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Evapotranspiration partitioning and variation of sap flow in female and male parents of maize for hybrid seed production in arid region

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ABSTRACT

Understanding the variation of sap flow in female and male parents of maize for hybrid seed production and evapotranspiration (*ET*) partitioning is useful in accurately determining water use of the female and male parents and improving irrigation management of maize for hybrid seed production. Sap flow rate, *ET*, soil evaporation (*E*), meteorological variable, soil water content (*SWC*) and morphological parameters in female and male parents were measured during April to September in both 2013 and 2014 in the arid region of northwest China. Sap flow rates in female and male parents and *E* were respectively monitored using heat-balance technique and micro-lysimeter. We found that the variations of sap flow rates in female and male parents were similar during the vegetative growth stage, but the female parents had higher sap flow rate per plant than the male parents after the detasseling, with the maximum difference of daily sap flow rate per plant of 0.28-0.33 L d^{-1}. Hourly sap flow rates in female and male parents were highly correlated with net radiation, while daily sap flow rates in female and male parents were highly correlated with net radiation, *SWC*, leaf area index, but not correlated with crop height. Daily *E* increased exponentially with *SWC*. Moreover, daily sap flow rates in the male parents were positively correlated with stem diameter. The total *ET* was 363.31-384.15 mm over the whole growth stage of maize, and the transpiration (*T*) of female parents per ground area accounted for 63–80% of the total *ET*, while the *T* of male parents per ground area accounted for 4–14% of the total *ET*, primarily due to different planting quantities between the female and male parents. And the soil evaporation was 47.77-62.21 mm over the whole growth stage, accounting for 13–16% of the total *ET*. Our results can provide scientific basis for accurate determination of water use of female and male plants and developing precise irrigation scheduling of maize for hybrid seed production in the arid region.

1. Introduction

Evapotranspiration (*ET*) is an important process in the terrestrial hydrological cycle and plays the key role in energy and water balance of agricultural system. *ET* is the total amount of soil evaporation (*E*) and plant transpiration (*T*). Transpiration is strongly linked to crop productivity since it occurs simultaneously with photosynthesis through the stomata (Pieruschka et al., 2010), while soil evaporation is not a contributing factor to crop productivity, and should be reduced by field management practice to conserve agricultural water (Allen, 2000). Therefore accurate partitioning between *E* and *T* is very useful in developing precise irrigation scheduling and improving crop productivity and water use efficiency.

The lysimeters (Ding et al., 2013), Bowen ratio energy balance system (Bethenod et al., 2000), and eddy covariance method (Li et al., 2014; Jiang et al., 2014) are often used to measure total *ET* of maize, but cannot distinguish between *E* and *T*. However, sap flow and micro-lysimeter method can directly measure *T* and *E*, respectively. Sap flow, based on heat balance principles in this study, can indicate the instantaneous transpiration of plants (Sakuratan, 1981; Baker and Van Bavel, 1987). In general, sap flow is assumed to be equal to plant transpiration since sap flow in the xylem is closely related to water loss from transpiration (about 99% of water uptake is lost by transpiration) (Gerdes et al., 1994). Many studies have concluded that heat balance technique is a useful tool to mea-

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Table 1
Irrigation scheduling, reference evapotranspiration (ET_0, mm d^{-1}), and total precipitation (P, mm) at different growing stages in 2013 and 2014.

Year	Growing stage	Period	Irrigation time	Irrigation amount (mm)	ET_0 (mm d^{-1})	P (mm)
2013	Seedling	Apr. 20–Jun. 8	Jun. 6	100	206.5	14.2
	Shooting	Jun. 9–Jul. 9	Jun. 26	100	109.0	16.6
	Heading	Jul. 10–Jul. 27	Jul. 11	100	59.2	4.0
	Filling	Jul. 28–Aug. 28	Jul. 30, Aug. 18	180	111.0	26.8
	Maturity	Aug. 29–Sept. 12	–	–	41.0	6.8
	Whole	Apr. 20–Sept. 12		480	527.0	68.4
2014	Seedling	Apr. 25–Jun. 10	Jun. 9	100	188.8	25.8
	Shooting	Jun. 11–Jul. 9	July. 1	100	109.3	44.0
	Heading	Jul. 10–Aug. 2	July. 20	100	105.8	30.4
	Filling	Aug. 3–Sept. 4	Aug. 23	80	108.1	94.6
	Maturity	Sept. 5–Sept. 20	–	–	37.7	11.4
	Whole	Apr. 25–Sept. 20		380	549.7	206.2

sure crop transpiration (Bethenod et al., 2000; Dragoni et al., 2006; Zhang et al., 2011). And the heat balance technique has been used to measure the sap flow of maize at an instantaneous interval (Aiken and Klocke, 2012; Hou et al., 2014).

