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Water use efficiency and evapotranspiration partitioning for three typical ecosystems in the Heihe River Basin, northwestern China

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ABSTRACT

It is crucial to improve water use efficiency (WUE) and the transpiration fraction of evapotranspiration (T/ET) for water conservation in arid regions. As a link between carbon and water cycling, WUE is defined as the ratio of gross primary productivity (GPP) and ET at the ecosystem scale. By incorporating the effect of vapor pressure deficit (VPD) on WUE, two underlying WUE (uWUE) formulations, i.e. a potential uWUE ($uWUEp = GPP\cdot VPD^{0.5}/T$) and an apparent uWUE ($uWUEa = GPP\cdot VPD^{0.5}/ET$), were proposed recently. Both uWUEp and uWUEa can be estimated from eddy covariance measurements, and the ratio of uWUEa and uWUEp was then used to estimate T/ET. This new method for ET partitioning was applied to three typical ecosystems in the Heihe River Basin. Growing season T/ET at the Daman site (0.63) was higher than that at the Arou and Huyanglin sites (0.55) due to the application of plastic film mulching. The effect of leaf area index (LAI) on seasonal variations in T/ET was strong for Arou ($R^2 = 0.74$) and Daman ($R^2 = 0.76$) sites, but weak for Huyanglin ($R^2 = 0.44$) site. Daily T/ET derived using the uWUE method agreed with that using the isotope and lysimeter/eddy covariance methods during the peak growth season at the Daman site. The estimated T using the uWUE method showed consistent seasonal and diurnal patterns and magnitudes with that using the sap flow method at the Huyanglin site. In addition, the uWUE method can estimate ecosystem T/ET without scaling issues, and can effectively capture T/ET variations in relation to LAI changes and the abrupt T/ET changes in response to individual irrigation events. These advantages make the uWUE method effective for ET partitioning at the ecosystem scale, and can be used for water resources management by predicting seasonal pattern of actual plant water requirements to support irrigation strategies in arid regions.

1. Introduction

The Heihe River Basin (HRB), located in the arid region of northwestern China, is one of the largest inland river basins in China. The landscape in the basin is quite diverse, including glaciers, frozen soil, alpine meadow and forests in the upper HRB, irrigated farmland in the middle HRB, and riparian ecosystem and desert in the lower HRB (Li et al., 2001). The farmland and riparian vegetation in the middle and lower HRB are supported by the precipitation and snowmelt from the Qilian Mountains, where the Heihe River originates. The middle and lower HRB is a typical arid region with competing water requirements for irrigated farmland and natural vegetation (Zhou et al., 2015b). Irrigation water in the middle and lower HRB accounts for more than 80% of runoff from the Heihe River (Zeng et al., 2012). The riparian forests in the lower HRB have diminished rapidly due to a lack of water over the past several decades (Qi and Luo, 2007). Given the water scarcity in the HRB, it is the primary goal for water resources managers to reduce unproductive water loss through evaporation, that is, to increase water use efficiency (WUE) and transpiration fraction of the evapotranspiration (T/ET) for the farmland and natural vegetation. To relieve water conflicts in the HRB, it is particularly important to investigate WUE and T/ET in different ecosystems from the upper to lower HRB.

Agricultural WUE usually refers to grain yield per unit amount of water used, and the latter is measured by ET (Hou et al., 2012; Zhang et al., 2004). Efforts have been made to estimate ET in the HRB to form

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the basis for determining water requirements and water allocation, especially for the irrigated croplands in the middle HRB. Bowen ratio-energy balance and reference evapotranspiration have been used to estimate crop ET using meteorological measurements in the middle HRB (Liu et al., 2009; Zhao et al., 2010). Several remote sensing based models, which can simulate ET over large geographic areas, were also used to obtain spatial patterns in ET in the HRB (Li et al., 2012; Luo et al., 2012). The estimated crop ET, an important indicator of water consumption, has been used for irrigation water allocation in the middle HRB (Ge et al., 2013). However, water resources management based on ET measurements may overestimate the actual water requirement of crops, resulting in low WUE and T/ET (Wu et al., 2015). Yang et al. (2015) found that irrigated maize extracted water primarily from the top 10cm soil layer, where only 24.7 $\pm$ 5.5% of the irrigation water was retained, and most of irrigation water was consumed through evaporation. Over-irrigation at the expense of reducing water availability for natural vegetation has led to serious eco-environmental problems, such as increased groundwater salinity and vegetation degradation, in the middle and lower HRB (Qi and Luo, 2007; Wang et al., 2011). Thus, water requirements for natural vegetation should also be satisfied to achieve a healthy balance between agricultural development and environmental conservation (Zhou et al., 2015a). Aggregated agricultural WUE measures water use in terms of the crop yield, but does not consider how the water use varies during the growing season. For water conservation during different stages of crop growth, and to effectively reduce agricultural water use for natural vegetation, a method is needed to define and quantify the temporal variation in WUE and T/ET for both irrigated cropland and natural ecosystems in the HRB.

