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Measurement of Cotton Transpiration

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Abstract

There are a few field methods available to directly measure water evapotranspiration (*ET*) along with its two components, evaporation from the soil (*E*) and from the crop (*T*). One such technique that measures *T*, uses sensors to calculate the sap flow (*F*) of water through the plant stem and is based on the conservation of mass and energy, *i.e.*, the stem heat balance method. This instrument consists of a flexible heater that is wrapped around the plant stem with temperature sensors to measure the difference in temperature of *F* below and above the heater. This is a null method, where all inputs and outputs are known and the calculated *F* is a direct measure of *T*. This method has been used to measure *T* in a variety of crops, including cotton, grapes, olive trees, soybean, ornamental and horticultural crops. A new version of the *EXO-Skin*™ is the *Stem Gauge Dual Channel Design* (SGDC™), which was commercially introduced and had a radically new design resulting in a different energy balance, compared to the original design, which needed experimental verification. An initial evaluation was done with potted cotton (*Gossypium hirsutum*, L.) plants in a greenhouse experiment showing that values of cotton-*T* measured with the new sensor were accurate; however, this comparison was limited to daily $T < 2$ mm/d. Thus, our objective was to expand the initial evaluation of the new sensor under field conditions and for daily values of cotton-*T* in the 2 - 7 mm/d range, representative of the semiarid Texas High Plains. For this purpose, cotton was planted on 12 June 2017 on a 1000 m^2 plot in a soil classified in the Amarillo series at the facilities of the USDA-ARS, Lubbock, TX. For a period of 15 days, 2 to 16 Sep 2017, we measured hourly cotton-*T* with the new sensors and with portable growth chambers (0.75 m × 1 m cross-section, and 1 m height) where water vapor flux was measured at a 10 Hz frequency using an infrared gas analyzer. We used three chambers and, in each chamber, the new sensors were installed on four cotton plants. We used linear regression analysis to compare hourly and daily values of cotton-*T* measured with the sap flow gauges against *T* measured by the chambers. Using a t-test ($p < 0.001$) we tested if the slope of the line was significantly different than 1 and if the intercept was significantly different than 0. Pooling all data yielded an almost 1:1 relation between values for a daily transpiration range from 2 to 7 mm/d. We concluded that the new sensor provides a robust and direct measure of hourly and daily cotton-T for a wide range of environmental conditions.

Keywords

Stem Flow Gauge, Growth Chamber, Water Use, Irrigation, Evaporation, Field Test

1. Introduction

Evaporation of water from a crop involves losses of water from the soil (E) and from the plant (T) and under field conditions the most accurate measurement of evapotranspiration ($ET = E + T$) is gravimetric by using weighing lysimeters [1] [2]. The partitioning of ET into its two components usually involves the direct measure of ET and of either E or T and may include simulation models to calculate the values of E, T, and ET throughout the growing season [3] [4]. Nevertheless, an independent measure of any two of the three terms, *i.e.*, E, T and ET, are needed as the unknown value can then be determined by difference. The direct measure of T under field conditions is a challenge and knowledge of this value throughout the growing season is important to manage both irrigation and plant productivity [4] [5]. Further, knowledge of T can also be used to evaluate the water use efficiency of a cropping system by determining the crop yield per unit of T [4] [5].

The direct measurement of ET under field conditions can be done by a variety of methods that include stem flow gauges [6] [7] [8], growth chambers [9] [10] [11], weighing lysimeters [1] [2] [12], and micrometeorological methods such as Eddy Covariance [13] [14], and Bowen ratio [15] [16]. Of these methods, and under field conditions only the stem flow gauge is available for routine measurement of T and can also be integrated as a tool for irrigation management [5]. In reality, lysimeters and micrometeorology are field methods mainly used to measure ET, although micro-lysimeters may be used to measure E and T is calculated by difference, *i.e.*, $T = ET - E$ [3] [4].

The measurement of transpiration with stem flow gauges is based on the principles of conservation of mass and energy and it is considered a null method, *i.e.*, all inputs and outputs are known. The sensor operates by applying a known amount of heat via a flexible heater that surrounds the stem that is well insulated. The method of operation is known as the Stem Heat Balance (SHB) as given by [6] [7]. The SHB method has been extensively used and tested in a variety of agricultural crops, e.g., in grapes by [17], in olive trees by [18], in woody plants by [19], in cotton by [8] [20], and soybean by [21] [22], as well as on other crops.

The general consensus is that the SHB method provides a direct and accurate measure of plant *T*.

The SHB as given by [6] was used to design stem flow gauges patented in 1993 and 1994, by [23] [24] and sold by a commercial company (Dynamax Inc., Houston, TX, USA). In 2013, a new patent was filed [25] introducing a new design of a stem flow gauge but still based on the SHB. The new design included a different heater, insulation material and wire positions for thermocouples. Further, the location and number of thermocouples were grouped to make fewer connections and a more accurate differential temperature to calculate water flux temperature increase. The new sensor was named the *Exo-Skin*™ *SGDC*™ *Sap Flow Sensor* [25] and as pointed by [8] there were significant changes from the original stem flow gauge design that warranted experimental verification of *T* measured with the new sensor. For this reason cotton-*T* measured with the *Exo-Skin*™ *SGDC*™ were compared to *T* values measured with lysimeters in a greenhouse experiment [8]. The results of this test indeed showed that the *Exo-Skin*™ *Sap Flow Sensor* provided an excellent measure of cotton-*T*; however, the greenhouse experiment only resulted in daily values of cotton-*T* < 2 mm/d. Thus, we needed to test the new sensor for higher daily *T* values of cotton in the 4 - 7 mm/d range, which are typical for the semiarid Texas High Plains [3] [5]. The immediate challenge was the selection of method, under field conditions, to independently measure *T* and compare to values measured with the new stem flow gauge design.

