HYDROLOGICAL PROCESSES
*Hydrol. Process.* **29**, 2983–2993 (2014)
Published online 8 January 2015 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/hyp.10417

# Canopy transpiration obtained from leaf transpiration, sap flow and FAO-56 dual crop coefficient method

Liwen Zhao[1,2] and Wenzhi Zhao[1,2]*

[1] *Linze Inland River Basin Research Station, Chinese Ecosystem Network Research, Lanzhou 730000, China*
[2] *Key Laboratory of Ecohydrology of Inland River Basin, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000, China*

## Abstract:

With a maize seed planting area of about 67 000 $hm^2$, Zhangye city supplies the seeds for more than 40% of the maize planting area in China. Irrigation water is often overused to ensure the quality of the maize seeds, leading to serious water shortage problems in recent years. An accurate and convenient estimate of canopy transpiration is of particular importance to ease the problem. In this paper, leaf transpiration and sap flow in a maize field were measured in 2012 using a portable photosynthesis system and a heat balance sap flow system. Based on a large amount of meteorological data and relevant maize plant-growing parameters, canopy transpiration was up-scaled from both leaf transpiration ($T_l$) and sap flow ($T_f$), and also calculated by the FAO-56 dual crop coefficient method ($T$). Comparing these three types of transpiration, $T_f$ was proved to be more reliable than $T_l$. Taking $T_f$ as a benchmark, the basal crop coefficient ($K_{cb}$, the key parameter of FAO-56 dual crop coefficient method) was further adjusted and verified for the maize plants in this region. In addition, the errors when using up-scaling methods and FAO-56 dual crop coefficient method are summarized. Copyright © 2014 John Wiley & Sons, Ltd.

KEY WORDS transpiration; sap flow; up-scaling; evapotranspiration; water shortage

*Received 25 December 2013; Accepted 8 December 2014*

## INTRODUCTION

Evapotranspiration (*ET*), an important hydrological variable, refers to the loss of water to the atmosphere by the combined processes of both soil evaporation and plant transpiration. On average, worldwide, transpiration accounts for two third of the total *ET* over land (Brutsaert, 2005). Transpiration is a primary determinant for leaf energy balance and plant water status (Granier *et al.*, 2000; Yunusa *et al.*, 2004). Plants contribute the major part of the atmospheric water balance through transpiration, away from the continental margins (Gat, 2000).

The importance of recognizing and reducing the errors in estimating transpiration is well known and relevant widely dispersed investigations on three different scales have been developed, i.e. leaf, individual plant and canopy. For leaf-scale studies, leaf gas exchange systems for monitoring carbon dioxide uptake and transpiration of the leaves were first introduced in the 1980s (Ehleringer *et al.*, 1991). Later, some other methods for measuring leaf transpiration became available and updated, such as the steady-state porometer (Horwitz *et al.*, 2008), diffusion porometer (Katerji *et al.*, 2003), CIRAS-2 portable photosynthesis (Uehlein *et al.*, 2008) and Li-6400/Li-6400XT portable photosynthesis systems (Wullschleger *et al.*, 2000; Peng *et al.*, 2009). At the same time, a series of photosynthesis-transpiration models were also established (Jarvis and McNaughton, 1986; Jones, 1992) and verified (Leuning and Moncrieff, 1990; Leuning, 1995; Yu *et al.*, 2003). On the individual plant scale, heat-balance-based sensors have been used to estimate transpiration of individual plants by continuously measuring sap flow at short intervals (Ham *et al.*, 1990; Meiresonne *et al.*, 1999). Sap flow measurements have been reported for a wide range of plants, including trees, vines, maize, cotton and other crops (Smith and Allen, 1996; Jara *et al.*, 1998; Meiresonne *et al.*, 1999; Chang *et al.*, 2006; Gong *et al.*, 2007; Tahir *et al.*, 2008; Zhao and Liu, 2010). At the canopy scale, canopy transpiration has been measured or determined by both direct and indirect measurements, such as the eddy covariance method (Wilson *et al.*, 2001), the Bowen Ratio technique (Hatton and Vertessy, 1990), the FAO-56 dual crop coefficient method (Allen, 2000), the Shuttleworth–Wallace dual model (Stannard, 1993) and so on. In

*Correspondence to: Wenzhi Zhao, Linze Inland River Basin Comprehensive Research Station, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000, China.
E-mail: zhaowzh@lzb.ac.cn

general, transpiration at each scale in a given environment is difficult to model because of the interaction of complex physical and physiological phenomena, and the multiplicity of ground surfaces, and exchange of matter and energy between plants and atmosphere (Dauzat *et al.*, 2001).

Up-scaling and down-scaling provide another way to obtain transpiration at one scale from another scale (Anderson *et al.*, 2003). The concept was first put forward by Jarvis and McNaughton (1986). Problems and strategies for scaling were extensively clarified by Jarvis (1995). Ham *et al.* (1990) first proposed the equations for up-scaling transpiration from leaf to individual plant to canopy. Much work about up-scaling transpiration has been done between different levels in recent years: from leaf to plant (Infante *et al.*, 1997; Van der Zande *et al.*, 2009), from leaf to canopy (Kim and Verma, 1991; Irmak *et al.*, 2008), from plant to canopy with only one kind of plant (stand-level in forestry) (Granier and Loustau, 1994; Fiora and Cescatti, 2006; Mackay *et al.*, 2010) and from plant to a large area with different species of plants (Vertessy *et al.*, 1995; Morén *et al.*, 2000; Čermák *et al.*, 2004; Oishi *et al.*, 2008; Jung *et al.*, 2011). In order to validate the effectiveness of the up-scaling method, the majority of previous studies focused on comparing the up-scaled transpiration from sap flow with the calculated transpiration from the converted Penman–Monteith equation (e.g. Zhang *et al.*, 1997; Yunusa *et al.*, 2008). The Penman–Monteith equation is widely accepted and successfully used (e.g. Allen, 2000; Bodner *et al.*, 2007; Suleiman *et al.*, 2007; Er-Raki *et al.*, 2010). So far, little comparative work has been done on up-scaled canopy transpiration from both leaf and individual plant, and the calculated transpiration using the FAO-56 crop coefficient method (containing ASCE Penman–Monteith equation). This would further confirm the effectiveness of the up-scaling method and also provide alternative way to obtain the canopy transpiration.

Zhangye city located in the middle reaches of the Heihe River (the second largest inland river in China) supplies maize seeds for more than 40% maize planting area in the country according to the local Bureau of Seed Management (Yang and Chen, 2014). In recent years, water shortage has become the main constraint to agricultural development in the city (Kang, 2004). In particular, many environmental and ecological problems have emerged, which was caused by the recent overuse of water sources (Cheng, 2002; Ren, 2005; Guo *et al.*, 2009). 86% of the agricultural and domestic water is supplied by the Heihe River, and 96% of this water is used for irrigation (Chen *et al.*, 2003). So, it is of great importance to investigate the water-balance state in the maize fields. Plant transpiration, the major part in use of the water sources, has become a priority.

