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Final Report

New Technology for Measuring Sap Flow and Transpiration in Agricultural and Native Ecosystems*

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Summary

A new type of sap flow gauge was developed to measure whole-plant transpiration using a modified heat pulse technique. Gauges were fabricated using 3D-printing technology and low cost electronics to keep the materials cost under $25 per gauge. Each gauge consisted of several small-diameter needle probes fastened to a 3D printed frame. Once attached to the plant, the needles penetrated to a depth of 4 to 6 mm into the stem. One needle contained a resistance heater to provide a 6 to 8 second heat pulse while the other probes measured the resultant temperature increase at several distances from the heat source for 180s. The data acquisition and control system for the gauges was built from a low-cost Arduino microcontroller. The system read the gauges every 10 minutes and stored the results on a SD card. Different numerical techniques were evaluated for estimating sap velocity from the heat pulse data. Prototype gauges were tested in the greenhouse on containerized corn and sunflower. Sap velocities measured by the gauges were compared to independent gravimetric measurements of whole plant transpiration - the potted plant was placed on a balance and the change in mass automatically recorded with a laptop computer. Typical midday sap flow rates were 150 to 250 g/h for corn and 300 to 400 g/h for sunflower. Results showed strong correlation between sap velocity and transpiration, which allowed development of calibration factors to convert measured velocity (mm/s) to mass flow (g/h, i.e., transpiration). Once calibrated for a specific design and plant species, the gauges could typically measure transpiration within +/-5 % when flows were greater than 20 g/h. The gauges were also tested in the field on irrigated corn near physiological maturity. Results showed good agreement between canopy transpiration measured by the gauges and reference crop ET calculated from weather data. A secondary goal was to use the heat pulse information to automatically determine the thermal properties of the stem, which should be strongly affected stem moisture content (i.e., water stress). A parameter estimation technique was developed to fit a numerical model to the heat pulse time-series and approximate stem thermal properties. While successful, it proved difficult to detect the small changes in stem thermal properties that occurred gradually as water stress developed. More research is needed to use the gauges as a method to track water stress. Nevertheless, the current version of the technology could have many practical uses to better quantify crop water use and canopy transpiration. The entire measurement system is 5 to 10 times less expensive than commercial alternatives and can be constructed in-house by researchers, producers, or students interested in the technology. The do-it-yourself simplicity and low cost of the approach make it possible to deploy large numbers of gauges in the field, which could be a real boon for researchers trying to measure differences in water use among agronomic plots or scale-up sap flow to measure canopy transpiration. Also, the technology could be a useful educational tool for schools, museums, and other venues where education on plant water use is important. Finally, this type of open-source, low-cost technology could help researchers working on limited budgets in developing countries. Results from the work will be published as a chapter in a Ph.D. dissertation, submitted to a peer reviewed journal, and presented at the fall meetings of the American Geophysical Union. Details on gauge fabrication and building the data acquisition system will be published online as part of the environmental physics *Learning* web page.

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Introduction

Sap flow gauges provide a unique way to measure the time course of whole plant water use under field conditions. When multiple gauges are deployed within a study area, results can be scaled up to estimate canopy transpiration (T) or partition evapotranspiration into soil and plant components (Ham et. al., 1991). Sap flow measurements provide insight into field-scale water consumption, water stress, and the utility of different irrigation or riparian water management strategies. One of the most recalcitrant problems when using sap flow gauges is obtaining enough replication to capture spatial and plant-to-plant variation. In agricultural work, it often takes more than 10 gauges per plot to allow statistical comparisons of treatments (e.g., Senock, Ham, et al., 1996.). The issue can be more pronounced when trying to use sap gauges to estimate water consumption of different species and sizes of plants growing along a river corridor or other ecosystem. In both cases, spatial variation in soil-water conditions and micrometeorology confound the problem. Thus, researchers that work at these scales need a research grade instrument that can be economically fabricated in large numbers. The objective of this proposal was to use new developments in theory, open-source electronics, and desktop manufacturing to deliver a new sap flow measurement tool to the CSU water research community. Our goal was not to compete with commercial products, but essentially create new category of open-source sap flow technology – tools that lay the groundwork for creating a multi-nodal, wide-area sap flow network.

While there are several types of sap flow gauges, there are two general approaches - heat balance (HB) and heat pulse (HP). Here we will focus on a new variation on the HP approach taking advantage of new developments in theory, open-source electronics, and desktop manufacturing (e.g., 3d printing). Some of the advantages of the HP approach include: 1) low power requirements, 2) easier installation and fewer parts, 3) the same gauge can be used on a wide range of herbaceous plants, woody shrubs, and trees; 4) simpler and more economical for DIY fabrication; and 5) can be monitored with a low cost, open-source data logger design.

