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The characteristics of evapotranspiration and crop coefficients of an irrigated vineyard in arid Northwest China

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ABSTRACT

Oasis effect may have significant impacts on the crop water use in irrigated fields of extremely arid conditions. Studies on crop coefficients and its relevant influence factors are essential to accurately determine the irrigation scheduling under such conditions. A two-year experiment was conducted in an irrigated vineyard to estimate evapotranspiration (*ET*) and its two components: evaporation (*E*) and crop transpiration (*T*), and to develop appropriate region-specific crop coefficients (K_c, K_{cb}) in arid Northwest China. The contributions of "oasis effect" to K_c, the relationships of both K_c and K_{cb} to canopy conductance (G_c) and leaf area index (*LAI*) were investigated. Local values of K_c for evapotranspiration and crop transpiration (K_{cb}) were calculated using the field data and the dual-K_c approach. The daily *ET* ranged from 0.80 to 9.87 mm d^{-1} and from 0.99 to 8.73 mm d^{-1} in 2014 and 2015, respectively, with corresponding *T/ET* values amounting to approximately 58.4% and 55.1%. The locally averaged K_c values were 0.79, 1.31, and 1.08 during the initial, middle, and late growth stages, respectively, versus corresponding K_{cb} values of 0.17, 0.97, and 0.64. Arid advection accounted for 16.9 to 57.4% and from 1.4 to 49.0% of daily K_c during the two study periods. Both K_c and K_{cb} to *LAI* is a linear regression but to G_c is an exponential one. *LAI* is a better indicator than G_c when it is used to predict K_c and K_{cb}. These results will help growers to improve irrigation efficiency and quantify the contributions of individual factors to K_c and K_{cb} in such conditions.

1. Introduction

Evapotranspiration (*ET*) is a significant process in terrestrial systems, where it represents a link among the hydrological, carbon, and energy cycles (Zhu et al., 2016a, b). About 60% of rainfall re-enters the atmosphere through transpiration (*T*) and evaporation (*E*), but this amount can reach 90% in agricultural ecosystems (Jung et al., 2010; Zhu et al., 2014). Thus, accurate measurement and estimation of *ET* and its components (*T* and *E*) in agricultural ecosystems are crucial both for managing irrigation and for improving crop yield (Allen et al., 2011; Sun et al., 2012; Kool et al., 2014; Zhao and Zhao, 2015). Many techniques have been developed to measure *ET* and its components, such as combining the sap-flow and eddy-covariance methods (Herbst et al., 1996; Cavanaugh et al., 2011; Zhang et al., 2011), developing land-surface models (Oleson et al., 2004; Dirmeyer et al., 2006), and isotope methods (Williams et al., 2004; Wang et al., 2010; Jasechko et al., 2013). Of these methods, the combination of sap-flow and eddy-covariance techniques supply a direct and robust observation of *ET* and *T*, and therefore provide basic data that can be used to assess the accuracy of other methods. Thus, this combination has been widely used to measure and partition the components of *ET* in various ecosystems (Ding et al., 2015).

In comparison with direct in situ measurements, accurately estimating *ET* based on meteorological data is appealing in irrigation scheduling due to its relative simplicity and ease of application (Jagtap and Jones, 1989; Ding et al., 2015). The dual crop coefficient (dual-K_c) method proposed by the Food and Agriculture Organization (FAO-56) has been widely used to estimate the components of *ET* (Allen et al., 1998). In this method, the crop coefficient (K_c) is partitioned into two parts: the basal crop coefficient (K_{cb}), representing crop transpiration and the soil evaporation coefficient (K_e). This method has been extensively applied in different crop ecosystems, including coffee (Flumignan et al., 2009), castor (Campbell et al., 2015), apple trees (Marsal et al., 2013), peach orchard (Paço et al., 2012), and grapevines (Fandiño et al., 2012; Picón-Toro et al., 2012; Poblete-Echeverría and Ortega-Farias, 2013; Zhao et al., 2015). However, the values of the crop

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coefficients (K_c or K_{cb}) have been reported to be sensitive to climate, hydrological, and environmental factors. As a result, the proposed adjustment method for K_c and K_{cb} in FAO-56 can only approximately explain the variations of K_c and K_{cb} in response to changes in relative humidity (*RH*), wind speed, and other environmental variables (Allen et al., 1998). Significant uncertainties in estimating *ET* and its components have been reported in previous studies when directly using the FAO-proposed coefficient values in different regions (Sánchez et al., 2014; Yang et al., 2016). Thus, it is necessary to identify the specific values of K_c and K_{cb} across different agricultural ecosystems and environmental conditions, as these values provide important guidance for local irrigation practices and can be used to improve water-use efficiency (Yang et al., 2016). In addition, the relationships of both K_c and K_{cb} to various ecological and environmental factors (e.g., canopy conductance, leaf area index [*LAI*], and vapor-pressure deficit) need to be investigated in detail. However, as far as we know, such studies are relatively few.

To improve regional food security, China has been forced to implement cultivation in many areas where water is scarce. For example, the landscape in arid northwestern China is characterized by widely distributed gobi desert (i.e., desert with a gravel surface) interspersed with many oases, where there is abundant light to support agricultural ecosystems but limited water resources (Zhu et al., 2007, 2008, 2014). In this region, a phenomenon known as the "oasis effect", which involves evaporative cooling over areas of water that leads to advection of warmer bodies of air, is often observed on clear days (Wang and Mitsuta, 1992; Lee et al., 2004). Previous studies have indicated that the oasis effect will increase *ET* in agricultural systems (Prueger et al., 1996; Lei and Yang, 2010; Ding et al., 2015). However, fewer studies have attempted to investigate the impact of the oasis effect on K_c and its components in the arid oasis agricultural systems in northwestern China.