In this study, a large amount of data including leaf transpiration, sap flow, meteorology and plant growing was collected at a $51.6 \times 51.6\,m^2$ maize seed planting field in Zhangye city in 2012. Canopy transpiration for the maize field was up-scaled from leaf transpiration and sap flow, and also calculated by FAO-56 dual crop coefficient method using meteorological data and plant-growing parameters. The objectives of this study were to (1) compare these three types of transpiration, (2) further adjust and verify the basal crop coefficient to obtain a better result when using FAO-56 dual crop coefficient method and (3) summarize the errors when using up-scaling methods and FAO-56 dual crop coefficient method.

## MATERIALS AND METHODS

### *Site description*

The research was conducted in a maize seed planting field of the Linze Inland River Basin Research Station of Chinese Academy of Sciences. The field is located in Zhangye City, Gansu Province, which is in the middle reaches of the Heihe River, as shown in the previous paper (Zhao and Zhao, 2014). Mean annual air temperature is about 7.6 °C, with a maximum of about 39.1 °C and a minimum of about −27.3 °C; Mean annual precipitation is about 117 mm, with 70% occurring from July to September; Mean annual pan evaporation is about 2390 mm; Mean wind velocity is $3.2\,m\,s^{-1}$, and the prevailing wind direction is northwest (Zhao *et al.*, 2010).

### *Monitoring program*

Figure 1 shows the layout of the monitored maize seed planting field, meteorological station, Flow32-1K system for monitoring sap flow, and Li-6400XT photosynthesis system for monitoring leaf transpiration. Six maize plants were selected in the monitoring region to monitor the leaf transpiration and sap flow. Only three stem diameters were common during the monitoring period (ca. 16, 19 and 25 mm). In combination of meteorological data and some plant-growing parameters, canopy transpiration was calculated by the FAO-56 dual crop coefficient method. The growing stage from tasseling to maturity (6 July–12 September 2012) was used as the monitoring period for both leaf and individual plant transpiration, as more than 60% of the total irrigating water during maize growing stages was used in this stage (Zhao and Zhao, 2014). In addition, measuring sap flow rate before tasseling would destroy either the sap flow sensors or the stems of the maize plants, since the maize plant grow very fast during the period. The details of monitoring of each factor are as follows.

 

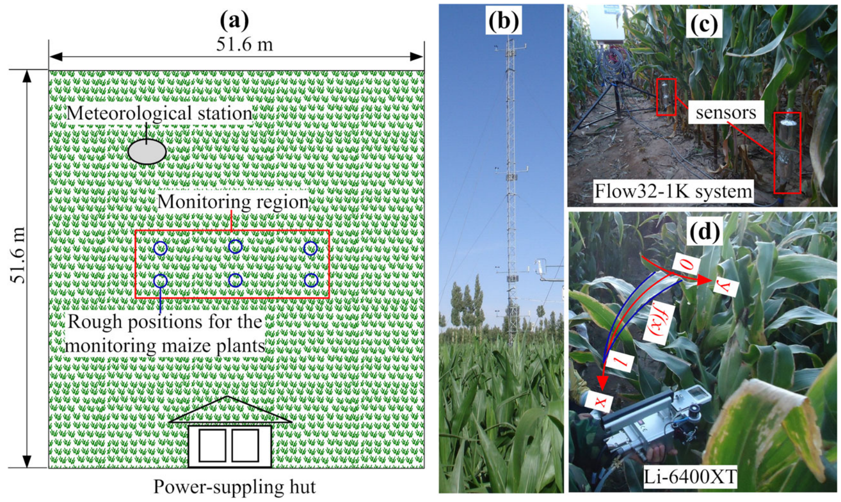


Figure 1. Layout of the monitoring maize seed planting field (a), meteorological station (b), Flow32-1K system for monitoring sap flow (c) and Li-6400XT photosynthesis system for measuring leaf transpiration (d)

*Meteorological factors*. An ENVIS Environmental Monitoring System was employed in the field. Detailed information of the system is listed in Table I. All the data were measured every 10 min or 30 min, and recorded with a Trimelogger (IMKO GmbH, Ettlingen, Germany).

*Sap flow*. Sap flow was measured by a Dynagage Flow32-1K system (Houston, TX, USA) based on the heat balance method. Sap flow was monitored for the six maize plants in the tasseling-maturity stage. The sensors and maize plants were checked on 14 July, and 1 and 15 August, because the sensors need to be changed to larger diameters due to the growth of maize plants. The monitored maize plants should also be changed since long-term mounting of the sensor may affect the growth of maize plant. Both sensors and maize plants were changed on July 14, but only maize plants were changed on 1 and 15 August as the diameters of the maize plants were constant. When changing the maize plants, the neighbouring maize plants were preferred; the approximate positions of the monitored maize plants are shown in Figure 1(a). The sensors were all installed at the height of more than 10 cm above the ground surface to prevent immersion in irrigation water.

*Leaf transpiration*. A Li-6400XT portable photosynthesis system (Li-COR, Inc., USA) was used to measure leaf transpiration ($T_i$), stomatal conductance ($g_s$) and

Table I. Environmental variables measured by the ENVIS Environmental Monitoring System

| Variables | Sensors | Observation positions |
|---|---|---|
| Net radiation | CNR-1 (Kipp & Zonen, Delft, The Netherlands) | 2 m above the canopy |
| Photosynthetically active radiation | LI-190 (LI-COR Inc., Lincoln, NE, USA) | 2 m above the canopy |
| Air temperature | HMP45D (Vaisala, Helsinki, Finland) | 2 m above the canopy |
| Relative humidity | HMP45D (Vaisala, Helsinki, Finland) | 2 m above the canopy |
| Air pressure | PTB100 (Vaisala, Helsinki, Finland) | 2 m above the canopy |
| Wind speed | LISA cup anemometer (Siggelkow GmbH, Germany) | 2 m above the canopy |
| Wind direction | Young 8100 (Siggelkow GmbH, Hamburg, Hamburg, Germany) | 2 m above the canopy |
| Canopy/surface temperature | PS12AF1 surface Pyrometer (Keller HCMGmbH, Ibbenbüren-Laggenbeck, Germany) | 2 m above the canopy |
| Soil temperature | Pt100 (IMKO GmbH, Ettlingen, Germany) | 5,10,20,40,80 and 120 cm depths in the soil |
| Volumetric soil water content | TRIME-IT (IMKO GmbH, Ettlingen, Germany) | 10,20,50,100,200,300 cm depths in the soil |
| Soil heat fluxes | Three HFP-01 heat flux plates (Hukseflux Thermal Sensors, Delft, The Netherlands) | 0.05 m in the soil surface |
| Precipitation | RG50 tipping bucket rainfall gauges (SEBA Hydrometrie GmbH, Gewerbestr,Germany) | the top of canopy |

 