As previously noted, there are three methods that could be used to measure field-cotton *ET*: lysimeter, growth chambers and micrometeorological. Of these, micrometeorological methods, e.g., Bowen ratio and Eddy Covariance are not practical. Lysimeters are the most accurate measure of crop *ET*; however, the type of lysimeter needed for this comparison must be of a relatively large soil volume (~5 m^3) with a profile depth (~2 m) to accommodate the root development of a crop under field conditions. This type of weighable lysimeters is available and measures *ET* with accuracies better than 0.05 mm [12] [26] [27] [28]. However, installation is expensive and requires maintenance that is laborious, which adds to the cost of operation. Conversely, growth chambers provide an alternative and less expensive method to measure whole plant *ET* under field conditions. Field growth chambers may be a fixed structure or portable and are classified as either open or closed systems [9]. Open systems measure the canopy gas exchange of CO_2 and H_2O from the difference between the input and output of gas concentrations through the chamber. In a closed system, water transpired raises the chamber humidity and this water is condensed, usually on chilled, refrigerated coils, to maintain a specific humidity set point. The water removed is *T* or *ET* depending on operational procedures [29]. Therefore, of the three available methods we selected portable growth chambers of the type designed and tested by [9] [10] [11] to measure whole plant canopy *T*.

The objective of this work was to expand our initial test [8] and evaluate the

Exo-Skin™ *SGDC*™ *Sap Flow Sensor* for larger values of *T*. Specifically, we wanted to compare hourly and daily values of cotton-*T* measured with the new sensor to values of *T* measured on the same cotton plants with portable growth chambers and under field conditions.

2. Materials and Methods

Herein, we present a follow-up of the initial evaluation of a new stem flow gauge sensor described by [8]. For additional and detailed information, the reader is referred to the patent describing the new stem flow gauge [25], and to the design of the growth chambers [9] [10] [11].

2.1. Field Experiment

The field work was done at the facilities of the United States Department of Agriculture-Agricultural Research Service (USDA-ARS), Cropping Systems Research Laboratory in Lubbock, TX (33˚35'38.7"N, 101˚53'51.9"W, 987 m above sea level). The soil of the experimental area is classified in the Amarillo soil series (fine-loamy, mixed, Thermic, Aridic Paleustalf) and soil physical and hydraulic properties are given by [30].

Cotton (*Gossypium hirsutum*, L.) cultivar Fibermax 9180 (BASF Corporation, Florham Park, NJ) was planted on 12 June 2017 (Day of Year, DOY = 163) on raised beds 1.02 m apart oriented North to South and after emergence, cotton seedlings were thinned to about 7 plants/m. The experimental plot was 1000 m^2 (20 × 50 m) and irrigated by a surface drip system with emitters on each planted row. The cotton was irrigated throughout the growing season and fertilized following local practices.

Three portable growth chambers (0.75 × 1 m in cross-section and 1 m in height) as shown in figure 1 in [9] and in figure 1 in [10] were used in our experiments. In this experiment, air was pushed through the system and air flow rate was measured at the entrance. The advantage of pushing the air through the chamber system is that this causes a slight positive over-pressure inside the chamber and thus eliminates the need for sealing the soil surface with a plastic barrier to prevent soil gases (including water vapor from the soil) from contaminating the chamber atmosphere and over estimating *T*. In previous experiments with these chambers, air was pulled through the chambers with the soil surface tightly sealed [9] [10]. The three chambers were placed on East, Central and West locations within the experimental plot, at ~5 m apart from each other. In each chamber, we installed four stem flow gauge sensors (SGDC-7 and SGDC-10 *Exo-Skin*™ *Sap Flow Sensors*, Dynamax, Houston, TX) on individual cotton plants. The sap flow sensor installed depended on the stem diameter as measured with a micrometer caliper. The two models of sap flow sensors used accommodated stem diameters between 6.5 and 13 mm. The sensors were installed following guidelines given by Dynamax as shown in a video (http://www.dynamax.com/technical-center/videos-and-tutorials/transpiration-s ap-flow) and as described by [8].

The three growth chambers, East, Central and West, each with four sap flow sensors were installed and prepared for data collection on the 30 August 2017 (DOY = 242). The first 48 hours were used to troubleshoot data collection from the sap flow sensors and growth chambers. Specifics on data collection with the sap flow sensors and growth chambers are given in the following sections. In the Central chamber we only used three sap flow sensors for our calculations of cotton-*T* due to the malfunction of one of the sensors.

Data collection started on the 2 Sep 2017 (DOY = 245) and ended on the 16 Sep 2017 (DOY = 259), *i.e.*, data was collected across 15 consecutive days. To obtain a wide range of cotton-*T*, the experimental plot was irrigated at nighttime with ~25 mm of water two days prior to data collection on the 30 Aug 2017 (DOY = 242), with ~25 mm on 8 Sep 2017 (DOY = 251), and with ~15 mm of water on the 9 Sep (DOY = 253).

On the 19 September 2017 (DOY = 262), all cotton plants within each growth chamber were harvested and for each plant, leaf area, dry aboveground biomass (stems and leaves), number of bolls, number of open balls, dry mass of boll and seed mass of cotton were recorded and measured. The cotton leaf area was measured with a benchtop leaf area meter (Li-3100C, Li-Cor, Inc., Lincoln, NE).

2.2. Stem Flow Gauge Sensor

In this section we give a brief description on the principles of operation of the *Exo-Skin*™ *SGDC*™ *Sap Flow Sensor* used in our experiments and how values of transpiration were calculated from measured parameters. For additional information see [8] [25].

