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Assessing crop coefficients for *Zea mays* in the semi-arid Hailiutu River catchment, northwest China

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ABSTRACT

To improve irrigation water-use efficiency, plant transpiration and soil evaporation in a maize (*Zea mays* L.) field in the Bulang sub-catchment of the Hailiutu River catchment in Northwest China were determined using in situ measurements. Crop transpiration (T_p) rates from Jul 15 to Oct 1, 2011 were measured with sap flow sensors, and soil evaporation (E_p) rates were measured with micro-lysimeters under an absence of water deficit. The two rates together gave the total evapotranspiration (ET_c) of the maize field. Cumulative T_p and E_p were 245 and 85 mm, accounting for 74 and 26% of total ET_c (330 mm), respectively. To calculate the total ET_c rate of the maize field for the entire growing season, the Penman–Monteith equation combined with a single crop coefficient method (FAO-56) was used. The estimated crop coefficient (K_c) was calibrated using actual sap flow and soil evaporation data to provide accurate estimates of actual evapotranspiration. The total crop ET_c of the maize field for the 2011 and 2012 growing seasons was 583 and 500 mm, respectively, with a mean daily value of ~4 mm d^{-1}. Groundwater contributed 33% of the maize ET_c in 2011 (average groundwater table of 1.12 m with full irrigation) and 27% in 2012 (average groundwater table of 0.89 m with full irrigation). These results will improve precise planning and efficient management of irrigation for maize in this region.

1. Introduction

In Northwest China, and particularly the Hailiutu River catchment, natural water resources are limited and irrigation is a necessary agricultural practice. Therefore, accurate estimates of crop evapotranspiration (ET_c) are critical in order to assume informed decisions regarding water management.

Two approaches can be used to estimate ET_c by means of ET-based models or sensor-based measurements. The first combines a reference crop evapotranspiration (ET_0), which incorporates the effects of various weather conditions, with a crop coefficient (K_c) that represents the entire potential evapotranspiration (ET_p). The impact of crop water stress is usually taken into account by using a specific "stress function" allowing to determine the stress coefficients, K_s, aimed to reduce potential (or maximum) crop evapotranspiration, ET_p, ($ET_p = K_c\, ET_0$), in actual evapotranspiration, ET_a, ($ET_a = K_s\, ET_p$), depending on the actual soil water content in the root zone. Following a macroscopic approach, several models have been proposed for the stress function (Feddes et al., 1978; Homaee et al., 2002; Li et al., 2006), as recently summarized by Rallo and Provenzano (2012). However, the applicability of the above method requires more extensive validation in arid and semi-arid regions, such as in the Hailiutu River catchment.

The second approach is the direct measurement of ET_c using, for example, soil water budget or eddy covariance at daily to annual time scales (Wilson et al., 2001). Some measurement methods impact the natural environment, such as weighing lysimeters, which disturb the soil, or field chambers, which deduce ET_c using air humidity but also modify the microclimate (Kang et al., 2003; Chabot et al., 2005). Chemical and isotopic tracers (Robertson and

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Gazis, 2006; Wenninger et al., 2010) have also been used to monitor canopy transpiration, although the data can be difficult to interpret, and these tracers do not permit sequential measurement. The Bowen ratio method, the eddy correlation technique (Stockle and Jara, 1998; Droogers, 2000; Cammalleri et al., 2013), the scintillometric technique (De Bruin, 2002; Cammalleri et al., 2010), and the aerodynamic combined method (Perrier and Tuzet, 1991) do not modify the natural environment and permit good temporal resolution. However, these methods are complex, require expensive equipment, and are affected by the uncertainty of partitioning between crop transpiration (T_p) and soil evaporation (E_p). Moreover, for sparse vegetation, partitioning the measured fluxes into T_p and E_p remains a challenge, given that irrigation depends only on the former (Cammalleri et al., 2013). Sap flow measurements have been used for several years to determine canopy transpiration (Swanson, 1994; Liu et al., 2008). These methods have several advantages, including the direct measurement of sap flux, relative ease of use, continuous monitoring over time, and minimal environmental impacts. Several sap flow measurement methods have been developed (Smith and Allen, 1996; Chabot et al., 2005). The energy balance method is one of the most established tools to directly measure transpiration, plant water stress, and water use by plants (Green et al., 2006; Kigalu, 2007). These methods are still under development, but they already show potential for continuous measurements of crop water consumption with relatively inexpensive equipment. In addition, micro-lysimeters can be used successfully to monitor soil evaporation in rain fed fields (Flumignan et al., 2011).

This paper describes an experimental study in an irrigated maize field located in the Hailiutu River catchment in Northwest China. Because the evapotranspiration for the irrigated maize (ET_p) was determined as the sum of potential transpiration (T_p) and potential evaporation (E_p) using sap flow sensors (Dynamax-Flow 32 system) and micro-lysimeters, respectively, the actual K_c measurements can be compared with the constructed K_c curves through the FAO single coefficient method, where actual K_c was calculated by dividing the measured ET_p by ET_0 following the FAO Penman Monteith equation. Through this comparison, the final K_c can be determined. The objectives of this study were: (1) to evaluate the crop coefficients K_c during the middle and final phenological stages for maize (*Z. mays* L.) in a semi-arid area of China; (2) to evaluate the errors in estimated ET_c when using the average K_c values for both phases of the phenological cycle; (3) to determine the total crop water use and the groundwater contribution to ET_c in the Hailiutu River catchment.

