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REGULAR PAPER

Extensive investigation of the sap flow of maize plants in an oasis farmland in the middle reach of the Heihe River, Northwest China

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Abstract A better understanding of the sap flow characteristics of maize plants is critical for improving irrigation water-use efficiency, especially for regions facing water resource shortages. In this study, sap flow rates, related soil-physics and plant-growth parameters, and meteorological factors, were simultaneously monitored in a maize field in two consecutive years, 2011 and 2012, and the sap flow rates of the maize plants were extensively analyzed based on the monitored data. Seasonal and daily variational characteristics were identified at different growth stages and under different weather conditions, respectively. The analyses on the relationships between sap flow rate and reference evapotranspiration (ET_0), as well as several plant-growth parameters, indicate that the irrigation schedule can exert an influence on sap flow, and can consequently affect crop yield. The ranking of the main meteorological factors affecting the sap flow rate was: net radiation > air temperature > vapor pressure deficit > wind speed. For a quick estimation of sap flow rates, an empirical formula based on the two top influencing factors was put forward and verified to be reliable. The sap flow rate appeared to show little response to irrigation when the water content was relatively high, implying that some of the irrigation in recent years may have been wasted. These results may help to reveal the bio-physical processes of maize plants related to plant transpiration, which could be beneficial for establishing an efficient irrigation management system in this region and also for providing a reference for other maize-planting regions.

Keywords Maize · Sap flow · Irrigation water · Crop yield · Meteorology

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Introduction

Plant transpiration is the major contributor to the water-balance shift from continent to atmosphere (Brutsaert 2005; Gat 2000). For agricultural crops, plant transpiration is closely correlated with crop yield (Shang and Mao 2006), and understanding this relationship is critical to the establishment of an efficient irrigation management system in water-deficient regions (Zhao and Zhao 2014). Thus, sap flow measurement through intact plant stems has become a routine component of investigations of vegetation water use, i.e., plant transpiration, particularly since commercial instrumentation systems became available in the 1990s (Grime and Sinclair 1999).

Sap flow is closely related with meteorological factors such as net radiation and air temperature (Dragoni et al. 2009; Liu et al. 2011), and with physiological parameters such as plant growth stages (Liu et al. 2012; Yamasaki 2003) and soil water content, which is dependent on irrigation and precipitation (Chen et al. 2014; Gavloski et al. 1992). Different relationships between sap flow and these influencing factors have been found for different plant species. For instance, Xia et al. (2008) found that vapor pressure deficit was the most important meteorological factor affecting the sap flow rate of *Caragana korshinskii*, whereas Huang et al. (2010) found that solar radiation was more important than vapor pressure deficit for *Artemisia*

Table 1 Climate conditions in the study area

Mean annual air temperature (°C)	Max. air temperature (°C)	Min. air temperature (°C)	Annual precipitation (mm)	Rainy season	Mean wind speed (m s^{-1})	Humidity range (%)	Mean daily net radiation (W m^{-2})
7.5	39.1	–27.3	116.8	Jul.–Sep.	3.2	7.3–80.9	<200

ordosica. The sap flow of cotton plants can change through different growth stages due to the rapid changes in leaf area and stem diameters (Zhang et al. 2014). Chen et al. (2014) found that the responses of sap flow to meteorological factors clearly differed under different soil moisture conditions, for jujubes. Zhao and Liu (2010) indicated that a large number of small rainfall events could have a large impact on the sap flow of plants in desert regions, such as *N. sphaerocarpa* and *E. angustifolia*. Different variational characteristics have also been detected for different plant species, such as grapevines (Braun and Schmid 1999), olives (Cammalleri et al. 2013), pines (Čermák et al. 1995), spruce (Clausnitzer et al. 2011), sugarcane (Chabot et al. 2002), apple trees (Gong et al. 2007), etc.

As for maize plants, their sap flow characteristics have been analyzed at several different time scales (Guo et al. 2014; Hou et al. 2014; Nie et al. 2009), and different results have been found in different regions. Generally, the daily maximum sap flow value usually shows up from 13:00 to 14:00, and the annual maximum value usually appears around July. The responses of sap flow to major meteorological factors have also been investigated for maize plants (Guo et al. 2014; Liu and Liu 2006), and the results have consistently shown that solar radiation was the main influencing factor. This may explain why sap flow rates on sunny days are usually higher than those on rainy, cloudy or windy days (Tang et al. 2011). The influences of some plant-related parameters on sap flow, such as plant density (Feng et al. 2014) and stem diameter (Li et al. 2011; Zhao et al. 2010), have also been analyzed. In addition, sap flow has been measured or simulated for crops with maize plants interspersed among them (Cohen et al. 1990; Gao et al. 2010; Ozier-Lafontaine et al. 1998). Although some previous work has been conducted on the sap flow of maize plants in different regions, an extensive investigation on the sap flow of maize plants for one specific region is currently lacking.