The energy balance of a heated stem is given by the following equation:

$$P-\left(q_a+q_r+q_c+S\right)=0, \tag{1}$$

where P is the power (heat flux) applied to the heater, q_a is the axial heat loss, q_r is the radial heat loss, q_c is the convective heat loss, and S is a storage term. The axial heat loss q_a has an upward (q_u) and downward (q_d) flow of heat along the axis, such that $q_a = q_u + q_d$. In general and for small plants, the magnitude of S is small compared to other terms in Equation (1) and thus assumed to be zero. An exception to this rule is when the SHB is used to measure the T of large trees [31]. All terms in Equation (1) have units of power, W.

The new sensor is based on the SHB method and due to a modification on the placement of thermocouples to measure the differential temperature (dT) resulted in a different energy balance equation compared to the original design. An example of several thermocouples threaded with constantan copper wire and used in the new design is shown in figure 2 in [8]. This is an example of a sensor that can accommodate plant stems within a 9 to 13 mm diameter, *i.e.*, model SGDC-10 [25]. In the new design, the measurement of a single and averaged value of the difference in temperature of the sap flow above and below the heater,

$dT_{u,d}$ is read by one channel, eliminating the need to individually calculate the vertical axial conduction (q_a), with its upward (q_u) and downward (q_d) flow of heat. Significant is that the thermocouples are angled to the stem tangent and measure the two opposite sides of the heated axial temperature rise, and thus these measurements are more representative of the temperature increase. Another result of the thermocouple placement is that all energy losses by conduction are grouped into a single value of q_c, which is calculated from the radial thermopile representing all heat conduction in and out of the stem. The thermopile signal is the second of the two channels in the Dual-Channel SGDC^{TM} design. It has been shown [25] that in the new sensor the axial (q_a) heat loss was about 10% to 20% of the radial (q_r) heat loss, and that when the two variables were combined into a single variable $q_f = q_a + q_r$, lead to a valid energy balance with only two terms compared to Equation (1), as follows:

$$P - \left(q_c + q_f\right) = 0. \tag{2}$$

As with the previous sensor design, the sheath conductivity (K_{sh}) was calculated assuming that the flux of water through the stem is zero at dawn and is calculated by:

$$K_{sh} = P/E\ , \tag{3}$$

where E is the input emf voltage (V) from the thermopile. In the new sensor, heat from conductivity is all derived from radial flow including any increase in K_{sh} due to the grouping of q_a and q_r into a single variable. By design in the new sensor the higher K_{sh} means that the vertical (axial) heat conduction q_a is included in q_c, resulting in a representative conductance term in the energy balance. Therefore, dT (˚C) is calculated from the average temperature (A_h and B_h in mV) measured with two thermocouples (type T-thermocouple, converted with 0.040 mV/˚C) as:

$$dT = \left(\frac{A_h + B_h}{2}\right) \Big/ 0.040. \tag{4}$$

The sap flow through the stem (F) as measured with the new sensor reduces to:

$$F = \left(P - q_c\right) \Big/ \left(dT \times C_p\right), \tag{5}$$

where F is the mass flux of water (kg/s), and C_p is the volumetric heat capacity of water (J/kg ˚C). This equation shows that the flow of water through the stem is calculated from three parameters: the power provided by the heater (P), the convective heat loss (q_c) and the average difference in temperature above and below the heater (dT). The calculation of F in the new design is a drastic simplification of the calculation of F for the original design as given by Equation (6) in [8]. Added simplification is that P, the power input, was measured as the input voltage (V_{in}) from the adjustable voltage regulator supply (AVRS) supplied by the datalogger to all four sensor cables. Setting in the agrisensors.net web site contained the heater resistance (R_h) and then we applied the AVRS signal,

$P_{in} = V_{in}^2 / R_h$. Therefore, each of four sensors were measured by the datalogger with eight channel connections in four sensor cables, and power was measured internally by the datalogger.

The output from each stem of the four flow gauge sensors was recorded with a datalogger (SapIP, Mesh Network Research Logger, Dynamax, Inc., Houston, TX). Signal data was fed by wireless network to the Agrisensors.net web site, and calculated on the cloud server with the algorithm, Equations ((2) to (5)). Output from each stem flow gauge sensor was sampled on a 3-minute interval, averaged and recorded internally and transmitted to Agrisensors.net on a 15-minute basis over the measurement period. Then mass flow was calculated concurrently on reception by the Agrisensors.net server.

Each growth chamber had four cotton plants with the new stem flow gauge sensors and the output from each sensor, units of mass of water per unit time (kg/s), as obtained with Equation (5) was divided by the corresponding measured leaf area of the cotton plant and assuming a water density of 1000 kg/m^3 yielded for each hour, cotton-T per unit leaf area, with units of mm/h. Then, by factoring the average plot leaf area index (LAI, m^2 leaf area/m^2 ground area) and multiplying by the sap flow we obtained units of mm/h as suggested by [17] [20]. These values represent the normalized transpiration per unit leaf area [20].

The average plot LAI was calculated from the average measured leaf area of all cotton plants in each of the three CETA chambers as given by [20]. To do so we divided the measured leaf area in m^2 by the row spacing of 1.016 m that gives a land area 1.03 m^2. For the average plot LAI we used the measured leaf area of 7 cotton plants in the East chamber, 8 cotton plants in the Central chamber and 7 cotton plants in the West chamber.

In these calculations we assumed that the leaf area over the 16-d measurement period remained constant and that plant-T between 9:00 PM and 6:00 AM (Central Daylight Time) was zero. Sunrise for this location was about 7:30 AM and sunset was about 8:00 PM. Further, for each chamber the average hourly and corresponding standard deviation, cotton-T was calculated from the four (n = 4) measured values, except for the Central chamber where n = 3, due to the malfunction of one of the sensors.