Table II. Mean values of the meteorological factors and soil water content

| Date | $R_n$ (W d$^{-1}$) | $T_a$ (°C) | $VPD$ (kPa) | $U_2$ (m s$^{-1}$) | $SWC$ (m$^3$ m$^{-3}$) |
|---|---|---|---|---|---|
| 13 July | 414.3 | 26.7 | 2.1 | 0.1 | 28.1 |
| 22 July | 313.2 | 25.5 | 2.7 | 0.1 | 31.1 |
| 4 August | 390.4 | 31.4 | 2.1 | 0.2 | 28.2 |
| 20 August | 354.1 | 23.1 | 0.4 | 0.4 | 29.4 |

$R_n$: net radiation; $T_a$: air temperature; $VPD$: vapour pressure deficit; $U_2$: wind speed at 2 m; $SWC$: soil water content.

some other parameters. Due to the very strict weather condition needed when using this system, only four sunny days were selected, i.e. 13 July, 22 July, 4 August and 20 August in the tasseling–filling stage. The main weather and soil information for the four days is listed in Table II. The six monitored maize plants were changed corresponding with those for sap flow monitoring. For each leaf of the maize plants, the mean transpiration rate was estimated from measurements repeated three times in the central 6 cm$^2$ of the leaf. The monitoring interval was 1 h from 8:00 to 20:00.

*Other plant-growing parameters*.
1. *Leaf area*: Every leaf on the plant was measured with a scanner with an accuracy of 0.001 m. Leaf area is shown in a rectangular coordinate system (Figure 1(d)). The total leaf area for a maize plant can be obtained from formula (1), while the area of each leaf can be calculated from formula (2).

$$A_j = \sum_{i=1}^{n_j} a_i \tag{1}$$

$$a_i = 2\int_0^{l_i} f_i(x)dx \tag{2}$$

where $A_j$ is the total leaf area of all the leaves of maize plant $j$ (m$^2$), $n_j$ is the number of the leaves of maize plant $j$, $a_i$ is the area of leaf $i$ of maize plant $j$ (m$^2$), $l_i$ is the long axis of the leaf $i$ and $f_i(x)$ is the expression of the curve of the half leaf edge, as shown in Figure 1(d).

2. *Density and height*: Density and height of the maize plants were measured from 18 samples (2×2 m$^2$ area of plants) every 10 days. Six of the samples with different stem diameters were used to measure both sap flow.

*Calculation methods*

*Canopy transpiration scaled up from leaf transpiration*. According to the up-scaling equations from leaf transpiration to canopy transpiration (Ham *et al.*, 1990), the canopy transpiration can be obtained from the following linear equation:

$$T_l = \frac{ck}{\rho m}\sum_{j=1}^{m}\left(\sum_{i=1}^{n_j} T_i a_i\right) \tag{3}$$

where $T_l$ is the canopy transpiration scaled up from leaf transpiration (mm h$^{-1}$), $T_i$ is the transpiration of leaf $i$ of plant $j$ measured with LI-6400XT (mol m$^{-2}$ s$^{-1}$), $m$ is the number of monitored maize plants (6 here), $\rho$ is the density of water (1 g cm$^{-3}$ here), $k$ is the plant density (m$^{-2}$) (10 here) and $c$ is a constant value for unit conversion.

*Canopy transpiration scaled up from sap flow*. When the maize plants basically stops growing during the monitoring period, this leads to a negligible amount of water needed in plant physiology (Lei, 1988); the monitored sap flow can therefore be taken as representing individual plant transpiration and up-scaled to canopy transpiration (Lagergren and Lindroth, 2002). The up-scaled canopy transpiration can be also obtained from sap flow measurements using the flowing linear equation (Ham *et al.*, 1990):

$$T_f = \frac{c\sum_{i=1}^{n}(f_i\rho_i)}{n\rho} \tag{4}$$

where $T_f$ is the canopy transpiration (mm h$^{-1}$), $f_i$ is the sap flow measured by a Dynagage Flow32-1K system (g h$^{-1}$), $\rho_i$ is the plant density (m$^{-2}$) and $n$ is the number of monitored maize plants.

*Canopy transpiration calculated by the FAO-56 dual crop coefficient method*. The FAO-56 dual crop coefficient method was used to estimate evapotranspiration, which can be separated into transpiration and evaporation (Allen *et al.*, 1998). The equation for calculating transpiration is shown as follow.

$$T = K_s K_{cb} ET_0 \tag{5}$$

where $T$ is canopy transpiration for the 51.6×51.6 m$^2$ maize field (Figure 1(a)), $K_s$ is the water stress reduction coefficient with a range from 0 to 1, which can be taken as 1 in this paper. This is because that the maize fields were planted for seed production, and water stress was not allowed, sufficient water was supplied by the local Bureau of Seed Management. $K_{cb}$ is the basal crop coefficient. To obtain this parameter, the growing period of plant is first divided into four stages, i.e. initial stage, crop development stage, mid-season stage and late season stage. The basal crop coefficient during the four stages can be linearly interpolated based on that in the initial ($K_{cb\ ini}$), mid-season ($K_{cb\ mid}$) and end of the last season

 

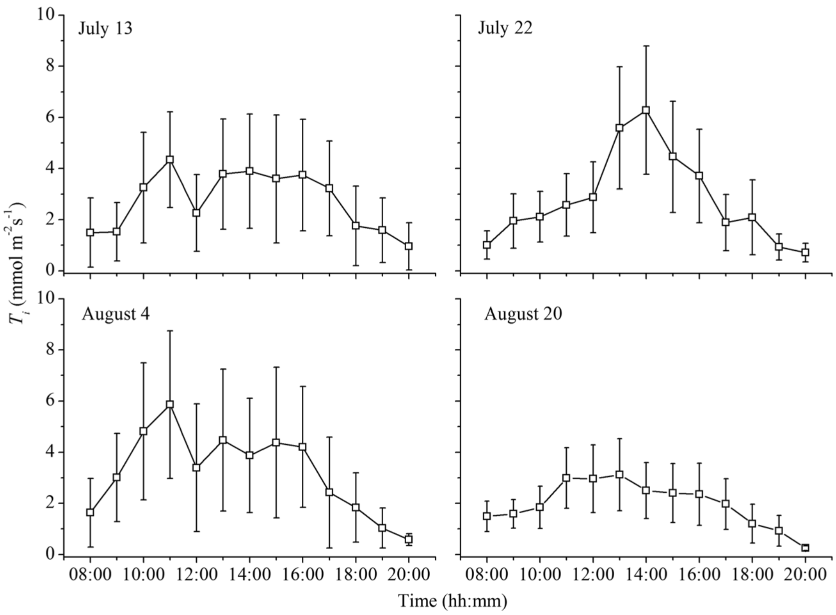


Figure 2. Leaf transpiration of the maize plants

stages ($K_{cb\ end}$). If the values of them are large than 0.45, the following equation must be used for adjusting (Allen *et al.*, 1998).

$$K_{cb} = K_{cb(Tab)} + [0.04(u_2\text{-}2)\text{-}0.004(RH_{min}\text{-}45)]\left(\frac{h}{3}\right)^{0.3} \tag{6}$$

The values of $K_{cb(Tab)}$ are 0.15, 1.15 and 0.5 for $K_{cb\ ini}$, $K_{cb\ mid}$ and $K_{cb\ end}$ respectively. $U_2$ is wind speed at 2-m height (m s$^{-1}$), $RH_{min}$ is the mean value of the daily minimum relative humidity during the middle or late season growth stage (%) and $h$ is the mean plant height during the middle or late season. $ET_0$ was calculated from the ASCE Penman–Monteith equation, as follow.