Previous studies showed that the factors controlling sap flow and soil evaporation were different (Yunusa et al., 2004). Sap flow rate is closely related to meteorological variables, soil water content (*SWC*) and crop parameters (Zhang and Gong, 2004; Qu et al., 2007; Si et al., 2007; Xu et al., 2011; Zhang et al., 2011; Liu et al., 2012). Net radiation (R_n), vapor pressure deficit (*VPD*) and air temperature (T_a) were the main factors controlling the sap flow in plants (Zhang and Gong, 2004; Qu et al., 2007; Si et al., 2007; Xu et al., 2011). Reference evapotranspiration (ET_0) is a comprehensive index of meteorological variables. Xu et al. (2011) indicated that daily sap flow rate in irrigated *Populus* is well correlated with the daily ET_0 over the growing season. Liu et al. (2012) noted that daily sap flow rates in apple tree had linear relationship with ET_0 at the rapid leaf and trunk growing and rapid fruit enlarging and maturing stages. Sap flow rate is also significantly correlated with *SWC* (Yin et al., 2003; Zhang et al., 2011; Liu et al., 2012; Chen et al., 2014), since higher *SWC* may stimulate the production of cytokinin that inhibits stomatal closure (Incoll and Jewer, 1987), and increased abscisic acid in the roots causes stomata to close as soil dries (Davies and Zhang, 1991). Moreover, sap flow rate over the whole growing period is also closely related to leaf area index (Cohen and Li, 1996; Zhang et al., 2011; Liu et al., 2012). Soil evaporation depends linearly on water gradients and energy availability. Zhang et al. (2011) noted the soil evaporation depended on *SWC* more than on R_n and *VPD*, and the relationship of the soil evaporation and *SWC* in a vineyard of northwest China was exponential.

Shortage of water resources in northwest China will not only result in serious environmental degradations, e.g. falling of groundwater table, shrinking of vegetation areas and soil desertification, but also restrict regional social and economy development (Kang et al., 2004). Because of abundant solar radiation and heat resources in this region, planting areas of maize for hybrid seed production have rapidly increased in recent years (Jiang et al., 2014), and maize for hybrid seed production has become the main irrigation crop. This crop, including the female and male parents, is obtained by the outcrossing of the pollens of male parent to the stigmas of female parent. However, the parent lines of maize for hybrid seed production are different from hybrid maize since the female and male parents are inbred lines without heterosis and short. With the problem of water shortages, the variation of evapotranspiration (*ET*) components and its partitioning, especially transpiration among parent lines used for producing maize seed, as well as the factors controlling plant water use of these lineages across the season are not clear and need to be investigated. Thus the objectives of this study were to: (1) investigate the variation of sap flow in female and male parents at hourly and daily scales and the differences; (2) understand the relationships among hourly or daily sap flow rate in female and male parents and environmental factors and crop parameters; and (3) determine the ratio of soil evaporation and transpiration of female and male parents to total *ET*, so as to accurately determine water use of the female and male parents and provide scientific basis for developing precise irrigation scheduling of maize for hybrid seed production in the arid region of northwest China.

2. Materials and methods

2.1. Experimental site and plants

The field experiments have been conducted at Shiyanghe Experimental Station for Water-saving in Agriculture and Ecology of China Agricultural University during April to September in both 2013 and 2014. The station is located in Wuwei city, Gansu province of northwest China (latitude 37°52′N, longitude 102°50′E, altitude 1581 m). The experimental site is in a typical continental temperate climate zone with a mean annual sunshine duration of over 3000 h, mean annual temperature of 8.8 °C and frost-free days of 150 days (Jiang et al., 2014). However, the site is limited in water resources with a mean annual precipitation of 164.4 mm (mostly during June to September) and mean annual pan evaporation of 2000 mm. The average depth to water table is below 25 m (Jiang et al., 2014). The experimental soil texture is light sandy loam, with a mean soil dry bulk density of 1.38 g cm^{-3}, mean volumetric water content at field capacity (θ_{FC}) of 0.29 cm^3 cm^{-3} and mean volumetric water content at wilting point (θ_{WP}) of 0.12 cm^3 cm^{-3} (Jiang et al., 2014).

The experimental plot covered 8 ha (400 m × 200 m) planted with maize for hybrid seed production (*Zea mays* L.). To ensure the emergence of maize (the temperature is low in April), 0.015 mm thick plastic films were mulched before the sowing with the width of 1.2 m and the bare soil of 0.4 m between two plastic films. The planting densities at the site were 97,500 plants ha^{-1} with row spacing of 40 cm and planting spacing of 25 cm. The male parent of parental lineage used for pollination was sown in every sixth row. Female parent of the parental lineage used to produce the hybrid seed were sowed on April 13 and April 16 in 2013 and 2014, respectively. Two batches of male parents were planted on April 20 and 27 in 2013, on April 23 and 30 in 2014. Detasseling plants were performed by cutting the tassels along with 1–3 top leaves on July 6 and July 4 in 2013 and 2014, respectively. The five stages in each growing season were divided and shown in Table 1. Precipitation in the growing period was 68.4 mm in 2013 and 206.2 mm in 2014, much less than total water requirement of maize for hybrid seed production, so supplemental irrigation was required. Irrigation amount and time in each stage followed local management practice, and the irrigation method is border irrigation. Irrigation