

The ratio of transpiration to evapotranspiration in a rainfed maize field on the Loess Plateau of China

Shanshan Zhou, Wenzhao Liu and Wen Lin

ABSTRACT

Maize (*Zea mays* L.) is a major crop on the Loess Plateau, and calculating the ratio of transpiration to evapotranspiration (T/ET) of maize is important for estimating field water balance. In this study, the sap flow method was adopted to measure transpiration (T) characteristics of maize. In order to calibrate the sap flow gauge, the sap flow rate was compared to the leaf T determined by the weighing method. The sap flow value was measured per hour for 3 days and the mean of the hourly values for each day was taken as the daily value to avoid the influence of hydraulic capacitance. There was a significant linear relationship between leaf T and sap flow rate. The slope and intercept of linear regression were 0.764 and 4.944, with an R^2 of 0.97 ($p < 0.01$). We also analyzed the T and ET of maize under field conditions. The T/ET of maize was 63.3% from July to September 2012. The T/ET and leaf area index had a good linear relationship. Partitioning of ET into soil evaporation (E) and T may have important implications for analyzing crop water use efficiency, evaluating the crop production potential of precipitation and optimizing field water management.

Key words | calibration, evapotranspiration, sap flow method, sap flow rate, transpiration rate

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INTRODUCTION

Crop transpiration (T) is an important component of plant-soil-atmospheric water cycling. Maize (*Zea mays* L.) is a major crop on the Loess Plateau, a semiarid region in north-western China. The main factors influencing crop production in the region are limited precipitation and high evaporation (E) (Zhou *et al.* 2009). Studying the evapotranspiration (ET) and T of maize is essential for optimizing crop water management in the region (Kang *et al.* 2003).

Determination of the T/ET is of importance in refining the calculation of field water balance, analyzing the crop water use efficiency (WUE) of crops, and evaluating the crop production potential of precipitation (Kang *et al.*

1994). However, E and T occur simultaneously, and it is difficult to separate the two processes. Researchers determine E from measurements taken by mini- or micro-lysimeters (Flumignan *et al.* 2012), or using models (Sutanto *et al.* 2012) for this calculation. However, measurements taken by mini- or micro-lysimeters that are positioned between crop rows to calculate T indirectly have limitations (Lv *et al.* 2009). For instance, the use of the mini-lysimeters is affected by rainfall and the device gives a declining rate of soil moisture in its use. In this study, we use the sap flow method to obtain crop T directly. This method was developed by Vieweg & Ziegler (1960) and improved by Cermak *et al.* (1973, 1976), Sakuratani (1981, 1984), and Baker & Van Bavel (1987). The method has substantial advantages over other techniques (Smith & Allen 1996). Comparatively, the sap flow method may give rise to very little disturbance and is able to reveal the time course of actual water loss without any noticeable time delay (Sakuratani 1981).

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It is also important to calibrate the sap flow gauge to reduce experimental errors because this method does not control stem temperature and fails to detect rapid changes in the T process (Ishida *et al.* 1991). Many studies have compared the results of sap flow sensors to the weight loss of potted plants in order to correct the sap flow value (Gutiérrez *et al.* 1994; Braun & Schmid 1999), but most were studied in greenhouses. The sap flow method has been widely used for measuring crop T under irrigation conditions (Tang *et al.* 2011); little research has been conducted under dryland conditions.

Therefore, the objectives of this study were: (1) to use the weighing method to calibrate the results determined by a packaged stem sap flow gauge in a pot experiment of maize; and (2) to analyze the T/ET of maize under dryland conditions and the relationships between the leaf area index (LAI) and T/ET.

MATERIALS AND METHODS

Site description

The field study was conducted in 2012 at the Changwu experimental station (35.28° N, 107.88° E, approximately 1,200 m above sea level) located in a typical dryland farming area on the Loess Plateau in northwestern China. The average annual precipitation in the area was 584 mm, with 466.4 mm and 307.9 mm falling between April and September (i.e., maize growth season) and between July and September (maize silking usually occurs in the middle of July), respectively. The rainfall during the spring maize growing season amounted to 480.8 mm in 2012, accounting for 91.5% of the annual precipitation. The annual average temperature is 9.7 °C, and the annual frost-free period is 171 days. The ground water table is at a depth of more than 50 m, making groundwater unavailable for plant growth. According to Chinese soil taxonomy, the soils at this site are Cumuli-Ustic Isohumosols (Gong *et al.* 2007) and contain 37% clay, 59% silt, and 4% sand with a pH of 8.4 and a bulk density of 1.3 g cm⁻³. The soil has gravimetric field water holding capacity of 20% ± 2 and gravimetric permanent wilting coefficient of 6% ± 2.