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{C_n}{T_a+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + C_d U_2)} \tag{7}$$

where $ET_0$ is reference evapotranspiration (mm h$^{-1}$), $R_n$ is net radiation at the crop surface (MJ m$^{-2}$ h$^{-1}$), $G$ is soil heat flux (MJ m$^{-2}$ h$^{-1}$), $T_a$ is air temperature at 2 m height (°C), $e_s$ is the saturation vapor pressure (kPa), $e_a$ is the actual pressure (kPa), $(e_s - e_a)$ is the saturation vapor pressure deficit (kPa), Δ is the slope of the vapor pressure curve (kPa °C$^{-1}$), $r$ is the psychrometric constant (kPa ° C$^{-1}$), $C_n$ is a numerator constant chat changes with reference type and calculation time step (K mm s$^3$Mg h$^{-1}$) and $C_d$ is the denominator constant (s m$^{-1}$). According to the ASCE standardized reference evapotranspiration equation, $C_n$ and $C_d$ should be taken as 37 and 0.24, respectively, for 1-h step cases (Allen *et al.*, 2005).

## RESULTS

### *Leaf transpiration*

Figure 2 shows the mean leaf transpiration for all the leaves of the monitored maize plants. The mean values of leaf transpiration were 2.7, 2.8, 3.2 and 2.0 mmol m$^{-2}$ s$^{-1}$ in the four monitoring days. The first increase in leaf transpiration from 13 July to 4 August was caused by the growth of the maize plants, while the latter decrease from 4 to 20 August was due to the aging of the leaves. On a daily scale, transpiration first increased and then decreased, reaching the maximum around 13:00. This is probably because the leaf transpiration was mainly influenced by the air temperature and solar radiation (both of them were high around 13:00).

Leaf transpiration also varied greatly with the height of leaves on the maize plants. One maize plant is selected to analyse the variational characteristics on the monitored days, as shown in Figure 3. The leaf numbers denote the leaves from bottom to top. It can be seen that leaf transpiration of the lower leaves was larger than the upper ones on 13 and 22 July, while larger leaf transpiration occurred in the upper leaves on 4 and 20 August. The transpiration of leaves may be affected by the changes in the plant physiology and environmental factors. One reason may be that the lower leaves started to senescence while upper leaves continued to grow during the period

 

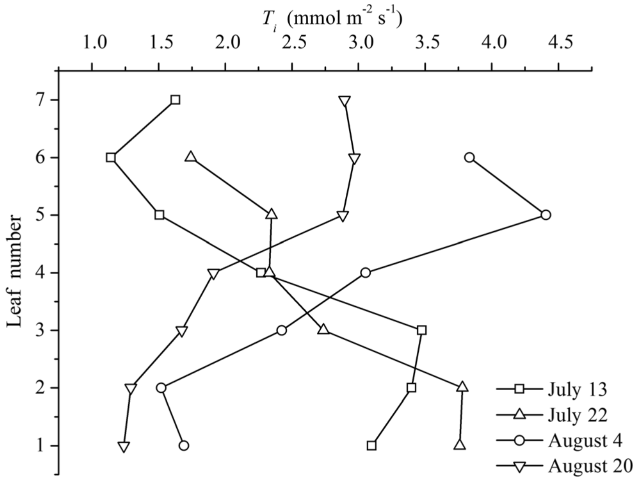


Figure 3. Leaf transpiration varying with leaves in the monitoring days (leaf numbers 1–7 denote leaves from bottom to top)

from 22 July to 4 August (Valentinuz and Tollenaar, 2004; Li and Si, 2006). On the other hand, the environmental factors, such as air temperature, vapour pressure deficit, wind speed and solar radiation, were different for the upper and lower leaves, and these environmental factors can also change during the plant growth.

*Individual plant transpiration–sap flow*

Figure 4 shows the variations of sap flow from 00:00 to 24:00 in the monitored days. The values are the average sap flow of the maize plants monitored by the same kind of sap flow sensor. As three types of sensors were used during the monitoring period, i.e. 16, 19 and 25 mm, three groups of average values were obtained. On 13 July, two kinds of sensors, 16 and 19 mm, were used to monitor six maize plants, but the data collected by 16-mm sensors were lost due to a human error. It can be seen that sap flow first increased and then decreased, and reached its maximum values around 13:00, showing the similar trends to leaf transpiration (Figure 2). From 00:00 to 6:30, sap flow was nearly zero, then it increased after 6:30 due to the increases in air temperature and solar radiation. After about 13:00, sap flow decreased because of the decreasing in same two major influencing factors.

Sap flow varied with the stem diameters of the maize plants. The larger the stem diameter was, the larger the sap flow. This may be caused by the maize plant with relatively large stem diameter having more leaves or leaves with larger areas. The maximum value of sap flow appeared in the maize plants ($d = 25$ mm) on 4 August with a value of 161.9 g h$^{-1}$. The differences in sap flow in maize plants with different stem diameters changed in the four days. On 22 July, sap flow was almost the same for the maize plants, but relatively large differences can be seen, on 4 and 20 August. The largest gap can also occurred around 13:00.

*Canopy transpiration*

Based on the meteorological data and plant-growing parameters, P–M model (Equation 7) suggested by ASCE was first used to calculate $ET_0$ at 1-h internal, and then FAO-56 dual crop coefficient method (Equation 5) was used to calculate canopy transpiration during the growing season in 2012. The variation of the calculated canopy transpiration can be seen in Figure 5. The variational trends were very similar to the leaf- and plant-scale. The total values of transpiration from 8:00 to 20:00 on the days, 13 July, 22 July, 4 August and 20 August, were 8.1, 5.6, 7.2 and 5.2 mm, respectively.

## DISCUSSION

*Comparison of up-scaled and calculated transpiration*

FAO-56 dual crop coefficient method is one of the most generally accepted methods (Allen *et al.*, 1998). The up-scaling method is another way to obtain canopy transpiration from single leaf and individual plant (Jarvis and Mcnaughton, 1986; Jarvis, 1995).