Maize (*Zea mays L.*) is the main crop in the middle reach of the Heihe River (the second largest inland river in China). With a maize seed planting area of about 670 km^2, this region produces more than 40 % of the maize seed in China (Yang and Chen 2014). In recent years, many serious issues have arisen because of over-exploitation of water resources to sustain the agricultural irrigation system (Ding and Zhang 2002): issues such as vegetation degradation, deterioration of water quality, soil salinization, desertification and so on (Ji et al. 2006; Ren 2005). Water shortage has already become the main restriction for sustainable economic development in this region (Cheng 2002). Thus, extensive investigation of the water requirements of maize plants, i.e., sap flow rates, could help improve irrigation water-use efficiency and consequently alleviate the water crisis for this region.

In this study, the sap flow of maize plants was extensively investigated from the following aspects: (1) daily and seasonal variational characteristics; (2) relationships between sap flow and both ET_0, stem diameter and LAI; and (3) responses of sap flow to meteorological factors and irrigation.

Materials and methods

Study area

The experiments were carried out in a maize-seed planting field in the middle reach of the Heihe River, which is located in the area of Zhangye city, Gansu province. The latitude and longitude are 39°21′N and 100°07′E respectively; the exact geographic position was shown in a previous paper (Zhao and Zhao 2014). The major climatic information from 1965 to 2000 is summarized in Table 1 (Ji et al. 2007; Liu et al. 2011; Zhao and Zhao 2014). Since the annual rainfall is very limited, large amounts of underground water are often consumed by irrigation. The underground water level is about 6 m. The annual potential evaporation ranges from 1900 to 2088 mm. No crops grow in winter because of the very low air temperature.

Monitoring program

Sap flow

Six maize plants were chosen for repeat measurements of the three representative sap flow rates from three typical stem diameters of about 16, 19 and 25 mm; their approximate positions are shown in Fig. 1a. The area of the maize field was 51.6 × 51.6 m^2 and included a meteorological station (Fig. 1b). The sap flow monitoring system

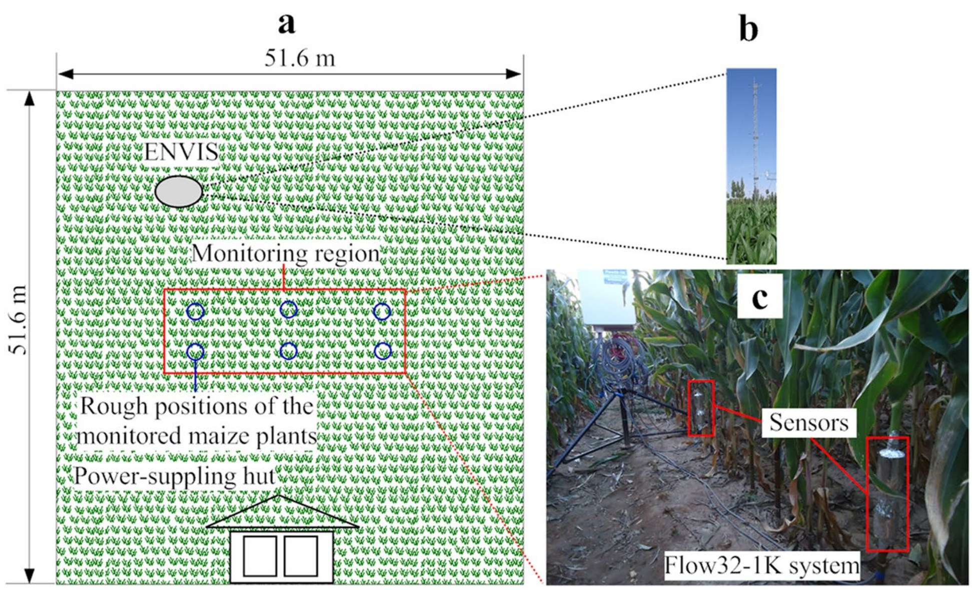

Fig. 1 Layout of **a** the monitored maize field, **b** the environmental information system (ENVIS), and **c** the sap flow monitoring system (after (Zhao and Zhao 2014). The *photos* were taken by the first author in 2012)

Table 2 Lengths of the major and minor axes for the stem cross sections

Year	Major axis (cm)	Minor axis (cm)
2011	1.83	1.61
	1.96	1.67
	1.94	1.65
	2.04	1.76
	2.07	1.86
	2.12	1.73
2012	1.93	1.64
	1.94	1.64
	2.15	1.89
	2.13	1.88
	2.95	2.56
	2.55	2.13

(Fig. 1c) contained six sap flow sensors, as well as a Flow 32-1 K system including a CR 1000 data logger (data collection and storage), a multiplexer (data selector), and an AVRD (powering the sensors with variable voltage). The heat balance method was employed to measure the sap flow by heating a small section of the stem and determining the amount of heat transported away from the heater by xylem water movement (Dynamax 2005; Grime and Sinclair 1999; Ishida et al. 1991). The monitoring instrument was developed by Dynamax Inc. in USA; more detailed information can be found in the technical manuals (Dynamax 2005, 2007). Stem cross section area is required when using this system. The stem cross sections in these samples were more elliptical than circular, a configuration that can introduce minor but acceptable errors; the lengths of the major and minor axes are presented in Table 2. The maize plant is a type of herbaceous plant. No cambium forms under the epidermis, and the epidermis thickness can be negligible in comparison to that of the xylem. The growth stage from tasseling to maturity (July 11-September 20, 2011) was taken as the monitoring period, for two reasons: (1) more than 60 % of the total irrigation water is consumed during this period (Zhao and Zhao 2014); and (2) the sap flow sensors would cause only negligible damage to the maize plants, thus allowing continuous and reliable data to be obtained, since the stems of the maize plants grow slowly during this period. A photograph of the maize plants mounted with sap flow sensors is shown in Fig. 1c.