2. Material and methods

2.1. Experimental site

The experiment was carried out in the Bulang sub-catchment of the Hailiutu River catchment, Shaanxi Province, Northwest China (38°23′33.87″N, 109°11′58.27″E, 1282 m a.s.l; Fig. 1). The climate is semi-arid with a long-term average annual precipitation of 340 mm y^{-1} and an average annual potential evaporation (pan evaporation) of 2184 mm y^{-1} (Wushenqi meteorological station, 1985–2004). Farmers in this area mainly practice subsistence agriculture, with irrigated maize as the primary crop. River water and groundwater are used for irrigation in the valley, but in the uplands, groundwater is the only option. The soil is classified as sand according to the United States Department of Agriculture classification, with average clay, silt, and sand contents of 0.2, 6.8, and 93.0%, respectively. The soil water contents at field capacity (SWC_{fc}) and wilting point (SWC_{wp}) were 0.30 and 0.05 $m^3 m^{-3}$, respectively, determined from the average water retention curve along the soil profile.

Every 10 min from Apr 30 to Oct 1 in 2011 and from Jun 3 to Sep 27 in 2012, the water table was measured using a Mini-Diver gauge (DI502, Eijkelkamp, Giesbeek, The Netherlands), and a Baro-Diver (DI500, Eijkelkamp) was used to measure the air pressure in a groundwater observation well located at the experimental site. The groundwater level range in inter-dune lowlands during the measuring periods was 93.1–130.9 cm in 2011 and 55.6–116.6 cm in 2012.

2.2. Experimental layout and irrigation management

The pilot experiment covered ~1.6 ha (145 × 110 m) cropped with maize. The field was equipped with surface irrigation systems. The experimental plot (1.8 × 9 m) was equipped with six sap flow sensors and had four rows of maize planted at 0.43 m spacing and an average density of 96 seeds, equivalent to ~60,000 plant/ha (Fig. 2). Because precipitation in the growing period was ~214 mm in 2011, much less than the total maize water requirement of ~583 mm, additional irrigation was required. The field was irrigated with groundwater from a pumping well using a pipe system (Rain Bird, Azusa, USA). Irrigation volumes were measured using a stainless-steel triangle weir (RBC Flume, Eijkelkamp) with a flow range of 0.1–8.7 L s^{-1} (with a metrical accuracy of ±0.05%). The total irrigation water depth was 177 mm over six irrigation events in 2011 and 60 mm over two irrigation events plus 411 mm of precipitation in the growing period of 2012. Irrigation events followed local management practices for the study area. In 2011, the irrigation water depths were 29.27, 29.37, 27.86, 29.9, 31.32, and 29.34 mm on May 25, Jun 21, Jun 30, Jul 15, Jul 26, and Aug 7, respectively. Both irrigations in 2012, on Jun 29 and Jul 13, were 30 mm in depth.

2.3. Crop measurements

The main stem diameter 25–30 cm above the ground surface and new shoot length were measured every month on nine plants in the experimental plot. Plant height and leaf area index (*LAI*) were monitored 2–3 times a week throughout the growing season (Fig. 3). Plant height was measured by a tapeline from the soil surface to the plant apex (before heading) or to the crest of the spike (excluding awn, after heading). Leaf area (*LA*) was determined using leaf length (*L*), maximum width (*W*), and the formula $LA = 0.7634 \times L \times W$ (Liu et al., 2011). *LAI* was calculated as:

$$LAI = \frac{LA_{9\text{samles}}}{9} \gamma_{\text{crop}} \quad (1)$$

where $LA_{9\text{ samples}}$ is the total leaf area of the nine plant samples (m^2) and γ_{crop} is the plant density per unit area (m^{-2}).

In the experimental field, the average maize yields were 10,527 and 13,703 kg ha^{-1}, and at harvest, plants were 262 cm tall in 2011 and 293 cm tall in 2012. These yields and heights were similar to the data reported by Du (2011) for maize in Yuyang District, Yulin City, Shaanxi Province, China.

2.4. Sap flow and soil evaporation

ET_c under an absence of water deficit generally consists of T_p and E_p. In this study, T_p was measured using sap flow sensors and E_p with micro-lysimeters. Stem flow gauges (Flow32; Dynamax, Houston, TX, USA) were used with the energy balance method to measure sap flow (*SF*) in the maize stems. When the plants were ~180 cm high with a stem diameter of ~25 mm (76 days after sowing), six plants were selected for *SF* measurements (Fig. 2). Flow32 sensors (110 mm long, 24–32 mm diameter) were installed on their stems at a height of 25–30 cm above the ground on Jul 15, 2011, when the plants were fully developed.