In the present study, direct measurements of the components of *ET* obtained by combining the sap flow and eddy-covariance techniques in a grapevine ecosystem in the arid region of northwestern China. Our main objectives were: (1) to investigate the seasonal variations of K_c, K_{cb}, and K_e under the advective conditions; (2) to identify the relationships of both K_c and K_{cb} to local ecological factors; and (3) to evaluate the impact of the "oasis effect" on K_c.

2. Materials and methods

2.1. Study sites

The experiment was conducted in a grapevine (*Vitis vinifera* cv. 'Thompson Seedless') ecosystem during the 2014 and 2015 growing seasons. The study site is located in the Nanhu Oasis of northwestern China (39°52′34″N, 94°06′19″E; 1300 m a.s.l.). One plot in an area of 7.2 ha (450 m × 160 m) was selected in this area to conduct our study. The canopy height of the vineyard was about 2.5 m above the ground (Fig. 1a, b). The planting pattern of the grapes was in rows, with a spacing of 3 m between rows and 1 m between grapes trellises (Fig. 1c), with the rows oriented from north to south. Weeds at the study site were removed regularly during the whole growth stage. Pruning was performed around DOY 230 during 2014 and 2015 to improve the yield and increase the water use efficiency. The root depth of the grapevines was about 2.0 m below the surface with about 1.5 m of the lateral root spread in the inter-row space, which was too shallow to reach the groundwater caused by the deep water table (10–50 m) in this region (Ma et al., 2013;). Therefore, the contribution of ground water was not considered in the computations. Plants received flood irrigation about every 20 days during the growth stages. Based on the FAO classification, the soil type is Arenosols, with a mean soil bulk density being 1.41 g cm^{-3} (Yan et al., 2015). The values of the measured field water capacity (θ_{FC}) at site was 0.28 m^3 m^{-3}, and the wilting point (θ_{WP}) by Allen et. al. (1998) was about 0.13 m^3 m^{-3}. The annual total solar radiation ranged from 5903.4 to 6309.5 MW m^{-2}, which provided sufficient sunlight for grapes in the study area. The annual mean temperature and rainfall were 9.3 °C and 36.9 mm, respectively, with mean monthly temperatures ranging from -9.3 °C in January to 24.9 °C in July (Yan et al., 2015).

2.2. Eddy covariance and sap flow measurements

Eddy-covariance method was used to measure the daily *ET* in the grapevine field. The eddy-covariance instrumentations (Fig. 1e) were installed at 4.0 m above the ground level, which consist of an open-path H_2O & CO_2 analyzer (LI-7500, LI-Cor Inc., Lincoln, NE, USA), and a three-dimensional sonic anemometer (R3-50, Gill Instruments, UK). There were four soil heat flux plates (HFP01SC; Hukseflux, Netherlands) installed at a depth of 50 mm below the ground surface, soil heat flux (*G*) was calculated by averaging the four directions of heat fluxes data from sensors. Measurements were made continuously from 15 April (day of year [DOY] 105) to 13 October (DOY 285) in 2014 and 2015. The dominant wind direction during the study period was north-east. The 80% of contributing source area was from 150 m (stable stratification) to 250 m (unstable stratification), and the dominant direction was north-east, indicating the measured fluxes were primarily contributed by the vineyard (Fig. 1b). All data were recorded at a frequency of 10 Hz using a data logger (CR1000, Campbell Scientific, Logan, UT, USA), and the average value of 30 min was computed, daily averages were calculated during post-processing. Linear interpolation method was used to complete daily ET values when the data gaps were less than 2 h in a day. Any day that did not have necessary measurements to complete a diurnal cycle were discarded in this study. In addition, observations during the rainfall events were not used as the eddy covariance measurements were less reliable during precipitation events (Zhao et al., 2015; Yang et al., 2016).

The energy-balance closure method, which is based on conservation of energy, was used to evaluate the quality of eddy covariance data. Fig. 2 shows strong and statistically significant fits for the energy-balance closure (slopes = 0.91 and 0.87 with R^2 = 0.82 and 0.87 in 2014 and 2015, respectively), which was comparable to that in previous studies conducted in vineyards under similar circumstances (Ferreira et al., 2012). Generally, between 10% and 30% of the energy was missing from the energy balance as being common in previous research (Oncley et al., 2007; Foken, 2008; Allen et al., 2011). The results suggest that the energy-balance closure in present study was reasonable. Meanwhile, to overcome the issue of energy imbalance, the Bowen ratio method was applied to correct the measured *ET*, and the results could be seen in Supplement.

Sap-flow measurements were made from 1 May (DOY 121) to 13 October (DOY 285) in 2014, and between 21 June (DOY 172) and 13 October (DOY 285) in 2015.Six grapevines that covered the whole range of diameters were selected each year, with their diameters at breast height ranging from 2.01 to 4.14 cm. Sap flow (*F*, g h^{-1}) was measured using a Flow 32A-1 K system (Dynamax, Austin, TX, USA) according to the heat-balance method (Sakuratani, 1981). The probes were mounted more than 40 cm above the ground on the grapevine's trunk to avoid damage from the irrigation water, and were wrapped in aluminum foil to minimize the effects of solar heating (Fig. 1d). Details of the installation and the theory behind the measurements were provided by Trambouze and Voltz (2001).

2.3. Other variables

Weather variables were measured at the study site using an automatic weather station. The global solar radiation was observed at a height of 3 m above the soil surface (NR01; Hukse Flux, Delft, the Netherlands). Both *RH* and air temperature (HMP60, Vaisala, Helsinki, Finland) were monitored at heights of 3.0, 2.5, 2.0, 1.5, and 1.0 m above the soil surface. The CR1000 data logger was used to store and