Figure 5 illustrates the up-scaled transpiration from leaf ($T_l$) and individual plant ($T_f$) transpiration, and the calculated transpiration from FAO-56 dual crop coefficient method ($T$). Similar diurnal patterns were obtained for the three types of transpiration, which to some extent verified the reliability of the results. A relatively large discrepancy can be seen on 22 July and 20 August, but good agreement among the three types of transpiration on

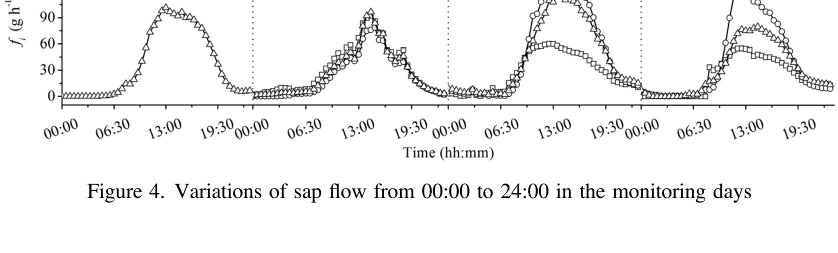


Figure 4. Variations of sap flow from 00:00 to 24:00 in the monitoring days

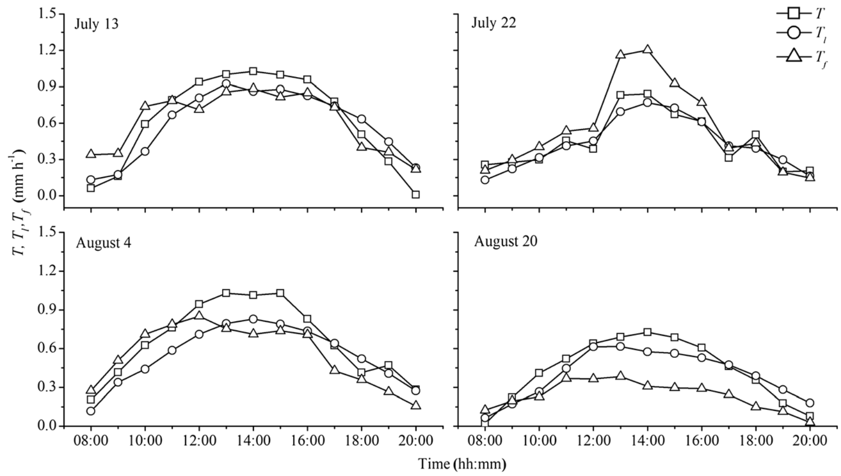


Figure 5. Up-scaled transpirations from leaf ($T_l$) and individual plant ($T_f$) transpiration, and the calculated transpiration from FAO-56 dual crop coefficient method ($T$)

13 July and 4 August. The discrepancy may be closely related with the sampling strategy and other errors in determining the transpiration.

It can be seen from Figure 6 that $T_f$ had a better agreement with $T$ than $T_l$, suggesting that sap flow should be preferred for up-scaling. More errors may occur in using leaf transpiration than sap flow when up-scaling to canopy transpiration (details in 'Errors in obtaining up-scaled and calculated transpiration'). This may explained by the fact that the coefficient of determination between $T_l$ and $T$ ($R^2 = 0.66$) was lower than that between $T_f$ and T ($R^2 = 0.9$). Of note is that the two fitted lines were very similar, which indicates the reliableness of the up-scaled transpiration especially from sap flow.

### *Further adjustment and verification of basal crop coefficient*

Although FAO-56 dual crop coefficient method has been successfully used in many fields (e.g. Allen, 2000; Bodner *et al*., 2007; Suleiman *et al*., 2007; Er-Raki *et al*., 2010), an unavoidable error can occur when using the empirical value of $K_{cb(tab)}$ (despite adjustment using Equation 6) since it is a constant value for the plants all over the world (Allen *et al*., 1998). As found in the last section, the measured sap flow data can be used to further adjust $K_{cb}$ for the maize plant in this region. In this section, the reliable measured hourly sap flow rate in the 4 days will be first used to adjust $K_{cb}$, and then sap flow rates under different weather conditions (that is, 10 July (sunny day), 16 July (cloudy day) and 16 August (rainy day)) were selected to verify the adjusted $K_{cb}$.

According to the ground coverage, plant maturity and harvest (Allen *et al*., 1998), the four stages of the maize plants for determining $K_{cb}$ in 2012 were: I initial stage from 10 April to 8 May, II crop development stage from 9 May to 15 June, III mid-season stage from 16 June to 3 August and IV final stage from 4 August to 12 September (Figure 7(a)). The sap flow rates on 13 and 22 July are

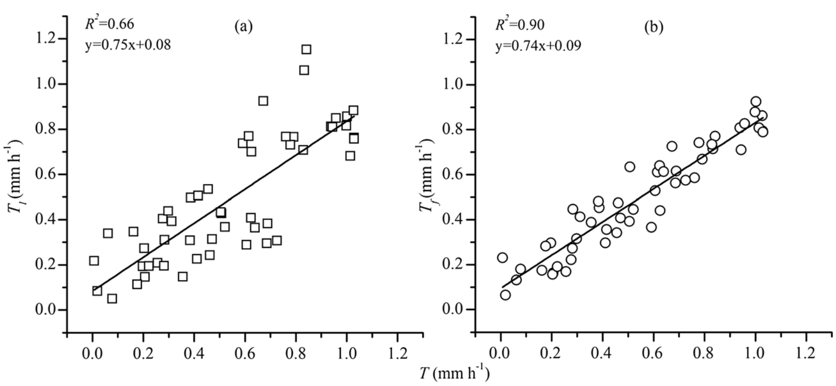


Figure 6. Comparisons between $T_l$ and $T$ (a), between $T_f$ and $T$ (b)

 