2.3. Growth Chamber

We used chambers designed and tested by [9] [10] [11]. These chambers were designed to monitor whole canopy carbon dioxide and water fluxes of crop fields and are known as CETA chambers, which is an abbreviation for **C**anopy **E**vapo-**T**ranspiration and **A**ssimilation chamber. The chambers are 0.75 × 1 m in cross-section and 1 m height. They are constructed of aluminum framework covered in a transparent material and are portable. The gas exchange was measured with an infrared gas analyzer (IRGA) (LI-7000, Li-Cor, Inc., Lincoln, NE) operating in absolute mode to measure both entrance and exit mole fractions of CO_2 and H_2O in the air sample stream. In this experiment we are only concerned with the water flux measurements, used to calculate transpiration. Measurements of H_2O concentration were collected at a frequency of 10 Hz using a datalogger (CR-3000, Campbell Scientific, Inc., Logan, UT) that averaged and recorded the IRGA readings for the last 5-s of each 10-s time interval. These values were used to calculate hourly values of water flux from the cotton plants in each CETA chamber. For additional details see [9] [10] [11].

The canopy transpiration rate [T, mol (H_2O)/(m^2 s)] in a flow through open system was calculated with [32]:

$$sT = u_o w_o - u_e w_e \tag{6}$$

where s is the measured cotton leaf area (m^2) of all plants in the chamber; u_e is the incoming chamber air flow rate (mol (air)/s) and u_o is the outgoing chamber air flow rate (mol (air)/s); w_e is the incoming mole fraction of water vapor flow (mol (H_2O)/mol air) and w_o is the outgoing mole fraction of water vapor flow (mol (H_2O)/mol air). In the current setup, as given by [9], air is pushed through the CETA chamber and the airflow rate was measured at the entrance (u_e). The canopy transpiration T adds water molecules to the air stream, such that $u_o > u_e$ and thus the outgoing flow u_o is given by:

$$u_o = u_e + sT. \tag{7}$$

The transpiration from the canopy T was obtained by combining Equation (6) with Equation (7) and rearranging terms as follows:

$$T = \frac{u_e\left(w_o - w_e\right)}{s\left(1 - w_o\right)}. \tag{8}$$

As with the stem flow gauges the T between 9:00 PM and 6:00 AM was assumed to be zero and cotton-T was expressed on a leaf area basis using the measured leaf area data from the final destructive sample. Further, the value of cotton-T measured with the CETA chamber includes the evaporation of water from the soil (E). However, this value is small, *i.e.*, $E \ll T$, as shown by [3] for a cotton crop in the Texas High Plains. Further, E in the chamber is minimized by pushing air through the system creating a small overpressure. Also, during the measurement period the majority of the soil surface remained dry except for the area surrounding the drip emitter immediately after irrigation.

There are only two environmental setpoints used in the CETA chambers. The first one is the CO_2 enrichment setpoint that is not applicable as it was not used in this study [11]. The second setpoint, is the air flow rate through the chamber [9]. A faster air flow rate is set for daytime hours and a slower rate is set for nighttime periods as suggested by [11]. In either case the average flow rate through the chambers is given as moles of air adjusted for temperature in the gas exchange equations. Also, we have a variable flow rate in m^3/s calculated and recorded by the data logger, that when divided by the CETA chamber surface area (0.75 m^2), gives the air flow rate in m/s inside the CETA chamber.

2.4. Statistical Analysis

All data analysis and statistics were done using a spreadsheet program (Microsoft® Excel for Mac, version 16.16.2) and a statistics software program (JMP® for Mac, version 14). All significance tests used a level of $p < 0.001$ unless otherwise specified. In our statistical analysis we designated the values measured with the CETA chambers as our independent variable and the values measured with the stem flow gauge as our dependent variable and we used linear regression to compare the two values as given by [33]. Linear regression, *i.e.*, $y = mx + b$, analysis of hourly values of cotton-T measured with the sensor (y) and the CETA chamber (x) were done for each chamber and slope (m) was tested for $\neq 1$ and intercept (b) was tested for $\neq 0$ using a t-test as previously done by [8] [33].

3. Results and Discussion

The experimental results comparing measured values of cotton-T obtained with the *Exo-Skin*™ *SGDC*™ *Sap Flow Sensor* and CETA growth chambers are given for hourly and daily values across the 16-day period, from DOY 245 to 259, 2017. The initial evaluation was given by [8] where cotton-T values were compared for daily $T < 2$ mm/d.

Measured values of leaf area and stem diameters for each cotton plant in each of the three CETA chambers are given in **Table 1**. The East and West chambers had 7 cotton plants and the Central chamber had 8 plants. The coefficient of

Table 1. Measured leaf area and stem diameter for each cotton plant in the East, Central and West CETA chambers. Given are the sum, calculated average, and standard deviation (SD) and coefficient of variation (CV) of the average leaf area. Also, given is the calculated leaf area index (LAI) for the field plot. The plants with a stem diameter had flow gauges (SGDC-7 and SGDC-10) sensors installed.

Plant #	East		Central		West	
	Leaf Area (cm^2)	Stem Diameter (mm)	Leaf Area (cm^2)	Stem Diameter (mm)	Leaf Area (cm^2)	Stem Diameter (mm)
1	1738	8.5*	2002	9.9	1294	10.2
2	2520	10.7	2220	10.9	2876	11.5
3	2029	9.6	1775	8.3*	1871	9.8
4	1313	7.9	1439	8.6	1167	8.4
5	454		1717		1768	
6	109		1857		1209	
7	1708		1710		1968	
8			530			
Sum (cm^2)	9870		13,249		12,154	
Average (cm^2)	1410		1656		1736	
SD	859		509		601	
CV (%)	61		31		35	
LAI (m^2/m^2)	0.96		1.28		1.18	

*Excluded from calculations due to malfunction of the sensor.

variation (CV) of the measured cotton leaf area was 61% for the East, 31% for the Central and 35% for the West chamber, which are typical values of CV of leaf area for cotton plants grown under field conditions [3]. To accommodate the measured range of stem diameters (7.9 - 11.5 mm) we used two models of the *Exo-Skin*™ *Sap Flow Sensor, i.e.*, the SGDC-7 and SGDC-10.