Meteorological factors

The related meteorological factors were monitored using an environmental information system, usually abbreviated as ENVIS (Fig. 1b). Net radiation, air temperature, and wind speed/direction were observed 2 m above the canopy, while precipitation was recorded at the very top of the canopy. ET_0 was calculated based on the related meteorological data using the FAO Penman–Monteith model (Allen et al. 1998). Kendall's tau coefficient, commonly referred to as the Kendall rank correlation coefficient, was employed to obtain the ranking of the main meteorological factors affecting the sap flow rate. More explanation about this method can be found in a previous research (Abdi 2007).

Soil physical parameters

Volumetric soil water content was monitored at six different depths in the soil layers: 10, 20, 50, 100, 200 and 300 cm. The main soil characteristics of the soil profiles

Table 3 Main soil characteristics of the soil profiles (Zhao and Zhao 2014)

Soil depth (cm)	Saturated water conductivity (mm min^{-1})	Dry density (g cm^{-3})	Saturated water content (vol. %)	Field capacity (vol. %)	Wilting point (vol. %)
0–10	0.12	1.61	37.9	27.4	11.6
10–20	0.2	1.61	41.8	28.6	10.4
20–30	0.14	1.61	38.9	27.5	12
30–40	0.14	1.61	39.1	28.1	11.5
40–60	0.26	1.56	42.7	27.7	9.9
60–100	0.53	1.59	41.5	24.4	8.6
100–120	0.33	1.58	40.5	28.5	12.4