For this study, the configuration of the needle probes was similar to the sensor described by Vandegehuchte and Steepe (2012), who developed their 4-probe HP design for use on trees. However, in this study, the fabrication of the body was done with a novel 3d printing approach and the fabrication of needle probes was unique to this project. This gauge uses the improved heat pulse theory of Kluitenberg and Ham (2004). By measuring temperature the lift in both the axial and tangential direction with respect to the heater, it is possible to estimate sap velocity and the thermal properties of the stem in a single measurement using a parameter estimation procedure

The goals and objectives of the project can be summarized as follows:

- Develop methods for DIY fabrication of a low-cost heat pulse gauge and data acquisition system using 3D-printed components and open-source electronics (i.e., Arduino).
- Test and calibrate different gauge designs in the greenhouse on sunflower and corn by comparing measured sap velocity to independent gravimetric measurements of whole plant transpiration.
- Evaluate different numerical schemes for converting the heat pulse data to sap velocity and approximating the thermal properties of the stem (i.e., a possible surrogate for stem water content and water stress).
- Deploy the gauges under field conditions on irrigated corn and compared scaled up estimates of canopy transpiration to reference crop ET.
- Publish results as part of a Ph.D. dissertation, submit to a peer-reviewed journal, and post the construction details and user's manual on-line for open-source distribution.

Design, Fabrication, and Testing

Gauge Design

The gauge included three needle probes: a central resistance-heater probe to apply a heat pulse, a temperature probe directly above the heater to measure axial heat flow downstream, and a second temperature probe located to the side of the heater to measure tangential heat flow (Fig. 1). In some cases a fourth upstream (i.e., lower) temperature probe was added. The distance between the heater and the temperature probes ranged from 5 to 8 mm – different spacings were tried in an attempt to find the best possible geometry. The heater probes and temperature sensors were fabricated from 25-cm-long 18-AWG hypodermic needles using the techniques in Ham and Benson (2004). The heater was made from two loops (four strands) of enameled heater wire (40 AWG Solid (0.0031), Nichrome 80, 222 Ohms/m; Pelican Wire Company, Florida, Naples, FL). The total resistance of the heaters after fabrication ranged from 26 to 35 ohms. Thermistor probes were made from 10K NTC thermistors (LSMC 700A010K, Selco Products Co, Reno, NV). After the heaters and thermistors were positioned in the needles, high thermal conductivity epoxy (TC-2810, 3M, St. Paul, MN or Omega Bond 101, Omega Engineering, Stamford, CT) was injected to back-fill the air space and secure the sensors. The finished heater and temperature probes were mounted into a water-proof plastic chassis fabricated on a 3-D printer from ABS plastic with three interchangeable parts: probe assembly (needles/sensors), a spacer, and a backside clamp (Figs. 1 and 2). This allowed the same sensor electronics to be installed on plant stems with different diameters and to adjust the needle penetration depth by simply changing the spacer and backside clamp. The materials cost of the sap flow gauge was about $25 per unit.