The main objective of this experiment was to evaluate the *Exo-Skin*™ *SGDC*™ *Sap Flow Sensor* to measure cotton-*T* for typical daily values in the 4 - 7 mm/d range [5]. For this purpose, we compared hourly and daily values of cotton-*T* measured with the *Exo-Skin*™ *SGDC*™ *Sap Flow Sensor* to values measured with the CETA chambers. The t-test comparison, between the two values, showed no difference of slope and intercept ($p > 0.05$) and thus all measured data were pooled and the intercept was forced through the origin, *i.e.*, $y = m(x)$. A summary of the linear regression analysis comparing hourly values of cotton-*T* measured with the stem flow gauge sensor and chambers are given in **Table 2**.

A plot of pooled data, from all three CETA chambers, of hourly cotton-*T* obtained with the stem flow sensor as a function of the corresponding measured value obtained with the CETA chamber is given in **Figure 1**. Also shown is the standard deviation of the mean calculated from the four stem flow gauge measurements in each chamber.

Values plotted and shown in **Figure 1**, indicated no significant differences between the two measured values of cotton-*T* (**Table 2**). The majority of measured values of *T* with the stem flow gauges were within one standard deviation of the mean value measured with the CETA chamber. In this comparison, where values of *T* measured with a stem flow gauge sensor are given per unit leaf area,

Table 2. Linear regression analysis comparing hourly measured values of *Exo-Skin*™ *SGDC*™ *Sap Flow Sensor* *T* (y) as a function of corresponding measured value for each growth chamber (x) and for pooled data of all three CETA chambers. Given are the number of observations (n), slope (m), intercept (b) and coefficient of determination (r^2) for a linear regression ($y = mx + b$) and when setting intercept to the origin, *i.e.*, to 0, $y = mx$.

Linear Regression ($y = mx + b$)				
CETA Chamber	n	Slope (m)	Intercept (b)	r^2
East	140	0.981a*	0.011a*	0.96
Central	140	1.035a	−0.0105a	0.96
West	140	1.030a	−0.0141a	0.96
Pooled	420	1.004a	−0.003a	0.97
Linear Regression ($y = mx$)				
East		0.997a		0.96
Central		1.000a		0.96
West		0.997a		0.96
Pooled		0.998a		0.97

*a indicates not significant different than a 1:1 relation which has a slope of one and an intercept of zero, using a t-test ($p < 0.001$).

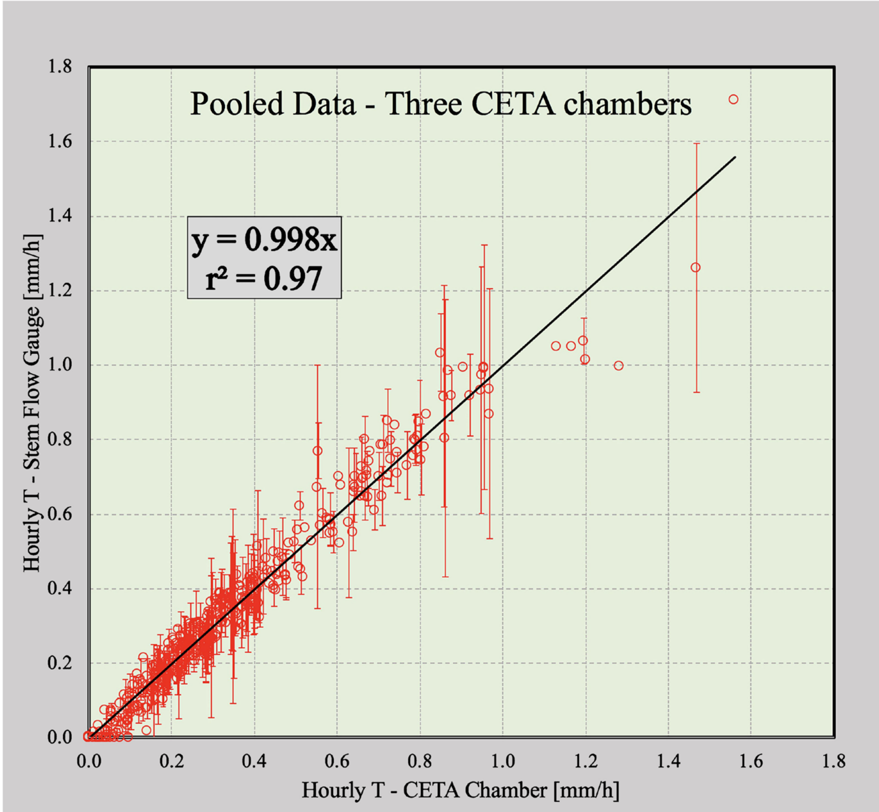

Figure 1. Pooled hourly average values of cotton-*T* measured with the *Exo-Skin*™ *SGDC*™ *Sap Flow Sensor* as a function of corresponding value measured with the CETA chamber. The values of the stem flow are the average of 4 measurements ± 1 standard deviation (SD). For clarity only half the values of SD are plotted. Given is the equation of the line, forced through 0 and data plotted is from all three CETA chambers.

i.e., mm/h, rather than with units of mass flow of water unit time, *i.e.*, g/h, tend to diminish the variability from plant to plant as shown by [8] [17] [20]. From this result we can conclude that the average hourly values of cotton-*T* measured with the *Exo-Skin*™ *Sap Flow Sensor* were not significantly different ($p < 0.001$) than the corresponding value measured with the CETA chamber.