Experimental design and field management

Pot calibration experiment

A pot experiment was conducted under field conditions in 2012. The soil was transferred to plastic pots (0.3 m top diameter × 0.25 m depth), each of which contained 12 kg of air-dried soil that had been fertilized with 2.4 g of N and 1.2 g of P₂O₅; to avoid soil crusting, irrigation water was provided through a supply tube (2 cm inner diameter) that was inserted from the soil surface down to a depth of 5 cm above the bottom of the pot. Maize seeds (cv Pioneer 335) were sown on April 23. After three leaves had expanded, one viable plant was established in each pot. The pots were watered to the soil field capacity, and the soil surface was covered with plastic film to restrain soil E before the stem flow gauge was installed after the 12-leaf stage. The gauge was installed on consecutive sunny days. There were four pots with similar growth in each test. The sap flow rate was measured using the stem sap flow gauge and the leaf T rate was measured according to the weighing method as the soil water content decreased from the soil field capacity to the permanent wilting coefficient. The objective of the pot experiments was to use the weighing method to calibrate the results determined by the sap flow method, and use the gained calibration equation to correct the sap flow rate values measured by the sap flow gauge in the field experiment.

Field experiment

In this experiment, the maize was planted with wide–narrow row spacing of 60 cm and 40 cm alternating arrangement and a planting spacing of 30 cm at a density of 65,000 plants ha⁻¹ to a depth of 5 cm using a hand-powered hole-drilling machine on April 29, 2012. During the maize growing season, the soil water supply was solely dependent on rainfall. The maize was harvested on September 13, 2012. The sap flow was measured by the stem flow gauge after the 12-leaf stage. Before planting, chemical fertilizers were applied at rates of 225 kg of N ha⁻¹ in the form of urea (46% N), 60 kg of P ha⁻¹ in the form of calcium superphosphate (12% P₂O₅) and 30 kg of K ha⁻¹ in the form of potassium sulfate (45% K₂O).

Measurements and data calculation

Transpiration (T)

The T (g h^{-1}) was determined by recording the weight loss in the pot experiment at 1 h intervals with an electronic balance that was accurate to 1.0 g.

Sap flow

The sap flow (g h^{-1}) was measured by the sap flow gauge. The sap flow system used in this study was a commercially available Flow32-1 K (Dynamax, Houston, USA), and the gauge signals were recorded using a CR1000 Datalogger, including PC400 data logger support software that was programmed to measure at 15 sec intervals and to store the average values over 1 h periods. The sensor type is SGB25 in this study.

Sensors were installed at the second internode above the roots on healthy plants (without grafts or scars). The leaf at this point had previously been detached from each plant. Plastic film was placed where the gauge was installed to avoid stem T; silicon film was placed at the contact between the stem and the sensor to improve the thermal exchange between them. The sensor thermocouples faced north. Aluminum film was placed on the gauges to protect them from rainfall, dew and solar radiation. The sensors were mounted on different plants every 7 days to prevent plant desiccation resulting from the heating of the sensor (Kjelgaard et al. 1997).

The sap flow gauge was installed to measure the sap flow of maize plants in the same period and under the same soil moisture conditions to identify differences among sensors, and these differences were not significant. Therefore, the error in this study was caused by factors other than the sensors.

The scaling up of T from single plant to whole plot requires an analysis of plant variability to correctly determine the mean plant value. This analysis was accomplished based on the variability of plant stem diameter (Bethenod et al. 2000). The results showed a diameter classification in the range of 20 to 32 mm (Figure 1). The crop was sufficiently homogeneous and plants with a diameter between 28 and 30 mm represented 80% of the total plants. We considered the plants belonging to this class to represent the 'mean plant' in the field.