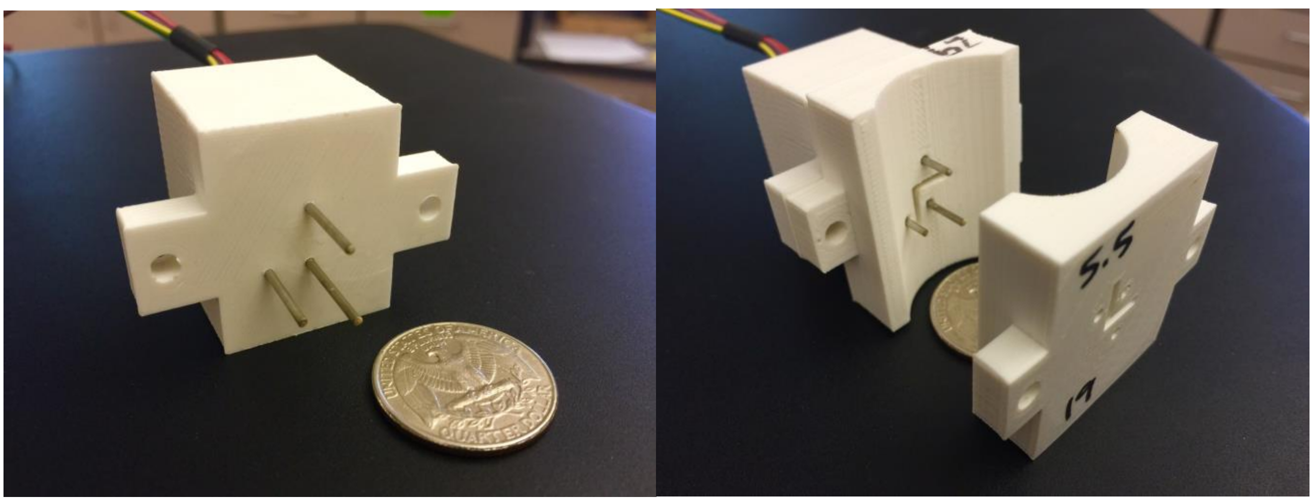


Figure 1. Sap flow gauge sensor module (left) showing the heater and temperature probes, and the full assembly (right) showing the spacer and backside clamp. In this example, the heater is the center needle and the temperature probes are at downstream and tangential positions. In the assembed photo (right), a spacer has been added to control the depth of penetration. In total, there are three 3-D printed parts per gauge. Note, the sensor module on the left can be reused on a wide range of stems sizes by simply printing a different spacer and clamp that matches the application.

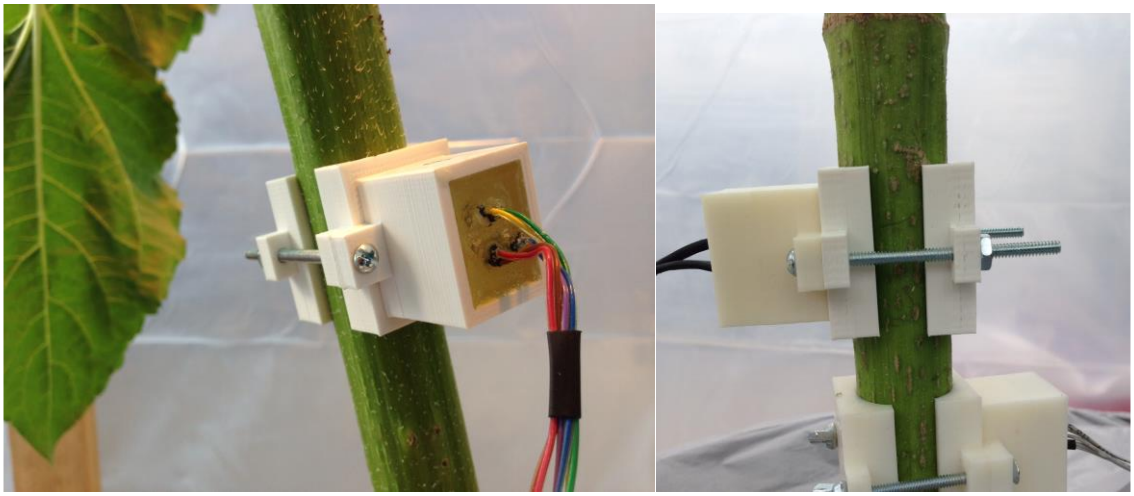


Figure 2. Sap flow gauges attached to sunflower plants in the greenhouse.

Data Logger Design

The data acquisition and control system was designed around an Arduino open-source microcontroller board (Arduino LLC) equipped with a data logger shield from Adafruit industries LLC, NY. The heat pulse (9 to 12V applied for 6 or 8 seconds) was controlled using an FET (FQP30N06L, Fairchild Semiconductor) and the current flowing through the heater was measured with high side DC current module (INA219, Adafruit Industries, LLC). Typical power applications per length of probe were between 600 and 900 J/m. The thermistors were excited using a precision 2.5V voltage source (LT1460-2.5, Linear Technology) and the transducer output from a 10K half- bridge circuit was measured with 16-bit ADC module (ADS1115, Adafruit Industries). Thermistor resistance was converted to temperature with the Steinhart-Hart equation using coefficients provided by Selco Products. The resolution of the temperature measurement was 0.002 C. The data logging system was configured to take readings every 10 minutes using the following protocol: 1) sample initial temperature of all sensors, 2) apply heat pulse for 6 or 8 seconds and monitor heater current and voltage during pulse, 3) measure the resultant temperature lift at all sensors at 2 Hz for a period of 180 seconds. When not taking a sap flow reading, the temperature of the stem was monitored at 1 minute intervals. These data were used to detrend the heat pulse data by knowing the background rate change in stem temperature before the heat pulse. Each data logger system had the capability to read two gauges simultaneously, store time-stamped data on an SD card, and display real-time results on an LCD (Fig. 3) . A simplified wiring schematic for reading one gauge is shown in figure 4.