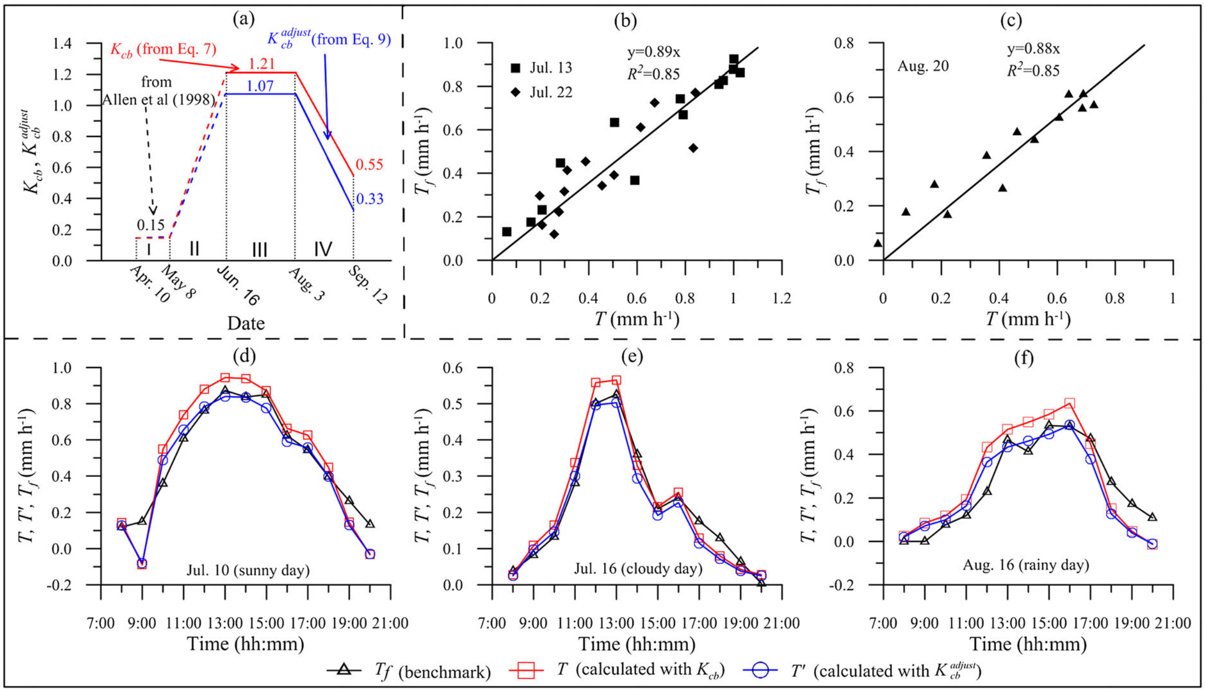


Figure 7. The adjusted basal crop coefficient ($K_{cb}$) by Equation 6 and further adjusted basal crop coefficient ($K_{cb}^{adjust}$) by Equation 8 (a), comparing $T$ with $T_f$ on 13 and 22 July (b) and 20 August (c), comparing $T_f$, $T$ and $T'$ under different weather conditions: sunny day (d), cloudy day (e) and rainy day (f)

used to adjust $K_{cb\ mid}$ but only that on 20 August is used to adjust $K_{cb\ end}$, because that on 4 August was very close to the boundary between mid-season and last stages. Figures 7 (b) and (c) show the relationship between $T_f$ obtained hourly sap flow rate and $T$ calculated by FAO-56 dual crop coefficient method. The adjusted basal crop coefficient ($K_{cb}^{adjust}$) can be obtained from the following equation.

$$K_{cb}^{adjust} = \alpha \cdot K_{cb} \tag{8}$$

where α is the slope of the fitted lines, $K_{cb}$ is first adjusted by Equation 6.

Figures 7 (d), (e) and (f) show the original canopy transpiration ($T$, calculated with $K_{cb}$), revised canopy transpiration ($T'$, calculated with $K_{cb}^{adjust}$) and the up-scaled canopy transpiration from sap flow rate ($T_f$). It can be clearly seen that $T'$ is closer to $T_f$ than $T$, indicating the reasonableness of $K_{cb}^{adjust}$. In addition, the revised $K_{cb(tab)}$ can be calculated from the inverted Equation 6 using $K_{cb}^{adjust}$: 1.0 for $K_{cb\ mid}$ and 0.3 for $K_{cb\ end}$ (The original values in Allen *et al*. (1998) are 1.15 and 0.5, respectively).

*Errors in obtaining up-scaled and calculated transpiration*

Accurate estimation of canopy transpiration plays an important role in determining irrigation measures in the region. Some errors may be unavoidable in obtaining the up-scaled or calculated transpiration, as follows:

1. Up-scaling from leaf transpiration: since spatial and temporal variation of stomatal conductance exists over leaf surfaces (Jones, 1999). The measured leaf transpiration from the central areas of leaves would induce a certain error. Leaf area obtained from scanning, fitting and then integrating would also lead to some error. Randomness in sampling maize plants would result in an unavoidable error, which would decrease with the increasing of samples. In addition, artificial operation and instrument measurement can also lead to some errors, especially in reading the values of leaf transpiration (the monitored values often fluctuate when measuring). In addition, leaf transpiration can only be measured by Li-6400 XT system in sunny days, and lack of data about leaf transpiration at nighttime would cause some error since 24-h continuous sap flow monitoring indicated leaf transpiration can be negligible only from 00:00 to 06:30 in the monitoring days (Figure 3).
2. Up-scaling from individual plant transpiration: the same error as leaf transpiration when selecting samples would be the priority. Relatively large discrepancies may be seen for maize plants with different stem diameters (Figure 4), so the maize plants were selected

 

with different stem diameters to minimize this error in this paper. To further reduce this error, statistical analysis of the stem diameter of all the maize plants in the study area and measurement for the sap flow of the maize plants with the different stem diameters should be conducted. Sap flow sensors should be changed during the growth of maize plants especially before tasseling, because of the increase of the stem diameters and possible damage to maize plants caused by long-term mounting of sensors. A certain error may occur when measuring sap flow for individual plant transpiration before tasseling, as a small part of water may be used by plant physiology (Lei, 1988).

3. Calculating using the FAO-56 dual crop coefficient method: the large amount of meteorological and plant-growing parameters required may cause some problems and potential errors, such as measuring plant height, obtaining basal crop coefficient by linear interpolation, and taking the monitored meteorological data as the average values for the $51.6 \times 51.6\,m^2$ maize seed planting field (Figure 1(a)). Some standard parameters and empirical equations obtained from FAO 56 (Allen *et al.*, 1998) may also induce some unavoidable errors, like basal crop coefficient.

## SUMMARY AND SUGGESTION

Canopy transpiration was up-scaled from leaf transpiration and sap flow and calculated by FAO-56 dual crop coefficient using meteorological data and relevant maize plant growing parameters in 2012 in Zhangye city. This area supplies the maize seeds for more than 40% of the maize planting area in China. Comparing the three types of transpiration in the four days (13 and 22 July, 4 and 20 August), it was found that the up-scaled transpiration is reliable, especially that from measured sap flow rate. Taking the up-scaled transpiration from sap flow rate in the 4 days as a benchmark, basal crop coefficient is further adjusted and then verified with the other three days under different weather conditions (that is, sunny day, cloudy day and rainy day). The adjusted basal crop coefficient is obtained and proved to be reliable. The revised $K_{cb(tab)}$ is obtained for the maize plants in the region, 1.0 for $K_{cb\ mid}$ and 0.3 for $K_{cb\ end}$. The original values in Allen *et al.* (1998) are 1.15 and 0.5, respectively.

When using the up-scaling method to obtain canopy transpiration, users must be aware of potential errors and take suitable precautions. Repeated measurement of leaf transpiration on different areas of each leaf, and using different methods to measure leaf areas would minimize the errors. As for strategy in sampling maize plants, increase the number of stem diameters (not only 16, 19 and 25 mm), use more selection criteria to choose samples (not only stem diameter) and increase the sampling region (no restriction to the monitoring region in Figure 1) would be favourable to obtain more reliable up-scaled canopy transpiration. As for the canopy transpiration calculated by FAO-56 dual crop coefficient method, one should be aware of some potential error even though it is widely accepted and has been successfully used in many fields.