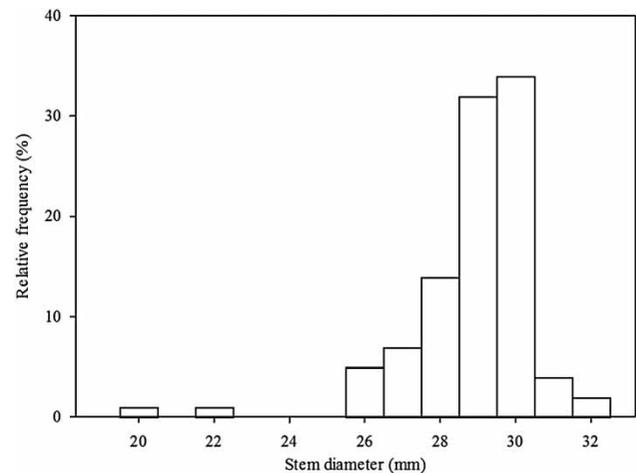


Figure 1 | Frequency distribution of the stem diameters of the maize plants ($n = 100$).

Evapotranspiration

The ET (mm) was determined by the following formula (Liu 2005):

$$ET = \Delta W + P \quad (1)$$

where ΔW is soil water depletion (mm) between planting and harvesting in a 0–300 cm soil layer, and P is the precipitation (mm) during the crop growing season. ET is the sum of soil evaporation (E) and crop transpiration (T). Since the plots are flat and surrounded by ridges, the groundwater is deep, and the surface runoff and deep drainage are usually neglected.

LAI measurement

Leaf area was calculated by multiplying the manually measured length and maximal width of leaves with a shape factor, k , empirically determined to be 0.75 for maize (McKee 1964). The LAI value was then calculated as the product of the leaf area value and plant density ($65,000 \text{ plants ha}^{-1}$), i.e., $\text{LAI} = \text{leaf area (m}^2 \text{ plants}^{-1}) \times 65,000 \text{ (plants ha}^{-1}) / 10,000 \text{ (m}^2 \text{ ha}^{-1})$. The measurements were taken approximately every 5 days.

Soil moisture content

The dynamic change of the gravitational soil moisture content (%) was determined using a neutron moisture meter

(CNC503B). There were three neutron probe tubes evenly distributed in the field. The water content in the soil profile was determined at 10 cm intervals down to 100 cm and at 20 cm intervals from 100 to 300 cm. The measurements were taken approximately every 5 days during the maize growing season.

Water use efficiency

WUE_T (g kg^{-1}) and WUE_{ET} (g kg^{-1}) were calculated by the formulas:

$$WUE_T = 0.1 \frac{Y}{T} \quad (2)$$

$$WUE_{ET} = 0.1 \frac{Y}{ET} \quad (3)$$

where Y is grain yield (kg ha^{-1}), T is transpiration (mm), ET is evapotranspiration (mm), and 0.1 is the conversion coefficient of the WUE unit from $\text{kg ha}^{-1} \text{mm}^{-1}$ to g kg^{-1} .

Shoot biomass, yield, and harvest index

At maturity, shoot biomass (kg ha^{-1}) and grain yield (kg ha^{-1}) were determined by harvesting plants. And all of the samples were dried to a constant weight by air drying. The harvest index (%) was calculated as the air dry grain yield divided by the total above-ground biomass at maturity.

Meteorological data

The meteorological data were collected at the Changwu automatic meteorological monitoring station situated within 50 m of the experimental field.

Statistical analyses

The sap flow rates measured in the field were calibrated by the regression equations obtained in the pot experiment. The means and standard deviations of all of the analyzed variables were calculated. The statistical significance of any identified differences was analyzed with a significance threshold of $p < 0.01$. The statistical analyses were performed using SPSS 13.0.

RESULTS

Calibration of the sap flow gauge

The daily weight loss of the potted maize and the sap flow are presented in Figure 2. There was a tendency for the sap flow values to overestimate the actual flow data measured by the weighing method, emphasizing the importance of testing the accuracy of the method before using it to quantify T .