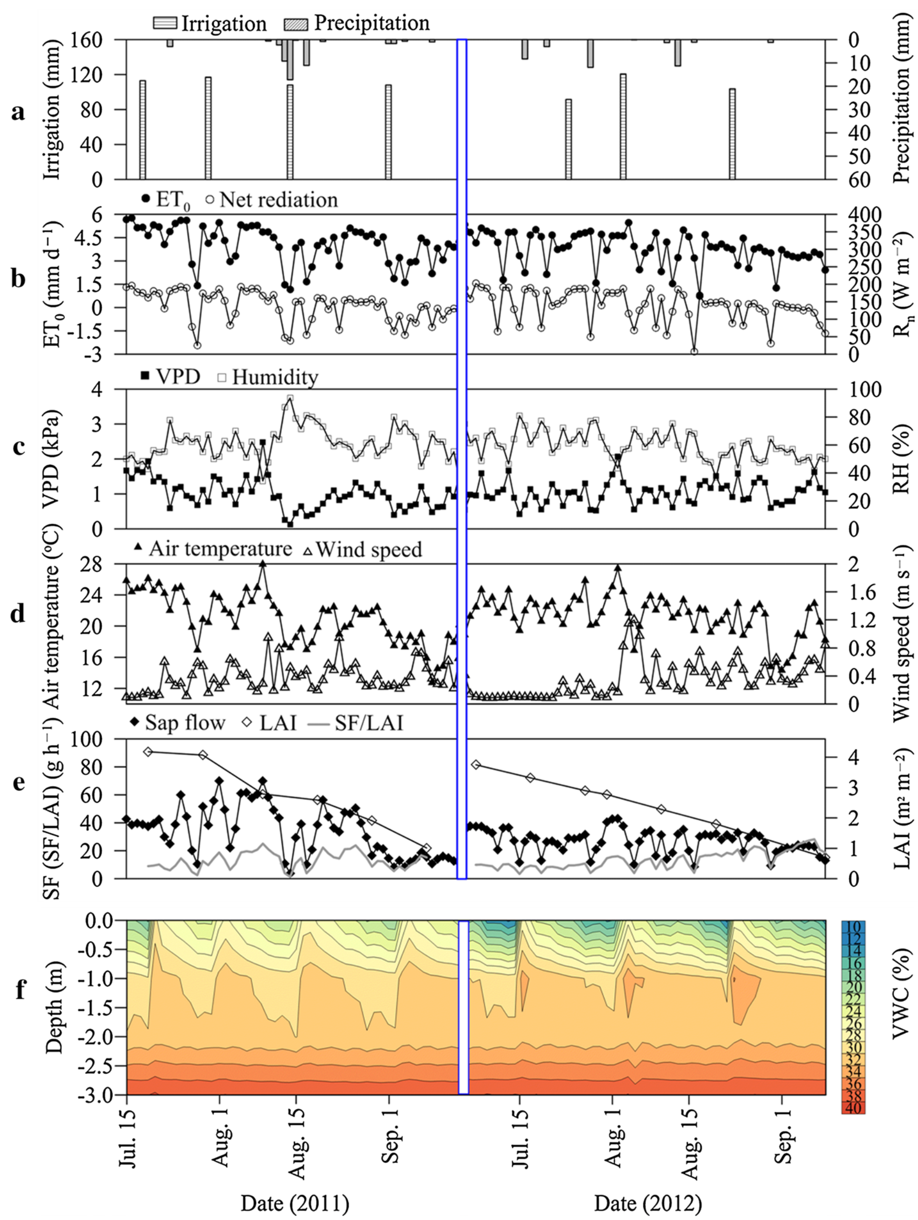

Fig. 2 Monitored data of **a** irrigation and precipitation, **b** ET_0 and net radiation (R_n), **c** vapor pressure deficit (VPD) and relative humidity (RH), **d** air temperature and wind speed, **e** daily average values of sap flow (SF), leaf area index (LAI) and LAI-standardized sap flow rates, and **f** volumetric water content in the 3-m-deep soil layers

Table 4 Average heights of the maize plants in 2011 and 2012

Date	Plant height (m)	
	In 2011	In 2012
Jun. 19	1.36	1.21
Jun. 29	1.68	1.67
Jul. 9	1.93	1.88
Jul. 19	1.83	1.87
Jul. 29	1.93	1.87
Aug. 9	1.79	1.85
Aug. 19	1.84	1.83
Aug. 29	1.89	1.79
Sep. 12	1.67	1.70

Table 5 Average sap flow rates of maize plants in different growth stages in 2011 and 2012

Year	Growth stages	Date	Mean sap flow rates (g h^{-1})
2011	Tasseling-to-filling	Jul. 10–Sep. 9	35.2
	Filling-to-maturity	Sep. 10–Sep. 16	13.8
	Monitoring period	Jul. 15–Sep. 14	33.5
2012	Tasseling-to-filling	Jul. 6–Sep. 3	27.4
	Filling-to-maturity	Sep. 4–Sep. 12	20.7
	Monitoring period	Jul. 6–Sep. 10	26.7

are summarized in Table 3, which was presented in a previous study (Zhao and Zhao 2014). The Kriging interpolation method was adopted to obtain the continuous volumetric water content in Fig. 2.

Plant-growth parameters

Leaf area indexes (LAI) were measured every ten days using either the Li-3100A and the Li-2100 canopy analyzer (LI-COR, USA). Density and height of the maize plants were measured in a 2 × 2 m^2 area with about 18 samples. The measured average heights of the maize plants are presented in Table 4. Crop yields over the 2 years were obtained by weighing after harvest.

Results and discussion

Figure 2 depicts the meteorological factors, plant-growth parameters, volumetric water content, etc. The precipitation was so limited that large amounts of irrigation water had to be consumed in order to sustain the maize plants (Fig. 2a). It can be seen that the variational pattern of ET_0 corresponded well with that of net radiation (Fig. 2b), indicating that net radiation was the dominant influencing factor for ET_0. During the monitoring period, vapor pressure deficit and relative humidity showed relatively large fluctuations around the middle of August in 2011 due to intensive rainfall (Fig. 2a, c). Air temperature ranged from 12.7 to 27.9 °C and the average value of the wind speed was about 0.36 m s^{-1} (Fig. 2d). Obvious decreasing tendencies can be seen for the leaf area indexes (LAIs), and the daily average value of the sap flow rate was about 30.0 g h^{-1}, while the LAI-standardized sap flow rates generally ranged from 0 to 20 g h^{-1} (Fig. 2e). The daily average value of sap flow in 2011 was about 33.8 g h^{-1}, with a maximum value of 69.9 g h^{-1} on August 1 and a minimum value of 3.8 g h^{-1} on August 14, while the daily average value in 2012 was about 26.8 g h^{-1}, with a maximum value of 43.0 g h^{-1} on August 3 and a minimum value of 8.4 g h^{-1} on August 17. The volumetric water content (VWC) in the top 2 m soil layers clearly varied, because of the intensive irrigation (seven applications) (Fig. 2a, f).

Seasonal and daily variations of sap flow

Seasonal variations in sap flow

Maize plants have five growth stages: seeding-to-emergence, emergence-to-jointing, jointing-to-tasseling, tasseling-to-filling and filling-to-maturity (Li et al. 2000; Zhao and Zhao 2014). The maize plants in this sample grew very fast during the first three stages, during which both the sap flow sensors and the monitored plants were fragile and could easily have been destroyed. During the last two growth stages, the maize plants grew relatively slowly. Table 5 summarizes the average values of sap flow during the growth stages in 2011 and 2012. It can be seen that sap flow rates during tasseling-to-filling were greater than those during filling-to-maturity, possibly because of the relatively large irrigation volume and plant physiological activity during the tasseling-to-filling stage. The mean annual value of the sap flow in 2011 was greater than that in 2012; this could be attributed to the larger irrigation volume in 2011 (Fig. 2a). Additionally, the differences in the varieties of the maize also contributed to the variations in the sap flow, in the different years.