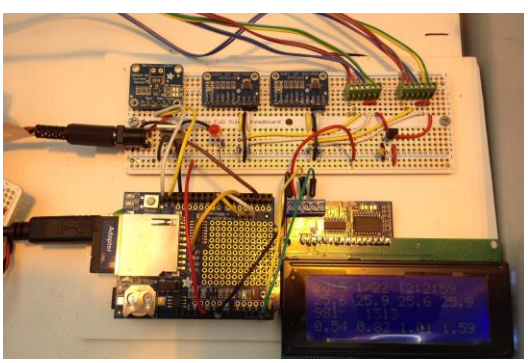


Figure 3. Arduino-based data logging system.

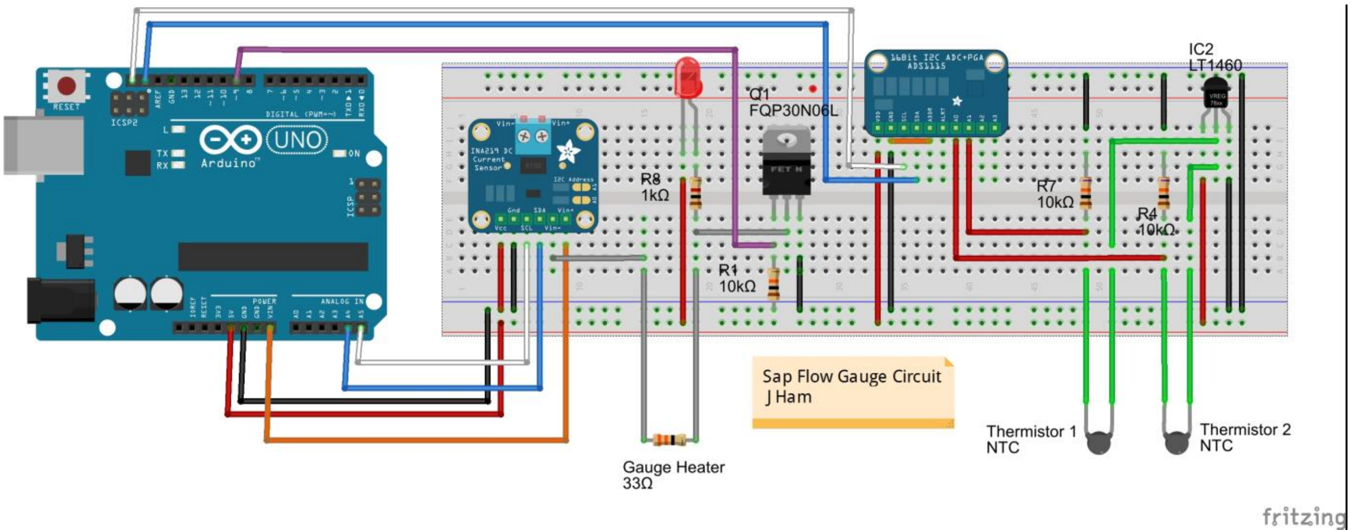


Figure 4. Simplified wiring schematic for reading one sap flow gauge. This represents the key components shown in Figure 3 without the additional 2nd gauge and less the LCD. The Adafruit logger shield that sits atop the Arduino is not depicted but the wiring is correct.

Calculating Sap Velocity and Mass Flow

Each sap flow reading results in a heat pulse curve at two locations relative the heater. The first step is estimate sap velocity from these data using heat transfer theory. Two approaches were evaluated.

T_{max} Method:

Cohen et al. (1988) describe a relatively straightforward method to estimate sap velocity based on the time required for the temperature at the upper (i.e., downstream) temperature sensor to reach maximum following an instantaneous heat pulse. Heat velocity, V (m/s), is calculate as

$$V = \frac{\sqrt{L_d^2 - 4\kappa_x t_{m,d}}}{t_{m,d}} \tag{1}$$

where L_d is the distance to the downstream sensor (m), κ_x is the thermal diffusivity of the stem in the axial direction (m^2/s), and $t_{m,d}$ is elapsed time (s) to when the temperature at L_d becomes maximal following the heat pulse (i.e., elapsed time to maximum). However, this approach is for an instantaneous heat pulse. In practice the heat pulse duration is usually 4 to 8 s in duration. Kluitenberg and Ham (2004) showed a similar solution for for velocity using a non-instantaneous pulse

$$V = \sqrt{\frac{4\kappa_x}{t_o}\ln\left(1 - \frac{t_o}{t_{m,d}}\right) + \frac{L_d^2}{t_{m,d}(t_{m,d} - t_o)}} \tag{2}$$

where t_o is the length of the heat pulse (s). One problem with both equations 1 and 2 is that thermal diffusivity, κ_x is unknown. Usually κ_x is determined by rearranging the velocity equations to solve for κ_x at night after assuming V is zero or very small. For equation 2 the solution κ_x for takes the form

$$\acute{\kappa}_x = \frac{t_o}{4}\left(V^2 - \frac{L_d^2}{\acute{t}_{m,d}(\acute{t}_{m,d} - t_o)}\right)\left[\ln\left(1 - \frac{t_o}{\acute{t}_{m,d}}\right)\right]^{-1} \tag{3}$$

where the prime accent on the variables indicates a predawn conditions. The nighttime-based value of κ_x is assumed to hold constant for the following day. In some cases, the plant stem is severed above the gauge to create true zero flow conditions (V'=0) for the calculation of κ_x.

$$\kappa_{x,0} = \frac{L_d^2 t_o}{4t_{m,d}(t_{m,d}-t_o)} \left[\ln\left(\frac{t_{m,d}}{t_{m,d}-t_o}\right)\right]^{-1} \tag{4}$$

The zero-flow based measure of $\kappa_{x,o}$ is then used to calculate V for the entire period prior to cutting the plant.

In practice, the T_{max} method has been problematic at low flows. Finite element modeling of low flow conditions in trees has shown that the relationship between $t_{m,d}$ and V is not unique when wounding effects are included. Also, Cohen et al. (1988) showed that using equation 1 with their gauge design was not accurate when V was small and they switched to the compensation method at flows less than 0.22 mm/s. This required the installation of an additional probe upstream (i.e., below) the heater. Many of the problems at low flows arise because the observed temperature increase at the downstream probe becomes small with a flat peak and creates uncertainty in determining $t_{m,d}$. However, improvements in electronics allow temperature measurements to within 0.002 C and numerical peak-finding algorithms can improve the determination of $T_{m,d}$.

Historically, most heat pulse probe designs included temperature sensors both above and below the heater. This is a requirement if the investigator needs to measure reverse sap flow, a common occurrence in trees. This is not a significant process in herbaceous plants like corn and sunflower. Thus, there may be an advantage to eliminate the upstream (i.e., lower) probe and instead put a temperature probe to the side (i.e., tangential) of the heater. The theory described in Kluitenberg and Ham (2004) can also predict velocity based on a heat pulse measured in the tangential direction

$$V = \sqrt{\frac{4\kappa_x}{t_o}\ln\left(1-\frac{t_o}{t_{m,t}}\right) + \frac{L_t^2}{t_{m,t}(t_{m,t}-t_o)}\frac{\kappa_x}{\kappa_y}} \tag{5}$$

where L_t is the distance between the heater and side probe, κ_y is the thermal diffusivity in the tangential direction,), and $t_{m,t}$ is the elapsed time (s) to maximum temperature at L_t. This case requires both κ_x (Eqs. 3 or 4) and a zero flow based estimate of κ_y

$$\kappa_{y,0} = \frac{L_t^2 t_o}{4t_{m,t}(t_{m,t}-t_o)} \left[\ln\left(\frac{t_{m,t}}{t_{m,t}-t_o}\right)\right]^{-1} \tag{6}$$

In this study, the T_{max} method was tested using the equations 2 and 5 where stem thermal properties were approximated using equations 3, 4 and 6. The times to maximum, $t_{m,t}$ and $t_{m,d}$, were estimated using a Savitsky Golay algorithm applied to the temperature vs. time curves following the pulse. Velocities were estimated with both the downstream and side probes using equations 2 and 5, respectively.