The measured weight losses and the corresponding sap flow calculated according to the sap flow gauge of the potted maize did not always match on an hourly basis. This is because maize plants showed hydraulic capacitance during transpiration when water transported from roots to leaves to atmosphere. In the morning, atmospheric evaporation increased, and leaf T rose. But around noon, leaf T was lower than the sap flow transported to leaf, leaf water potential decreased, and plant water outflowed. In the afternoon, atmospheric evaporation reduced, leaf T was higher than the sap flow, and plant water inflowed.

Thus, in order to avoid hydraulic capacitance influence, the value was measured per hour for 3 days and the daily value was calculated as an hourly mean value for each day. There was a good linear relationship between sap flow and weight loss, so that an equation for correcting measured sap flow rates was determined using linear

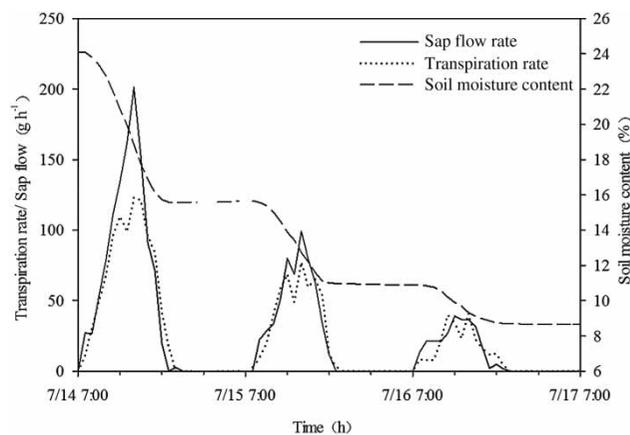


Figure 2 | Daily change of the weight loss of potted maize and sap flow as measured with the sap flow gauge from July 14 to 17, 2012.

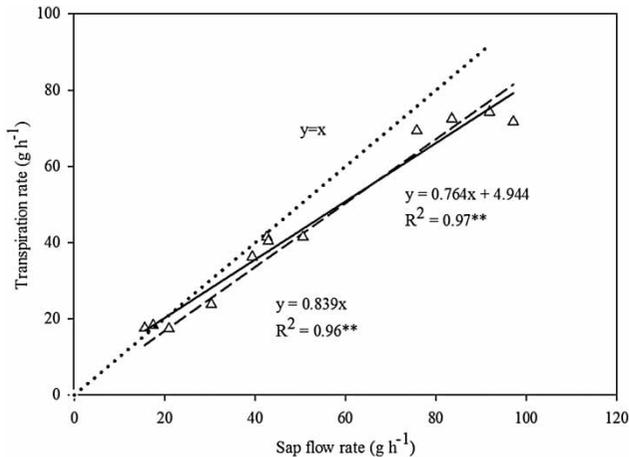


Figure 3 | Compared measured weight loss on a balance with the corresponding sap flow rate calculated according to the sap flow gauge of potted maize; statistical significance level is at $p < 0.01$.

regression. The slope of the regression lines was 0.764, the constant term was 4.944, and R^2 was 0.97 ($p < 0.01$)

Compared with the 1:1 line, at low flow rates (less than 21 g h^{-1}), the sap flow rates tended to underestimate the T, whereas at the highest flows (more than 21 g h^{-1}), the sap flow overestimated the T as a result of the omission of conductive heat losses (Figure 3).

Transpiration and ET

Using this calibration equation to correct the sap flow values in the field experiment, the cumulative T and

cumulative ET from silking to maturity are shown in Figure 4. The T was calculated by multiplying the daily accumulated sap flow per plant by a density of 65,000 plants ha^{-1} , using the equation of $T \text{ (mm)} = T \text{ (g)} \times 10^{-7}$ to change the unit of T from ' g ha^{-1} ' to ' mm '. The daily mean ET was 2.6 mm and the daily mean T was 1.6 mm. From silking to maturity, T/ET decreased by 27.6% and the average was 63.3%.

The relationship between the T/ET and LAI

From the perspective of the soil-plant-atmosphere continuum (SPAC), the variations in T, ET are influenced by meteorological factors, soil (moisture) condition and vegetation factors. We compared the T/ET and LAI to analyze their relationships. The T/ET and LAI showed a good linear relationship (Figure 5).