Accurate and easy estimates of canopy transpiration are very important in the regions facing water shortage. It is hard to eliminate all the errors for both up-scaling method and FAO-56 dual crop coefficient method. However, with the improvement of the monitoring techniques and sampling strategy, as well as the long-term monitoring data collecting, it will be helpful in obtaining a more accurate assessment of canopy transpiration.

## ACKNOWLEDGEMENTS

This work was supported by the National Science Fund for Distinguished Yong Scholars (No. 41125002) and National Natural Science Foundation of China (Key Program No. 40930634). The authors greatly appreciate the help from Dr. Xibin Ji, Dr. Bowen Jin, Dr. Qiyue Yang and Mr. Dongsheng Li in carrying out the experiments, and also thank the two anonymous reviewers for their constructive comments. A special thank is given to Geoffery Gay for his kind help in revising this paper.

## REFERENCES

Allen RG. 2000. Using the FAO-56 dual crop coefficient method over an irrigated region as part of an evapotranspiration intercomparison study. *Journal of Hydrology* **229**: 27–41.

Allen RG, Walter IA, Elliott RL, Howell TA, Itenfisu D, Jensen ME, Snyder RL. 2005. *The ASCE Standardized Reference Evapotranspiration Equation*. American Society of Civil Engineers: Reston, US.

Allen RG, Pereira LS, Raes D, Smith M. 1998. *Crop evapotranspiration—guidelines for computing crop water requirements—FAO Irrigation and drainage paper 56*, Vol. **300**. FAO: Rome; 6541.

Anderson MC, Kustas WP, Norman JM. 2003. Upscaling and downscaling—a regional view of the soil–plant–atmosphere continuum. *Agronomy Journal* **95**(6): 1408–1423.

Bodner G, Loiskandl W, Kaul HP. 2007. Cover crop evapotranspiration under semi-arid conditions using FAO dual crop coefficient method with water stress compensation. *Agricultural Water Management* **93**(3): 85–98.

Brutsaert W. 2005. *Hydrology: An Introduction*. Cambridge University Press: Cambridge, UK.

Čermák J, Kučera J, Nadezhdina N. 2004. Sap flow measurements with some thermodynamic methods, flow integration within trees and scaling up from sample trees to entire forest stands. *Trees* **18** (5): 529–546.

Chang XX, Zhao WZ, Zhang ZH, Su YZ. 2006. Sap flow and tree conductance of shelter-belt in arid region of China. *Agricultural and Forest Meteorology* **138**: 132–141.

Chen DJ, Xu ZM, Chen RS. 2003. Design of resources accounts: a case of integrated environmental and economic accounting. *Advances in Water Science* **14**: 631–637.

 

Cheng GD. 2002. Study on the sustainable development in Heihe River watershed from the view of ecological economics. *Journal of Glaciology Geocryology* **24**: 335–343.

Dauzat J, Rapidel B, Berger A. 2001. Simulation of leaf transpiration and sap flow in virtual plants: model description and application to a coffee plantation in Costa Rica. *Agricultural and Forest Meteorology* **109**(2): 143–160.

Ehleringer JR, Sage RF, Flanagan LB, Pearcy RW. 1991. Climate change and the evolution of $C_4$ photosynthesis. *Trends in Ecology & Evolution* **6**(3): 95–99.

Er-Raki S, Chehbouni A, Boulet G, Williams DG. 2010. Using the dual approach of FAO-56 for partitioning ET into soil and plant components for olive orchards in a semi-arid region. *Agricultural Water Management* **97**(11): 1769–1778.

Fiora A, Cescatti A. 2006. Diurnal and seasonal variability in radial distribution of sap flux density: implications for estimating stand transpiration. *Tree Physiology* **26**(9): 1217–1225.

Gat JR. 2000. Atmospheric water balance—the isotropic perspective. *Hydrological Processes* **14**: 1357–1369.

Gong DZ, Kang SZ, Yao LM, Zhang L. 2007. Estimation of evapotranspiration and its components from an apple orchard in northwest China using sap flow and water balance methods. *Hydrological Processes* **21**(7): 931–938.

Granier A, Loustau D. 1994. Measuring and modelling the transpiration of a maritime pine canopy from sap-flow data. *Agricultural and Forest Meteorology* **71**(1): 61–81.

Granier A, Biron P, Lemoine D. 2000. Water balance, transpiration and canopy conductance in two beech stads. *Agricultural and Forest Meteorology* **100**(4): 291–308.

Guo QL, Feng Q, Li JL. 2009. Environmental changes after ecological water conveyance in the lower reaches of Heihe River, northwest China. *Environmental Geology* **58**: 1387–1396

Ham JM, Heilman JL, Lascano RJ. 1990. Determination of soil water evaporation and transpiration from energy balance and stem flow measurements. *Agricultural and Forest Meteorology* **52**(3): 287–301.

Hatton TJ, Vertessy RA. 1990. Transpiration of plantation Pinus radiata estimated by the heat pulse method and the Bowen ratio. *Hydrological Processes* **4**(3): 289–298.

Horwitz DA, Zheng SG, Gray JD. 2008. Natural and TGF-β–induced Foxp3$^+$ CD4$^+$ CD25$^+$ regulatory T cells are not mirror images of each other. *Trends in Immunology* **29**(9): 429–435.

Infante JM, Rambal S, Joffre R. 1997. Modelling transpiration in holm-oak savannah: scaling up from the leaf to the tree scale. *Agricultural and Forest Meteorology* **87**: 273–289.

Irmak S, Mutiibwa D, Irmak A, Arkebauer TJ, Weiss A, Martin DL, Eisenhauer DE. 2008. On the scaling up leaf stomatal resistance to canopy resistance using photosynthetic photon flux density. *Agricultural and Forest Meteorology* **148**(6): 1034–1044.

Jara J, Stockle CO, Kjelgaard J. 1998. Measurement of evapotranspiration and its components in a corn (*Zea Mays* L.) field. *Agricultural and Forest Meteorology* **92**(2): 131–145.

Jarvis PG. 1995. Scaling processes and problems. *Plant, Cell and Environment* **18**: 1079–1089.

Jarvis PG, McNaughton KG. 1986. Stomatal control of transpiration: scaling up from leaf to region. *Advances in Ecological Research* **15**(1): 49.

Jones HG. 1992. *Plants and Microclimate: A Quantitative Approach to Environmental Plant Physiology*. Cambridge University Press: Cambridge, UK.

Jones HG. 1999. Use of thermography for quantitative studies of spatial and temporal variation of stomatal conductance over leaf surfaces. *Plant, Cell and Environment* **22**(9): 1043–1055.

Jung EY, Otieno D, Lee B, Lim JH, Kang SK, Schmidt MWT, Tenhunen J. 2011. Up-scaling to stand transpiration of an Asian temperate mixed-deciduous forest from single tree sapflow measurements. *Plant Ecology* **212**(3): 383–395.