Daily variation of sap flow under varying weather conditions

Different variational characteristics of sap flow were detected under different weather conditions, since meteorological factors greatly influence sap flow (Guo et al. 2014; Huang et al. 2010; Liu and Liu 2006). Therefore,

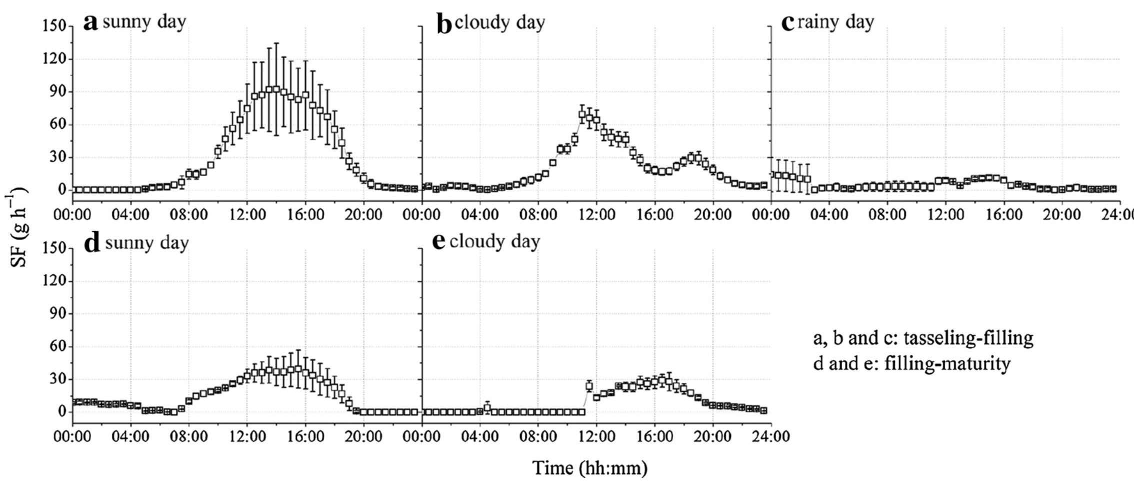

Fig. 3 Sap flow rates on selected **a** sunny, **b** cloudy and **c** rainy days during the tasseling-to-filling stage, and **d** sunny and **e** cloudy days during the filling-to-maturity stage. The *error bars* indicate the daily variational ranges from six repetitions

3 days, representing three different weather conditions (sunny, cloudy and rainy) were selected to analyze how the sap flow varied with the weather. Since growth stage also influences variational characteristics, two growth stages were selected: tasseling-to-filling and filling-to-maturity.

Figure 3 shows the sap flow rates under these different weather conditions and in the different growth stages. Only sunny and cloudy days are presented for the filling-to-maturity stage, since only very small amounts of rainfall were recorded during this stage (Fig. 2a). The daily sap flow rates during the monitored days were 57.7 g h^{-1} on August 7 (a sunny day), 20.3 g h^{-1} on July 27 (a cloudy day), and 3.7 g h^{-1} on August 14 (a rainy day) during tasseling-to-filling, while they were 14.8 g h^{-1} on September 12 (a sunny day) and 8.4 g h^{-1} on September 2 (a cloudy day) during filling-to-maturity. It can be seen that the sap flow rate was at its maximum on the sunny days, at its minimum on the rainy day, and at an intermediate value on the cloudy days. This result may indicate that net radiation was the most important meteorological factors for sap flow in maize plants (Guo et al. 2014; Tang et al. 2011). It also can be seen that the differences among sap flow rates under the different weather conditions were smaller during the filling-to-maturity stage than during the tasseling-to-filling stage, possibly because filling-to-maturity is a period when the vegetative growth of maize plants ceases, thus decreasing the sap flow rate. It is worth mentioning that an obvious diurnal-cycle variation was observed for sap flow rates on the sunny days, while on the cloudy or rainy days this cycle was not so clear. The diurnal-cycle variational characteristic of sap flow rates on sunny days was closely associated with those of the two top influencing factors, net radiation and air temperature.

As for the error bars in Fig. 3, they were caused by the varying sap flow rates of the maize plants with different stem diameters, possibly because larger stem diameters are often associated with more leaves, which, to a great extent, determine the magnitude of plant transpiration (Zhang et al. 2014). The differences were larger in the midday than at other times, on the sunny days than on the cloudy or rainy days, and during the tasseling-to-filling stage than during the filling-to-maturity stage, perhaps because high sap flow rates are closely associated with large variations.