Grain yield and WUE

Transpiration (T) is mainly used for plant growth. The WUE_T was 3.2 g kg^{-1} , while the WUE_{ET} was 1.7 g kg^{-1} (Table 1). The T/ET of the whole growth period was 53%. The T in early season which could not be measured by the sap flow gauge was calculated by the equation in Figure 5.

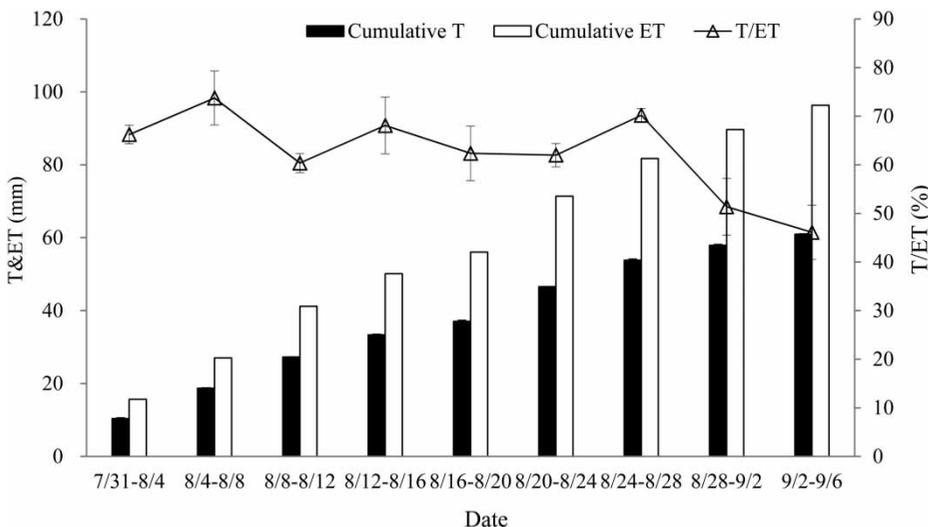


Figure 4 | Cumulative transpiration (T), cumulative evapotranspiration (ET) and T/ET of maize during the mid-late growth period (7.31–9.6, 2012).

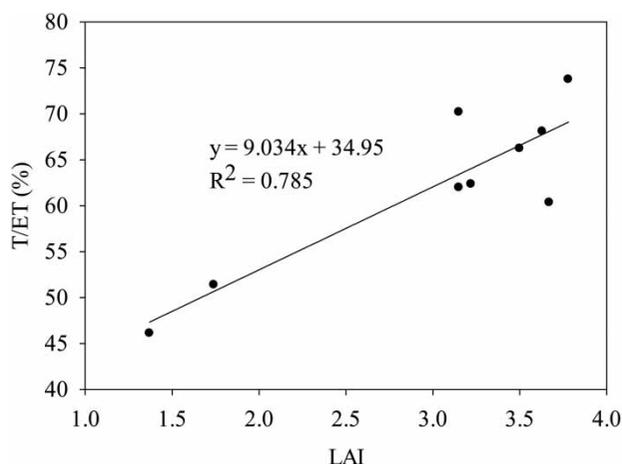


Figure 5 | Relationship between the variation in the ratio of transpiration and evapotranspiration (T/ET) and the leaf area index (LAI); statistical significance level is at $p < 0.01$.

DISCUSSION

Studies (Liu *et al.* 2002; Thomas *et al.* 2007) have used sap flow gauges directly without calibration, causing instrumental errors. Weibel & de Vos (1994) estimated that the flow's maximum deviation from the mass loss was less than 22% on potted apple trees in the Netherlands. Ishida *et al.* (1991) calibrated the sap flow results of potted sunflower, potato and maize in Japan, and considered that the reason for the error was that this method does not control the stem temperature. In this study, we also found that this error leads to erroneous estimates of T. The sap flow method overestimated T when the flow was more than 21 g h^{-1} , but provided low estimates under 21 g h^{-1} flow rates. The higher the flow rate, the greater the error. For instance, when the flow rate was 30 g h^{-1} , actual T rate was 27.86 g h^{-1} ; when the flow rate was 80 g h^{-1} , actual T rate was only 66.06 g h^{-1} . In addition, the comparison of sap flow rates on an hourly basis indicated that this sort of error was not negligible. Thus, it is important to improve the measurement accuracy of the sap flow gauge.

