreen forest sites, WUE decreased linearly with the reduction of SWC, indicating that theses ecosystems had high susceptibility of canopy function to drought (Reichstein et al., 2002).

Solar radiation decreased globally about 5–10% in the late 20 century and it dropped 15–30% in some regions of the north hemisphere (Stanhill and Cohen, 2001). In recent 50 years, solar radiation in the North China indicated a reduction trend and diffusion radiation increased in most stations (Ma et al., 2011). Many studies on the impact of diffusion radiation on carbon uptake by the plants were carried out, and the results showed that the amount of net carbon uptake by forest ecosystems under cloudy sky conditions was more than that under sunny sky conditions (Law et al., 2002; Gu et al., 1999, 2003; Niyogi et al., 2004; Jenkins et al., 2007; Mercado et al., 2009; Zhang et al., 2010, 2011; Urban et al., 2012). However, the influence of diffusion radiation on ecosystem WUE is lacking (Zhang et al., 2011).

Forest plays a vital role in global carbon and water cycles (Dixon et al., 1994; Goodale et al., 2002; Houghton, 2005). The area of plantations in the North China occupied 8.21 million ha, accounting for 13% of the total plantation area in China (Jia, 2009). The augment of the plantation area has an advantage to offset the increasing CO_2 concentration in the atmosphere. However, carbon storage gains are corresponding to an amount of water cost. As a vital ecological barrier, the hilly area in the North China, located at the warm-temperate monsoon climate zone, with spring drought, is one of the crucial regions of forest ecological engineering in China. Water resource has become a limiting factor of forest development in this region. In the past three decades, water carrying capacity was not taken into account in the process of afforestation in this region, resulting in retarding the growth of part of afforestation trees and decreasing the survival rates of trees when drought occurred. In this study, the eddy covariance method was used to measure CO_2 and water vapor fluxes over a broadleaf dominant mixed plantation in the hilly area of the North China. Our objectives are: (1) to analyze the variety characteristics of GPP, ET and ecosystem WUE to well understand the relationship between carbon gain and water consumption, (2) to investigate the influence of climatic variables on the variations in monthly GPP and ET, and (3) to explore the environmental factor controlling interannual variation in WUE and discuss the response of WUE to the changes of cloudiness. The results obtained from this study will help us indentify the environmental controlling mechanisms of WUE and provide references for selecting afforestation trees in future.

2. Materials and methods

2.1. Site description

This study was conducted in a broadleaf dominant mixed plantation at Xiaolangdi forest experimental site, Jiyuan, Henan province, China (35°01′N, 112°28′E; elevation 410 m) (Fig. 1). The experiment station is located at the south of Taihang Mountain and the north of Yellow River Basin. This study station experiences a warm-temperate continental monsoon climate. The 30-year annual mean temperature and annual rainfall are 13.4 °C and 642 mm, respectively. The seasonal distribution of precipitation is uneven and rainfall between June and September accounts for 68% of whole year. The soil parent material is composed of limestone and the soil is mainly brown loam. The tree species for the mixed plantation are cork oak (*Quercus variabilis blume*), black locust (*Robinia pseudoacacia* L.) and arborvitae (*Platycladus orientalis*), with ages of 32, 28 and 30 years old and heights of 10.5, 9.3 and 8.2 m, respectively. Stand density was 1905 stems ha^{-1}.

2.2. Measurements of water vapor and CO_2 fluxes, microclimatic variables

Water vapor and CO_2 fluxes were measured at the height of 30 m above the ground by the eddy covariance system consisting of a 3-D sonic anemometer (model CSAT3, Campbell Scientific Inc., USA) and an open-path and fast response infrared CO_2/H_2O analyzer (IRGA, Model Li-7500, Li-Cor Inc., USA). The eddy covariance system can monitor the fluctuations of 3-D wind components, sonic temperature, water vapor and CO_2 concentrations. Raw data were collected at a frequency of 10 Hz and half-hour flux data were recorded by a datalogger (Model CR5000, Campbell Scientific Inc., USA). Meteorological variables, such as air temperature, air humidity, solar radiation, net radiation, photosynthetically active radiation (PAR) and precipitation, were measured at the same time. In addition, soil temperature at five depths (0, 5, 10, 15 and 20 cm), soil moisture at the 20-cm depth and soil heat flux were monitored. All above microclimatic and soil variables were recorded by two dataloggers (Model CR10XT and CR23XTD, Campbell Scientific Inc., USA). More detailed information on the instruments was described in Tong et al. (2012).

2.3. Flux calculation and data proceeding

The fluxes of CO_2 (F_c) and latent heat (λE) were determined as:

$$F_c = \rho(\overline{w'c'}) \tag{1}$$

$$\lambda E = \lambda\rho(\overline{w'q'}) \tag{2}$$

where ρ is air density, w' is the vertical wind velocity, c' is CO_2 concentration, λ is the latent heat of vaporization, E is water vapor flux and q is the specific humidity. 2-D coordination rotation (McMillen, 1988) and Webb–Pearman–Leuning algorithm (Webb et al., 1980) were applied to obtain half-hourly CO_2 and latent heat fluxes.

At night, CO_2 flux data were deleted when friction velocity (u^*) was lower than 0.35 m s^{-1} (Tong et al., 2012). The data more than three times variance with the average were regarded as the abnormal values. Moreover, the abnormal data owing to instrument malfunction and unfavorable meteorological conditions (rain and dew) were deleted. The short gaps (<2 h) were filled by a linear method. The longer gaps in the daytime and nighttime were filled using the mean diurnal variation (MDV) and nonlinear regression methods, respectively (Falge et al., 2001).

2.4. Calculation of WUE

Ecosystem water use efficiency (WUE) was calculated as:

$$\mathrm{WUE} = \frac{\mathrm{GPP}}{\mathrm{ET}} \tag{3}$$

where GPP is gross primary productivity and its calculation can be found in Tong et al. (2012), ET is evapotranspiration and can be obtained from Eq. (2).

2.5. Defining sunny sky conditions

The clearness index (k_t) can be used to describe the impact of the atmosphere on solar radiation and it can be obtained as follows (Gu et al., 1999):