Relationships between sap flow and ET_0, stem diameter and LAI

Sap flow vs. ET_0

The daily reference evapotranspiration rate, ET_0, is a comprehensive index reflecting weather conditions (Allen et al. 1998). Figure 4 presents the relationships between the field transpiration (T) and ET_0 during the tasseling-to-filling stages in 2011 and 2012 respectively. The field transpirations were obtained from the monitored sap flow rate (that is, individual plant transpiration) by an up-scaled equation from Zhao and Zhao (2015). Of note is that there was a significant linear relationship between field transpiration and ET_0 in 2011 ($R^2 = 0.79$), but no relationship was found in 2012 ($R^2 = 0.03$). Small variations were found in ET_0 between the 2 years (Fig. 2b); these were closely associated with the similar meteorological conditions (Fig. 2b–d). By contrast, large variations were found in the water content of the top soil layers (Fig. 2f); these were probably caused by the different irrigation amounts and times (Fig. 2a). Thus, the different T–ET_0 relationships in the 2 years (Fig. 4) may have resulted

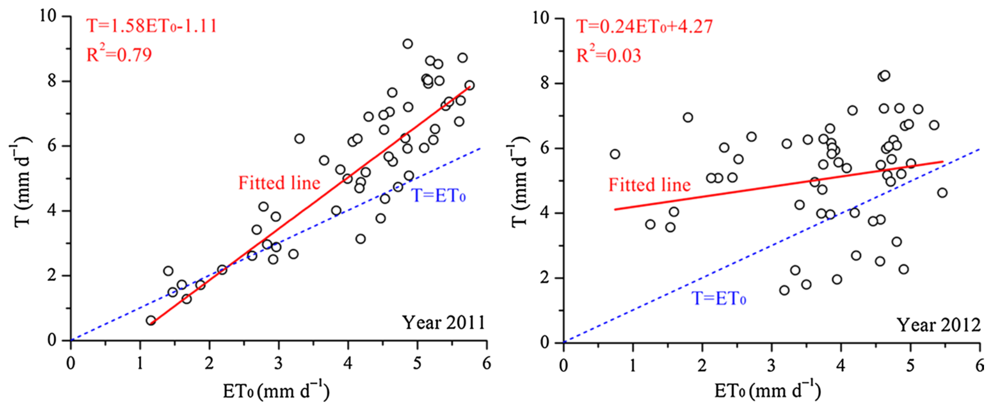

Fig. 4 Relationship between field transpiration and reference evapotranspiration during the tasseling-to-filling stages in 2011 and 2012

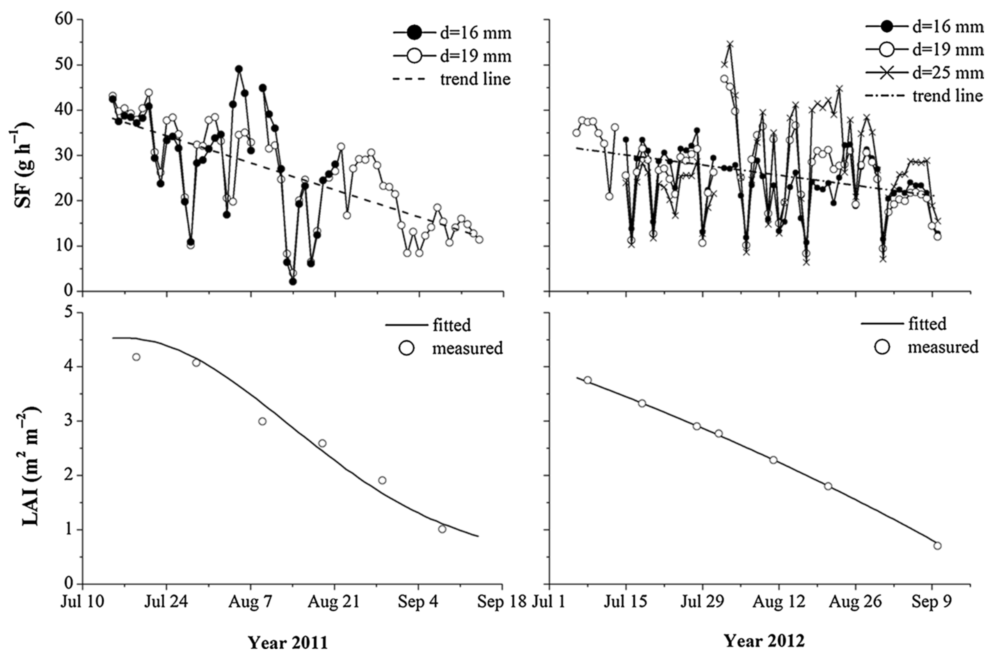

Fig. 5 Measured sap flow rates and LAIs in 2011 and 2012

from the difference in sap flow rates caused by the different irrigation schedules, since irrigation has been shown to be an important influencing factor on sap flow (Galoski et al. 1992). In addition, the different irrigation schedules may also be one of the reasons why the crop yields were higher in 2011 (847 g m^{-2}) than in 2012 (195 g m^{-2}).