Sapflow+ Method:

Vandegehuchte and Steepe (2012) developed a method for estimating V using measurements of both axial and tangential heat movement following a heat pulse. Referred to as the Sapflow+ method, this technique uses the same underlying theory of Klutienberg and Ham (2004). Gauges that use this approach must have a temperature probe to the side and downstream of the heater (Fig. 1) but a upstream probe is not required unless reverse flow measurements are needed. The 2D heat flow equation is fitted to the data using numerical techniques that allow the thermal properties of the stem and V to be estimated simultaneously by parameter estimation. Assumptions about stem thermal diffusivity are not required. Because temporal changes in stem thermal properties are mainly a function of stem water content, this approach could provide a dynamic method for measuring water stress. Thus, one could measure diurnal patterns of stem water content while simultaneously measuring sap flow. The Sapflow+ method was implemented in Matlab and the parameter estimation was done using the Levenberg–Marquardt algorithm.

Converting Sap Velocity to flow rate

The measured velocity, V, of the heat pulse (m/s) must be converted to mass or volumetric flow (e.g. mg/s or mm^3/s) to determine whole plant transpiration. This conversion is difficult in theory because: 1) wounding effects on sap velocity in the region of the needle, 2) the hydroactive area of the xylem for stem is unknown, 3) heat capacity in the conductive area is affected by changes in stem water content, 4) model error caused by an oversimplified mathematical representation of heat flow, and 5) measurement errors causes by the presence and non-deal response of the needle probes themselves. In practice, these factors are accounted for using an empirical calibration. In our case, the actual flow (i.e., whole plant transpiration, T, mg/s) was measured gravimetrically while V was measured by the gauge. A linear relationship is expected between T and ρVA, where A is the cross sectional area of the plant stem (mm^2) at the gauge location and ρ is the density of sap (g/cm^3, approximately 1.0) Assuming sap density is that of water and the regression analysis reduces to

$$T = \alpha\,(AV) \tag{7}$$

The value of α was determined by a regression of T vs. AV over a range of flow rates. Cohen et al (1993) found the slope, α , averaged 1.6 for corn and 0.73 for sunflower. Given that the hydroactive area of the xylem vessels is only a small portion of the stem area, V must be severely underestimated. For example, if one assumes the xylem area is 15% of the total, then measured V could be 5 times to 10 times lower than actual for sunflower and corn respectively. The discrepancy is most likely the result of wounding and flow disruption around the needles as well the other factors mentioned previously. Thus, the slope correction is lumping a group of errors into one term, which is reasonable if the errors themselves are not strong functions of velocity. Previous research has successfully used this approach (Cohen et al, 1993; Cohen and Li, 1996). A simple linear correction used in Eq. 7 is only valid if the errors remain proportional to T. If the errors in the measurement of V are nonlinear, then a polynomial correction might produce more better results

$$T = \alpha\,(AV) + \beta(AV)^2 \tag{8}$$

Summary of Calculation Methods

Use of the Sapflow+ method requires considerable expertise in numerical methods and extensive post processing of data in Matlab, R, or other complex programming languages. Given that the goal was to develop an open-source, simple, user-friendly system, the use of the Sapflow+ approach seemed to be at odds with the philosophy and intent of the hardware development. That is, why design a low-cost DIY sensor with an Arduino-based data logger, only to require very complex computing skills and massive post processing to convert the heat pulse data to sap flow? Thus, this report will limit the analysis to the T_{max} method, which can be programmed into the Arduino and provide real time measurements of sap flow (no post processing).

Testing Procedures

Prototype gauges were testing in the greenhouse using plants grown in containers. Mature plants were placed on a 20 kg digital balance (0.1 g resolution) and the soil surface was covered with plastic film to prevent soil water evaporation. A windscreen was erected around three sides of the testing area to keep the greenhouse fans from shaking the plant and affecting the balance readings. The mass of the containerized plant was recorded automatically every one minute using a laptop computer. The rate change in weight provided a gravimetric determination of whole plant transpiration in grams per hour. One or two sap flow gauges were attached to the stem at the second internode below the first leaf. Most stems were between 20 and 30 mm in diameter as measured with a digital caliper. Because some of the work was done during winter, high pressure sodium lamps were sometimes used in combination with natural lighting to increase transpiration. Midday maximum sap flow rates typically ranged between 200 to 250 g/h for corn, and 350 to 450 g/h for sunflower. Nighttime flows were typically 5 g/h and 40 g/h for corn and sunflower, respectively. Most tests were done under well-watered conditions but in a few cases irrigation was withheld to create water stress.

Additional tests were performed in August 2014 at ARDEC on Irrigated corn near physiological maturity. Six gauges were installed along an 8 meter section of row in the portion of the field receiving the most irrigation water (100% of Reference ET). Average sap flow measured by the gauges was scaled up to an area basis using plant density. Canopy transpiration estimated from the gauges was compared to reference crop ET calculated using the ASCE Penman-Monteith equation for tall crops. The CoAgMet weather station at ARDEC was used as the data source for the reference ET calculations. Assuming soil evaporation was a small fraction of ET , good agreement between the two estimates of crop water use was expected.