As an example of hourly measured cotton-*T* throughout the 16-day measurement period with the *Exo-Skin*™ *Sap Flow Sensor* for cotton plants in the Central CETA Chamber are given **Figure 2**. Also as an example, an hourly comparison of cotton-*T* measured with the stem flow gauge and CETA chamber or two days, DOY 257 and 258, for the plants in the Central CETA chamber are given in **Figure 3**. The integrated hourly cotton-*T, i.e.*, daily transpiration values for the stem flow gauges and CETA Central chamber for the 16-day period are shown in **Figure 4**.

The hourly average values of *T* (**Figure 2**) show a typical pattern for cotton plants throughout the day where *T* increases in the morning hours to a peak value around solar noon and thereafter gradually decrease [3] [20]. The maximum hourly value measured with the sap flow gauges decreased from 0.4 mm/h

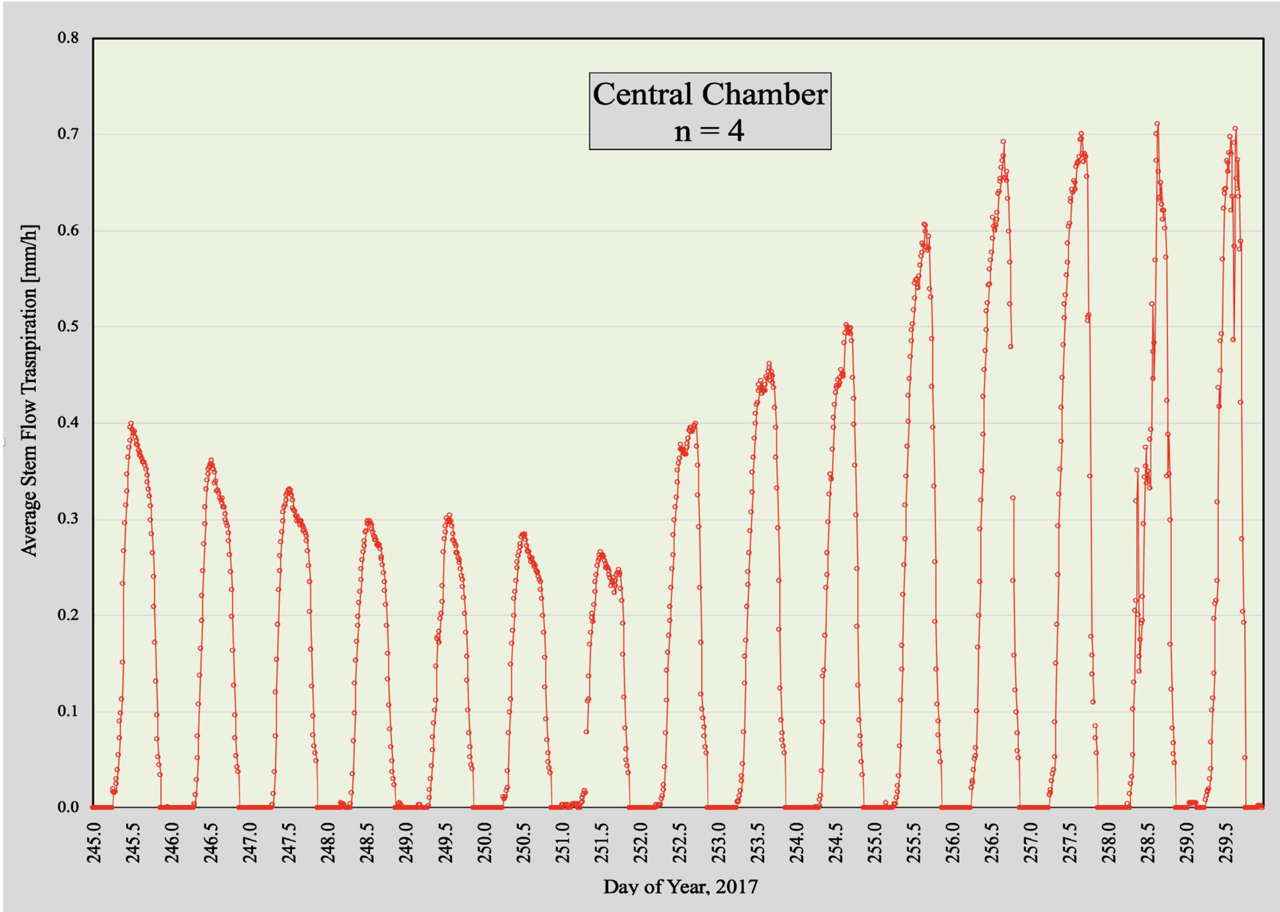

Figure 2. Hourly measured values of cotton-*T* obtained with the *Exo-Skin*™ *SGDC*™ *Sap Flow Sensor* in the Central CETA chamber for a period of 16 days from DOY 245 to DOY 259, 2017. The values plotted are the average of four measurements.

on DOY 245 to about 0.25 mm/h on DOY 251 and illustrates the gradual decline of transpiration during the first 7 days. On the evening of DOY 251 and DOY 252, the plants were irrigated and as a result the peak hourly-T increased from 0.4 mm/h on DOY 252 and increased to 0.7 mm/h during the last three days (DOY 257 - 259).