Kang ES. 2004. Water resources relating to desertification in the Hexi area of Gansu Province, China. *Journal of Glaciology Geocryology* **26**: 657–667.

Katerji N, Van Hoorn JW, Hamdy A, Mastrorilli M. 2003. Salinity effect on crop development and yield, analysis of salt tolerance according to several classification methods. *Agricultural Water Management* **62**(1): 37–66.

Kim J, Verma SB. 1991. Modeling canopy photosynthesis: scaling up from a leaf to canopy in a temperate grassland ecosystem. *Agricultural and Forest Meteorology* **57**(1): 187–208.

Lagergren F, Lindroth A. 2002. Transpiration response to soil moisture in pine and spruce trees in Sweden. *Agricultural and Forest Meteorology* **112**(2): 67–85.

Lei ZD. 1988. *Soil Water Dynamics*. Tsinghua University Press: Beijing.

Leuning R. 1995. A critical appraisal of a combined stomatal-photosynthesis model for $C_3$ plants. *Plant, Cell & Environment* **18**(4): 339–355.

Leuning R, Moncrieff J. 1990. Eddy-covariance $CO_2$ flux measurements using open-and closed-path $CO_2$ analysers: corrections for analyser water vapour sensitivity and damping of fluctuations in air sampling tubes. *Boundary-Layer Meteorology* **53**(1-2): 63–76.

Li WD, Si YG. 2006. *Maize Cultivating Technique*. China Social Sciences Press: Beijing.

Mackay DS, Ewers BE, Loranty MM, Kruger EL. 2010. On the representativeness of plot size and location for scaling transpiration from trees to a stand. *Journal of Geophysical Research*, **115**(G02016). DOI: 10.1029/2009JG001092.

Meiresonne L, Nadezhdin N, Cermak J, Van Slycken J, Ceulemans R. 1999. Measured sap flow and simulated transpiration from a poplar stand in Flanders (Belgium). *Agricultural and Forest Meteorology* **96** (4): 165–179.

Morén AS, Lindroth A, Flower-Ellis J, Cienciala E, Mölder M. 2000. Branch transpiration of pine and spruce scaled to tree and canopy using needle biomass distributions. *Trees* **14**(7): 384–397.

Oishi AC, Oren R, Stoy PC. 2008. Estimating components of forest evapotranspiration: a footprint approach for scaling sap flux measurements. *Agricultural and Forest Meteorology* **148**(11): 1719–1732.

Peng ZY, Wang MC, Li F, Lv HJ, Li CL, Xia GM. 2009. A proteomic study of the response to salinity and drought stress in an introgression strain of bread wheat. *Molecular & Cellular Proteomics* **8**(12): 2676–2686.

Ren JH. 2005. Effects of water resources exploitation on ecoenvironment of Heihe River Basin. *Bulletin of Soil and Water Conservation* **25**: 94–96.

Smith DM, Allen SJ. 1996. Measurement of sap flow in plant stems. *Journal of Experimental Botany* **47**(12): 1833–1844.

Stannard DI. 1993. Comparison of Penman–Monteith, Shuttleworth–Wallace, and modified Priestley–Taylor evapotranspiration models for wildland vegetation in semiarid rangeland. *Water Resources Research* **29**(5): 1379–1392.

Suleiman AA, Tojo Soler CM, Hoogenboom G. 2007. Evaluation of FAO-56 crop coefficient procedures for deficit irrigation management of cotton in a humid climate. *Agricultural Water Management* **91**(1): 33–42.

Tahir ISA, Nakata N, Yamaguchi T, Nakano J, Ali AM. 2008. Influence of high shoot and root-zone temperatures on growth of three wheat genotypes during early vegetative stages. *Journal of Agronomy and Crop Science* **194**(2): 141–151.

Uehlein N, Otto B, Hanson DT, Fischer M, McDowell N, Kaldenhoff R. 2008. Function of Nicotiana tabacum aquaporins as chloroplast gas pores challenges the concept of membrane $CO_2$ permeability. *The Plant Cell Online* **20**(3): 648–657.

Valentinuz OR, Tollenaar M. 2004. Vertical profile of leaf senescence during the grain-filling period in older and newer maize hybrids. *Crop Science* **44**(3): 827–834.

Van der Zande D, Mereu S, Nadezhdina, N, Cermak, J, Muys, B, Coppin P, Manes F. 2009. 3D upscaling of transpiration from leaf to tree using ground-based LiDAR: application on a Mediterranean Holm oak (Quercus ilex L.) tree. *Agricultural and Forest Meteorology* **149**(10): 1573–1583.

Vertessy RA, Benyon RG, O'sullivan SK, Gribben PR. 1995. Relationships between stem diameter, sapwood area, leaf area and transpiration in a young mountain ash forest. *Tree Physiology* **15**(9): 559–567.

Wilson KB, Hanson PJ, Mulholland PJ, Baldocchi DD, Wullschleger SD. 2001. A comparison of methods for determining forest evapotranspiration and its components: sap-flow, soil water budget, eddy covariance and catchment water balance. *Agricultural and Forest Meteorology* **106** (2): 153–168.

Wullschleger SD, Wilson KB, Hanson PJ. 2000. Environmental control of whole-plant transpiration, canopy conductance and estimates of the decoupling coefficient for large red maple trees. *Agricultural and Forest Meteorology* **104**(2): 157–168.

Yang Y, Chen JX. 2014. Reasons and countermeasures for frequently maize seed planting without certificate. *Seed Word* **7**: 1–2.

Yu GR, Kobayashi T, Zhuang J, Wang QF, Qu LQ. 2003. A coupled model of photosynthesis-transpiration based on the stomatal behavior for maize (*Zea mays* L.) grown in the field. *Plant and Soil* **249**(2): 401–415.

Yunusa IAM, Walker RR, Lu P. 2004. Evapotranspiration compoents from energy balance, sapflow and microlysimetry techniques for an irrigated vineyard in inland Australia. *Agricultural and Forest Meteorogy* **127**(1-2): 93–107.

Yunusa IAM, Nuberg IK, Fuentes S, Lu P, Eamus D. 2008. A simple field validation of daily transpiration derived from sapflow using a porometer and minimal meteorological data. *Plant and Soil* **305**(1-2): 15–24.

Zhang HP, Simmonds LP, Morison JI, Payne D. 1997. Estimation of transpiration by single trees: comparison of sap flow measurements with a combination equation. *Agricultural and Forest Meteorology* **87**(2): 155–169.

Zhao WZ, Liu B. 2010. The response of sap flow in shrubs to rainfall pulses in the desert region of China. *Agricultural and Forest Meteorology* **150**(9): 1297–1306.

Zhao LW, Zhao WZ. 2014. Water balance and migration for maize in an oasis farmland of northwest China. *Chinese Science Bulletin* **59**(34): 4829–4837.

Zhao WZ, Liu B, Zhang ZH. 2010. Water requirements of maize in the middle Heihe River basin, China. *Agricultural Water Management* **97**(2): 215–223.

 