Figure 5. Sap flow gauges being tested on sunflower in the greenhouse (left) and on corn in the field (right). The field deployed gauge is covered with a plastic shield to protect the system from sprinkler irrigation and rain.

Results and Discussion

Example Heat Pulse Data

Figure 6 shows temperature increases following a heat pulse at two different flow rates in corn. The magnitude and pattern at both probes was strongly affected by flow. The downstream sensor peaked at 1.48 C about 50 s after the pulse during high flow, while at low flow the peak was much lower (0.4 C), moderated, and occurred around 120 s. The side probe had the opposite tendency, showing much more response at low flow. This shift is caused by convection- vs. conduction-dominated heat transfer at high and low flow, respectively. Figure 6 also demonstrates the precision and fidelity of the temperature measurements made with the low-cost Arduino board. Temperature resolution was 0.002 C and signal was very steady even in a greenhouse (i.e., potential electromagnetic noise from fans, lights, etc.).

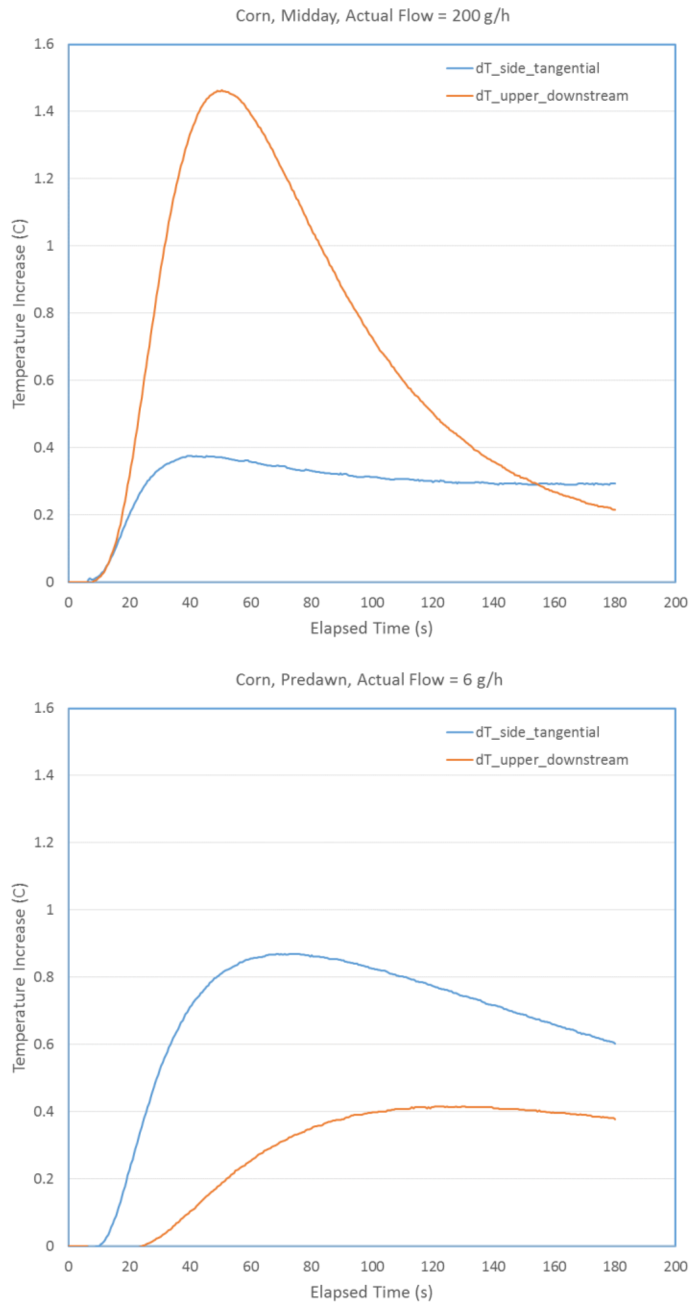


Figure 6. Comparison of the heat pulse signal in corn at two different flowrates. Shown are data from the upper probe located 8.5 mm downstream of the heater and data from the second probe located 5.9 mm to the side of the heater. The heat pulse was 8 s at 825 J/m.