An hour-to-hour comparison of cotton-*T* for DOY 257 and 258 measured with the stem flow gauge and the Central CETA chamber are given in **Figure 3**. On DOY, 257, the hourly transpiration increases, from 0 mm/h at 06:00 hours to about 0.7 mm/h at 12:00 hours, at a rate of about 0.1 mm/h, and declines in the afternoon hours. The effect of clouds closing stomata can be seen in the morning hours of DOY 258, where the hourly cotton-*T* increases to 0.2 mm/h at 9:00 hours and declines to 0.15 mm/h in the next two hours and thereafter increases to 0.7 mm/h at noon. The interesting pattern is that in most cases the average value of cotton-*T* measured with the stem flow gauges is within one standard deviation of the value measured with the CETA chamber.

Daily values of cotton-*T* measured with the stem flow gauge and the CETA chamber for the 16-d period in the Central chamber are shown in **Figure 4**. To

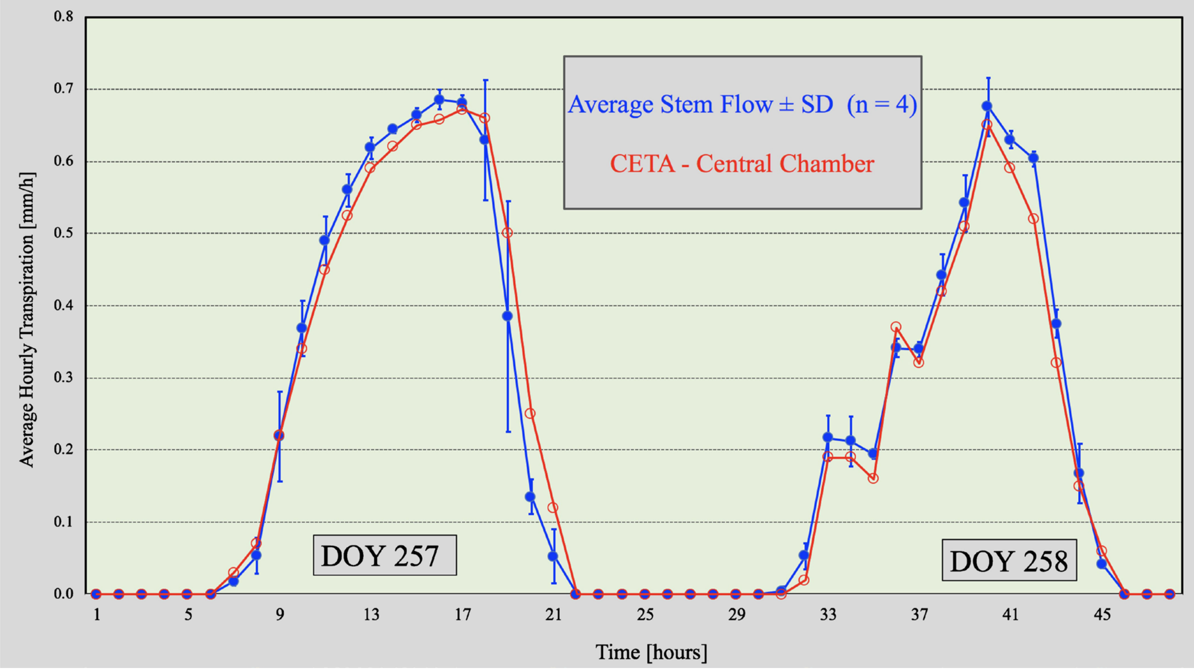

Figure 3. Hourly average values of cotton-T measured with the *Exo-Skin*™ *SGDC*™ *Sap Flow Sensor* and plants in the Central-CETA chamber on DOY 257 and 258, 2017. The stem flow values plotted are the average of 4 measurements ± one standard deviation (SD).