Focusing on the interactions between carbon and water cycles, WUE is commonly defined as the ratio of gross primary productivity (GPP) and ET at the ecosystem scale (Law et al., 2002). Because WUE is affected by vapor pressure deficit (VPD) (Beer et al., 2009), an underlying WUE (uWUE = GPP·VPD$^{0.5}$/ET) was proposed by Zhou et al. (2014) to incorporate the nonlinear effect of VPD. Since the uWUE is derived by combining both the direct impact of VPD on plant transpiration and the response of stomatal conductance to VPD, it is recognized as a better indicator to represent plant physiological regulation of water and carbon exchange than WUE (Zhou et al., 2014; 2015c). There has been little research in relation to ecosystem WUE or uWUE based on carbon and water interactions in the HRB. It was not until 2010 that the Heihe Watershed Allied Telemetry Experimental Research (HiWATER) was initialized to improve our understanding of the hydrological and ecological processes in the HRB (Li et al., 2013). Since 2012, the exchange of carbon and water between the atmosphere and the land surface has been observed across various ecosystems over the basin using eddy covariance technique, which facilitated our investigation into uWUE in the HRB.

In situ measurements, such as stable isotopes, lysimeter, sap flow and eddy covariance techniques, were used to estimate ET and its components, namely vegetation transpiration (T), and canopy interception and soil evaporation (E) in the HRB (Li et al., 2013; Wen et al., 2016). The isotope method, which is based on different isotopic compositions of T and E, has been used to partition ET, especially in dryland ecosystems (Good et al., 2014; Wang et al., 2010; Zhang et al., 2010). However, the estimation of isotopic compositions of T, E and ET relies on a series of assumptions, part of which are invalid under field conditions, such as the spatial and temporal variability in the isotopic compositions of T, E and ET, resulting in large uncertainty in the isotope method (Sutanto et al., 2014). As a simple method, the micro-lysimeter is used for under-canopy or bare soil evaporation measurements based on the principle of water balance (Liu et al., 2002), but it cannot measure canopy interception evaporation. To measure transpiration at a plant scale, sap flow techniques were applied to shrubs (Zhao and Liu, 2010), orchards (Fernández et al., 2011), and forests (Du et al., 2011). The combination of lysimeter or sap flow with eddy covariance has also been used for ET partitioning (Cammalleri et al., 2013; Williams et al., 2004), but this method is subject to the mismatch of spatial scales. Based on a flux-variance similarity assumption, Scanlon and Kustas (2010) proposed a method for ET partitioning based on carbon and water fluxes data at the ecosystem scale. However, this method has not been widely used due to the requirements of high frequency (10 Hz) flux data and the uncertainty in the WUE parameter. Given the assumptions and limitations associated with the ET partitioning methods, no consensus has been reached as to which method is most accurate and large uncertainty in the components of ET still exists (Schlesinger and Jasechko, 2014; Sutanto et al., 2014).

Recently, Zhou et al. (2016) presented a new method to partition ET based on the concept of uWUE. By distinguishing two uWUE formulations, i.e., a potential uWUE (uWUEp = GPP·VPD$^{0.5}$/T) and an apparent uWUE (uWUEa = GPP·VPD$^{0.5}$/ET), the ratio of uWUEa over uWUEp was used as a surrogate measure of T/ET. Within a uniform ecosystem, uWUEp is identical to the uWUE at the leaf scale that depends on atmospheric CO_2 concentrations and a relatively constant marginal WUE under non-water stress conditions, according to the optimal stomatal behavior for carbon and water exchange (Zhou et al., 2016). Therefore, uWUEp is assumed to be relatively constant under steady state conditions (relatively constant atmospheric CO_2 and water stress) for a given vegetation type, while uWUEa varies with T/ET and reaches its maximum, i.e., uWUEp when T = ET. As both uWUEp and uWUEa can be derived from flux tower observations, T/ET can therefore be estimated as the ratio of uWUEa over uWUEp, and T can be estimated as well at the ecosystem scale. Berkelhammer et al. (2016) estimated T/ET using the uWUE method and the isotope method at two needleleaf forested sites in the United States, and found strong agreement between T/ET from these two independent approaches. The advantage of the uWUE method over the other three ET partitioning methods is that the method can be used to estimate T/ET continuously at different time scales based on flux observations (Zhou et al., 2016). Thus, we can use the uWUE method to quantify temporal variations in T/ET in the HRB. Compared to most AmeriFlux sites for which the uWUE method for ET partitioning was developed, some of the sites in the HRB receive extremely low precipitation ($< 50\,\mathrm{mm\,yr^{-1}}$), and the middle and lower parts of the basin entirely depend on irrigation for agriculture. Little is known about the reliability of the new uWUE method for this arid and intensively managed environment. Although it is almost impossible to carry out an absolute validation of the uWUE method with ecosystem T and E measurements, it is interesting to compare the uWUE method with other ET partitioning methods in terms of the temporal variations in T/ET or T at different ecosystems in the HRB.

The objectives of this study are: 1) to investigate seasonal variations in GPP, ET, VPD, uWUEa, and T/ET for three typical ecosystems in the upper (alpine meadow), middle (irrigated cropland) and lower (*Populus euphratica*) HRB; 2) to evaluate the uWUE method in comparison with the stable isotope, lysimeter/eddy covariance, and sap flow methods in terms of ET partitioning at both daily and half-hourly time scales; and 3) to have a better understanding of the carbon-water interactions for the three typical ecosystems for developing more informed water allocation and management strategies in the HRB.

2. Materials and methods

2.1. Site descriptions and field observations

Data from three sites were used in this study: Arou (henceforth AR) in the upper HRB, Daman (DM) in the middle HRB, and Huyanglin (HYL) in the lower HRB in northwestern China (Fig. 1). Brief descriptions regarding the three sites are presented in Table 1. The three sites represent three different kinds of climate and land cover that characterize the HRB. The AR site located in the Qilian Mountains is covered by alpine meadow, with relatively low temperature and high precipitation (Table 1). The DM site is located in an irrigated cropland in