Sap flow vs. stem diameter and LAI

Figure 5 shows the sap flow rates monitored at three different stem diameters: 16, 19 and 25 mm. In 2011, only two diameters (16 and 19 mm) were used for monitoring. The average values for the two groups of sap flow rates were 25.1 and 29.4 g h^{-1}. In 2012, three groups of sap flow rates were obtained, with average values of 23.6, 26.1 and 27.2 g h^{-1} respectively. It can be seen that the larger the stem diameter, the higher the sap flow rate. Again, this may be because the maize plants with larger stem diameters also had more leaves. Similar variational characteristics were also detected on a daily scale by Zhao and Zhao (2015). Different variational characteristics of sap flow rate, however, were identified in the 2 different years. From the trend lines, it can be seen that the sap flow rate in 2011 decreased with the decrease in LAI, but it remained nearly constant during the monitoring period in 2012. This may also have resulted from different irrigation schedules in the 2 years (446 mm at four times in 2011, and 316 mm at three times in 2012).

Responses of sap flow to meteorological factors and irrigation

Response of sap flow to meteorological factors

Table 6 shows the Kendall's tau correlation between sap flow rates and metrological factors in both 2011 and 2012.

Table 6 Kendall's tau correlation between sap flow rate and metrological variables in 2011 and 2012

Meteorological factors	R_n (W m^{-2})	T (°C)	VPD (kPa)	U (m s^{-1})
Correlation coefficient (R)	0.546**	0.505**	0.411**	–0.123*

R$_n$ net radiation, *T* air temperature at 2 m, *VPD* vapour pressure deficit, *U* wind speed, and the number of the samples is 129

* $P < 0.05$; ** $P < 0.01$ (two-tailed)

The results indicate that sap flow rate was positively correlated with net radiation, air temperature and vapor pressure deficit, while it was negatively correlated with wind speed. Relative humidity is not included, since it can be estimated from vapor pressure deficit and air temperature. According to the absolute values of the correlation coefficients, the ranking of the main meteorological factors affecting the sap flow rate were: net radiation, air temperature, vapor pressure deficit and wind speed.

The modified Penman–Monteith equation is widely accepted for calculating plant transpiration, but some key parameters, such as aerodynamic and stomatal conductances, are very difficult to obtain (Jarvis 1986; Langensiepen et al. 2009). Under this circumstance, an empirical formula based on the most two important meteorological factors, i.e., net radiation and air temperature, would be very convenient for calculating plant transpiration (that is, sap flow rate), especially for regions lacking sufficient meteorological data. The empirical formula for calculating sap flow rates based on the monitored data in 2011 is:

$$\mathrm{SF} = -26.707 + 0.075\mathrm{R_n} + 2.059T \qquad \left(R^2 = 0.72\right) \tag{1}$$

The units of the sap flow rate (SF), net radiation (R_n) and T (air temperature at the height of 2 m) are g h^{-1}, w m^{-2} and °C, respectively. The formula was obtained based on data taken at half-hour intervals. Since the formula is linear, daily average values of sap flow rates can also be obtained by using the daily average values of net radiation and air temperature. This formula was verified with the monitored data in 2012, and with those from a previous research (Yan et al. 2011). The relationships between the measured and simulated sap flow rates are shown in Fig. 6. The high coefficients of determination of about 0.9 indicate that the equation can be employed for a quick estimation of the sap flow rate of maize plants based on limited meteorological data.

Response of sap flow to irrigation/volumetric water content

Since irrigation was the main water source for maize plant growth in this study area, it is of particular importance to investigate the response of sap flow to irrigation (Chen et al. 2014; Gavloski et al. 1992). Two sets of seven continuous sunny days with one round of irrigation were selected (three days before and after irrigation), as shown in Fig. 7. The irrigation volumes were 113 mm on 19 July 2011 and 121 mm on 4 August 2012. During the period from 15 to 21 July 2011, a large increase can be seen in volumetric water content caused by irrigation. The volumetric water content at the depth of 10 cm increased from 20 to 30 %, and there were but small changes in the other environmental factors during these days. However, a small increase was found in the sap flow rate after irrigation. During the period from 1 to 7 August 2012, sap flow decreased even though soil water increased from 15 to 25 % at the depth of 10 cm. This result may indicate that the decrease in sap flow was caused by decreases in net radiation and air temperature. It seems that when the current volumetric water content was relatively high, the influences of meteorological factors on sap flow were greater than those from irrigation. However, previous researches concerning the rainfed

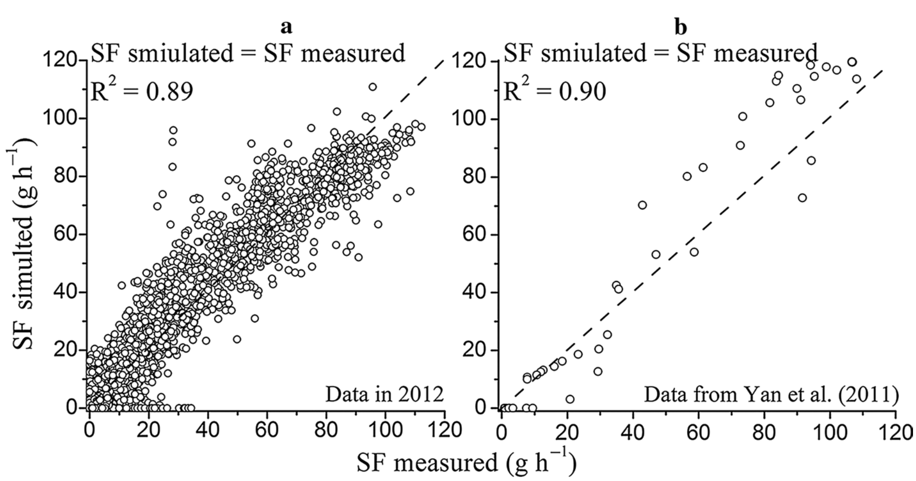

Fig. 6 Relationships between measured and simulated sap flow rates based on Eq. (1)