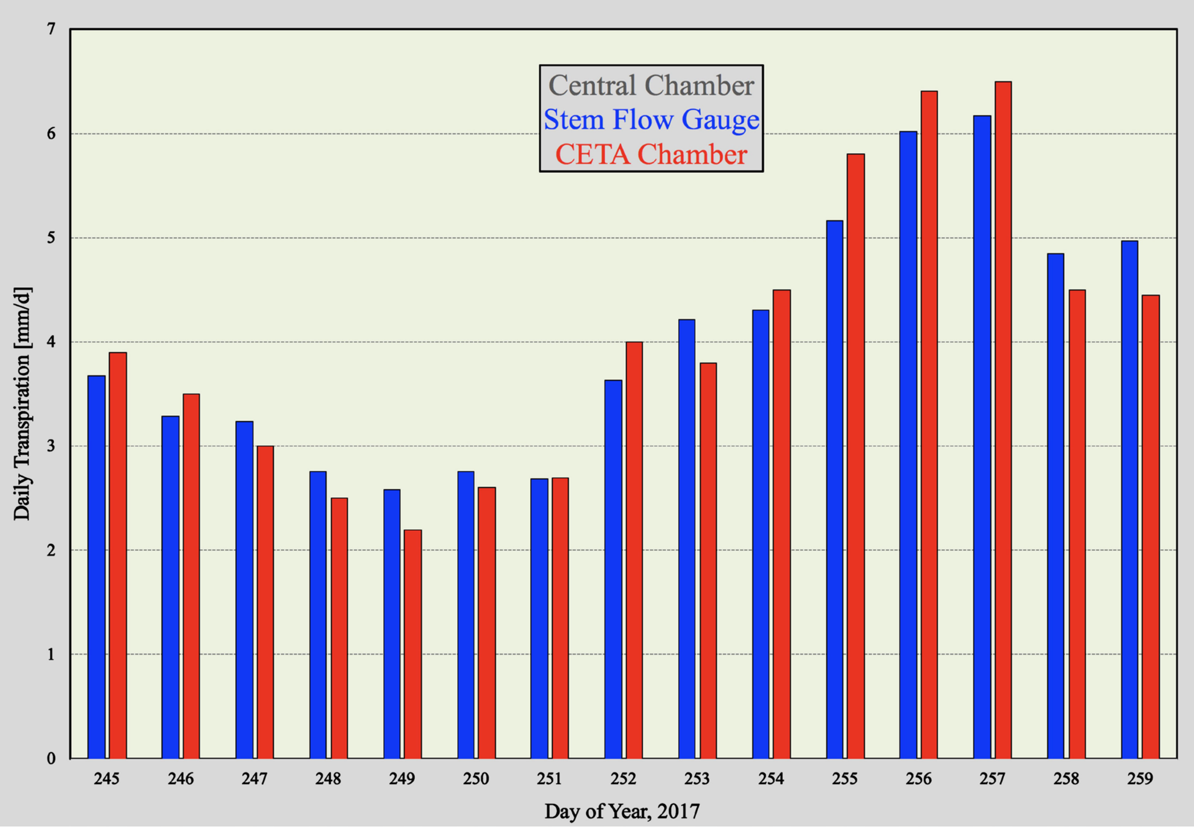

Figure 4. Daily values of cotton transpiration measured with the *Exo-Skin*™ *SGDC*™ *Sap Flow Sensor* and the Central CETA growth chamber for a period of 16 days from DOY 245 to DOY 259, 2017. The cotton crop was irrigated on DOY 251 and DOY 252.

establish a wide range of transpiration, the experimental plot was irrigated three days prior to data collection, on DOY 241 and again on DOY 251 and DOY 252. The daily cotton-*T* during the initial 7-days decreased from about 4 mm/d on DOY 245 to 2.5 mm/d on DOY 249, an indication that the cotton plants were water stressed. On the night of DOY 251 and DOY 252 the cotton plants were irrigated and subsequently the daily cotton-*T* increased to a maximum value of 6.5 mm/d on DOY 256 and 257. A similar pattern was observed in all three CETA chambers. These values are representative of cotton-*ET* in the Texas High Plains [3] [5]. The cumulative water used by the cotton plants in this 16-day period was 60 mm for the stem flow and for the CETA chamber.

In this experiment we compared hourly values of cotton-*T* measured with *Exo-Skin*™ *SGDC*™ *Sap Flow Sensor* to corresponding values measured with CETA chambers. This comparison confirmed the results from the initial evaluation given by [8] for daily *T* values of <2 mm/d in that the new sensor provides an accurate measure of cotton-*T*. The design of the new sensors, based on the stem heat balance method of [6] provides an accurate measure of cotton-*T*. The new sensor, compared to the original design, uses less wiring and copper connectors and the number of channels used to record the signal in a data-logger is reduced by 50% [25]. Further, the new design of the stem flow sensor has a different number of thermocouples and their placement to measure the difference in temperature of the sap flow above and below the heater is different from the original design. These modifications resulted in a different energy balance equation used to calculate the sap flow (*F*) through the stem as given by Equation (5). An obvious improvement of the *Exo-Skin*™ *SGDC*™ *Sap Flow Sensor* is the flexibility of the heater that gives better contact between the plant stem and the thermocouples used to measure the temperature difference above and below the heater.

Results from this field experiment showed that the measurements of hourly values of cotton-*T* under field obtained with the *Exo-Skin*™ *SGDC*™ *Sap Flow Sensor* were the same as the values obtained with CETA chambers on the same plants. There were no statistical differences between the two measurements (**Table 2**) over a wide range of environmental conditions that yielded daily values of cotton-*T* in the 2 - 7 mm/d range. The design of the new *Exo-Skin*™ *SGDC*™ *Sap Flow Sensor* with a new energy balance to calculate sap flow provides an accurate method to directly measure plant *T* across a wide range of environmental conditions.

4. Summary and Conclusions

The initial evaluation of the *Exo-Skin*™ *SGDC*™ *Sap Flow Sensor* was conducted on potted cotton plants, weighed with lysimeters, in a greenhouse experiment that resulted in daily values of cotton *T* < 2 mm/d [8]. We needed to further verify the performance of the new sensors for higher values of daily transpiration and for this purpose we designed a field experiment to measure cotton-*T* using the portable growth CETA chambers designed by [9] [10] [11]. We used three CETA chambers and in each chamber, we installed four *Exo-Skin*™ *SGDC*™ *Sap Flow Sensor* to four of the cotton plants in each chamber. Hourly measurements of cotton-*T* for a period of 16 days were collected and compared between the two systems. The statistical comparison indicated no significant differences between the two values of measured hourly *T*, which leads us to conclude that the design of the new stem flow gauge sensor [25] produces robust measures of sap flow, which is a direct measure of transpiration, for a wide range of environmental conditions.

The direct measure of plant *T* under field conditions is a difficult value to obtain and the *Exo-Skin*™ *SGDC*™ *Sap Flow Sensor* provides a simple and economical method to obtain this value. This new sensor is based on the stem heat balance method given by [6] and the resulting energy balance to calculate the sap flow through the stem is a simplification of the original design. The new sensor requires less wiring and copper connectors and uses 1/2 less channels to record the signal in a data-logger. The flexibility of the heater used in the new design results in better thermal contact with the plant stem and the thermocouples more accurately measure temperature differences above and below the heater.

Results showed that the *Exo-Skin*™ *SGDC*™ *Sap Flow Sensor* provides an accurate measure of plant *T* as tested with cotton plants in a field experiment for values of *T* in the 2 - 7 mm/d range. Sensors that are based on the stem heat balance method and are used to measure plant transpiration provide an accurate and direct measure of a value that can only be achieved by using large weighing lysimeters. These *Exo-Skin*™ *SGDC*™ *Sap Flow Sensor* provide a tool that can be used for a variety of field applications to optimize irrigation and plant productivity.

Declarations

Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the US Department of Agriculture. The USDA is an equal opportunity provider and employer.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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