To resolve the problem, we calibrated the gauge by the weighing method, and the results indicated that the sap flow and T (as calculated by the weight loss on a balance) showed a good linear relationship, so that a linear equation for correcting measured sap flow rates by the sap flow method was determined. The slope of the regression lines was 0.764, and the intercept was 4.944, and R^2 was 0.97 ($p < 0.01$). Similar to this study, Li *et al.* (2013) and Braun & Schmid (1999) reported a linear relationship for spring wheat in northwestern China and potted vine in the Netherlands, respectively.

Under irrigation conditions, Zhao *et al.* (2009) demonstrated that the T/ET of maize was 79.0% during the mid-late growth period using a sap flow gauge on the North China Plain. Tang *et al.* (2011) reported that the T/ET of maize was 66.4% during the same period in Khorchin sandy land by the sap flow method too. Sun *et al.* (2005) observed that the T/ET was 61.7% to 67.7% by calculating T indirectly from measurements of micro-lysimeters on the North China Plain. Compared with the above studies, our study was under dryland conditions without irrigation in loess tableland. The result showed that the T/ET of maize was 63.3% from July to September. The T/ET was lower under dryland farming conditions. In addition, the T/ET of maize decreased in the mid and later periods of the growing season. That is presumably because as plants mature, maize leaves begin to yellow and fall, and LAI decreases, causing leaf T to reduce.

Brisson *et al.* (1992) proposed that the T/ET and LAI showed a relationship in a logarithmic function, with the equation $T/ET = 1 - \exp(-\delta \text{ LAI})$, where δ is a coefficient. Most studies under irrigation demonstrated that E/ET and LAI were related by a logarithmic function. For instance, Liu *et al.* (2002) found that the equation was described as $E/ET = 1.12 \exp(-0.34 \text{ LAI})$, $R^2 = 0.895$; Sun *et al.* (2005) showed that $E/ET = 86.616e^{-0.2079 \text{ LAI}}$, $R^2 = 0.93$; Wang *et al.* (2007) showed that $E/ET = 0.9845e^{-0.345 \text{ LAI}}$, $R^2 = 0.93$.

Table 1 | Grain yield (Y) and crop WUE

| Y (kg ha ⁻¹) | Biomass production (kg ha ⁻¹) | Harvest index (%) | T (mm) | ET (mm) | WUE _T (g kg ⁻¹) | WUE _{ET} (g kg ⁻¹) |
|--------------------------|---|-------------------|-------------|--------------|--|---|
| 7,088 ± 738 | 13,339 ± 1,356 | 48.2 ± 2.0 | 219.7 ± 6.2 | 414.5 ± 15.3 | 3.2 ± 0.1 | 1.7 ± 0.2 |

Y (kg ha⁻¹) means grain yield; T (mm) means transpiration; ET (mm) means evapotranspiration; WUE_T means grain weight in g divided by T in kg; WUE_{ET} means grain weight in g divided by ET in kg; values with different letters are significantly different at the 0.05 probability level.

Our research directly studied the relationship of maize T and ET under dryland conditions. And the results indicate that the T/ET increased linearly with increasing LAI. The equation was $T/ET = 9.034LAI + 34.95$, $R^2 = 0.785$. This is because as LAI increased, more net radiation was intercepted by the canopy, causing T to be raised.

CONCLUSION

In this study, we measured the T characteristics of maize using the stem sap flow method, calibrated the T results by the weighing method and analyzed the T/ET of maize under dryland conditions.

The results indicated that the sap flow gauge has certain errors. Therefore, it is important to calibrate the sap flow gauge and improve the precision of measurement. An equation for correcting measured sap flow rates was determined using linear regression. The slope and intercept of linear regression were 0.764 and 4.944 ($R^2 = 0.97$). Using the equation to calibrate the T of field maize, the results showed that T/ET was 63.3% from July to September, and 53% in the whole growth period. The relationship of T/ET and LAI was linear.

It was found that E was high in the early age of maize. It is necessary to restrict water loss from E, and increase T by taking adaptive measures, such as film mulching. The measures could increase LAI, improve soil water storage and water use dynamics, improve precipitation use efficiency and optimize field water management.

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