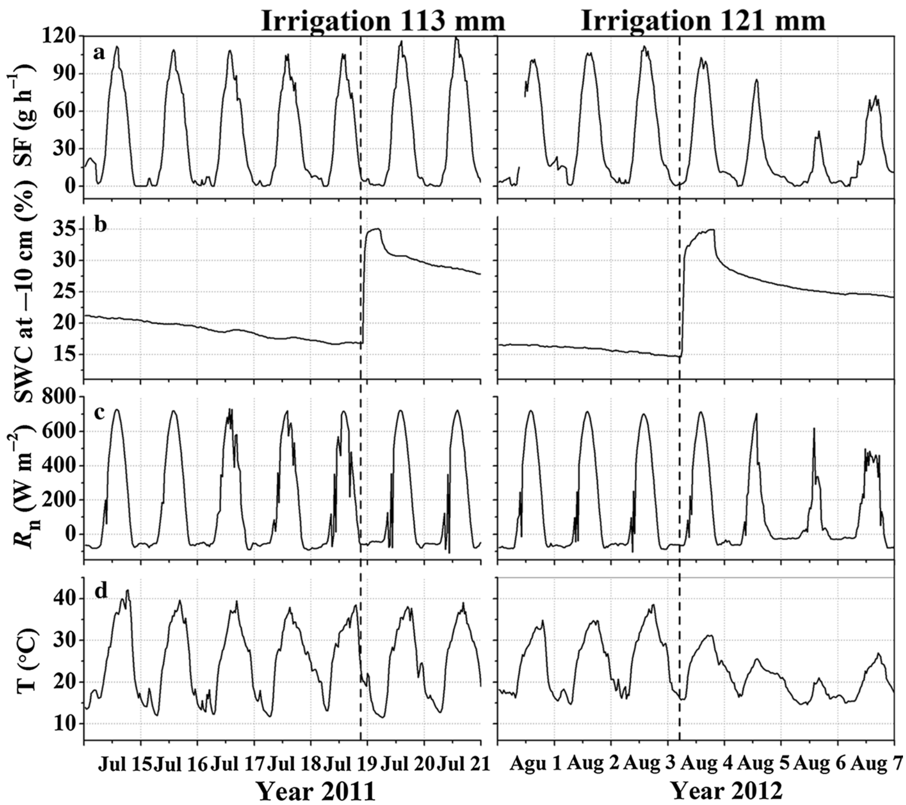

Fig. 7 **a** Sap flow rate, **b** volumetric water content at the depth of 10 cm, **c** net radiation, and **d** air temperature, **b**

plants in semiarid or aid regions have indicated that soil water content has a great influence on sap flow, since the water content is relatively low (Chen et al. 2014; Zhao and Liu. 2010). This may to some extent indicate that the current irrigation management system is unreasonable, as Mastel (2002) suggested that irrigation should be carried out when the water content is lower than 60 % of the field capacity.

Summary and conclusions

In order to extensively investigate the sap flow rate of maize plants, a monitoring program was initiated in an oasis farmland in the middle reach of the Heihe River, Northwest China. Based on the analyses of the monitored data of sap flow rates, meteorological factors, soil physics and plant-growth parameters, the major conclusions can be summarized as follows.

1. Because of sufficient irrigation water and physiological activity of the maize plants during the tasseling-to-filling growth stage, the sap flow rates were usually greater than those during the filling-to-maturity stage. As for the variational characteristics under different weather conditions, the maximum was on sunny days, the minimum on rainy days, and the intermediate on cloudy days. The largest difference in the sap flow rates of the maize plants occurred at noon on sunny days during the tasseling-to-filling stage.
2. Irrigation schedule can affect the sap flow, and consequently the crop yields of maize plants. This would explain why there was a significant linear relationship between sap flow and ET_0 in 2011 ($R^2 = 0.72$), but no relationship in 2012 ($R^2 = 0.03$). Further research work should be conducted on the influence of cob growth on sap flow. Generally, the sap flow rate decreased with a decrease in LAI. A similar variational pattern was found for maize plants with different stem diameters: the larger the stem diameter, the higher the sap flow rate.
3. The ranking of the main meteorological factors affecting the sap flow rate was: net radiation > air temperature > vapor pressure deficit > wind speed. Based on the two top influencing factors, an empirical formula was put forward for a quick estimation of the sap flow rate of the maize plants in this region. This formula has been proved to be reliable by the mentored data in this study and also from a previous study. When the current volumetric water content was relatively high, the response of sap flow rate to irrigation was not significant, implying that some of the irrigation water may have been wasted.

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