Greenhouse Results

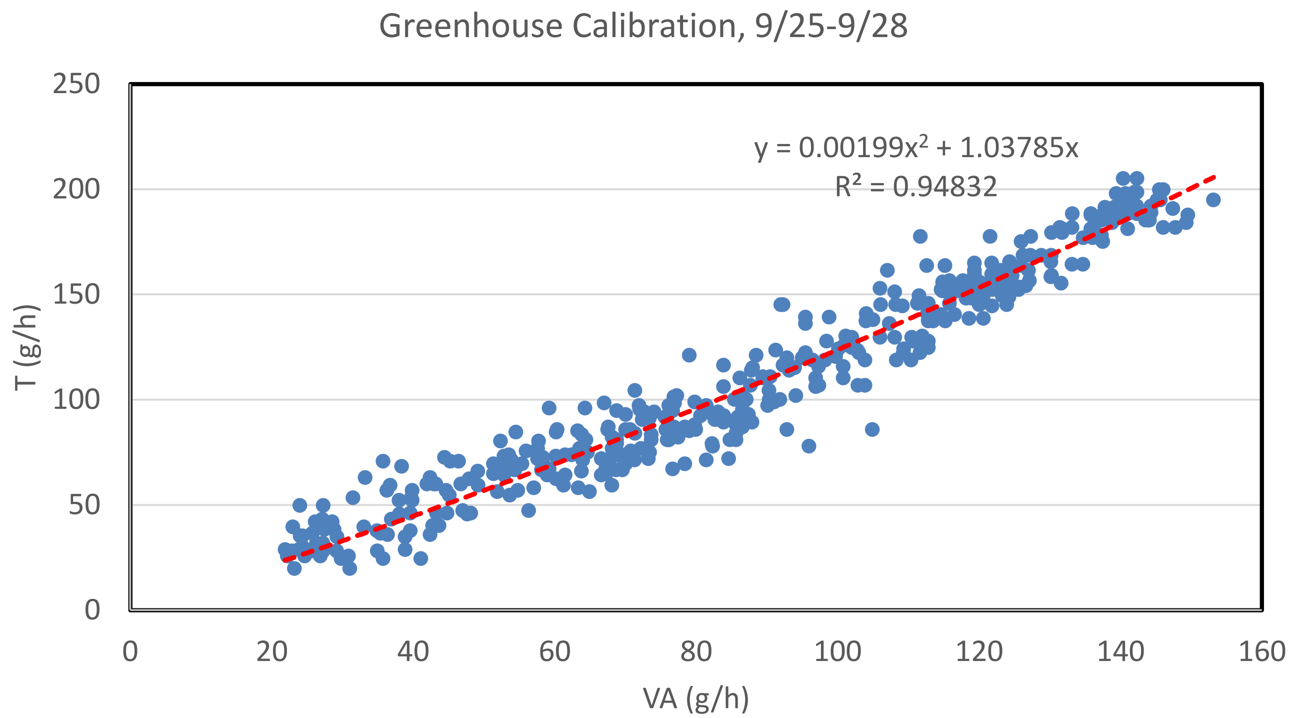
The main goal of the greenhouse studies was to compare the measured sap velocity to the gravimetric measurements of whole plant transpiration. Data were used to evaluate the formula for calculating V (eqs. 2 and 5) and developing the calibration factor to convert VA to mass flow in g/h (eqs. 7 and 8). The thermal diffusivities of the stems, which are required to calculate V, were estimated daily using predawn data between 3:00 and 5:00 LST from equations 3 and 6. In general, the thermal diffusivities were between 1.2×10^{-8} and 1.4×10^{-8} m^2/s, which were somewhat lower than reported in previous work with herbaceous plants (Cohen et al., 1988). Large differences between k_x and k_y were not observed, suggesting that it might be reasonable to assume stem thermal properties are isotropic.

The relationship between whole plant transpiration and sap velocity (i.e., VA, sap velocity x stem cross-sectional area) demonstrated a strong linear or slightly quadratic relationship (Fig. 7). Data from two gauges on the same stem were pooled to develop the relationship. While the quadratic fit was slightly better during the September study, a good fit was also obtained with a linear equation ($T=1.35*VA-9.3$, $R^2=0.94$). The slopes of the linear fits were 1.35 and 1.27 in Sept. and Dec., respectively. The December study used an 8 s pulse and inserted the temperature probes to a depth of 6.0 mm, whereas the September study used a 6 s pulse and 7.5 mm insertion depth. Cohen et al. 1996 also found that deeper insertion depths caused the slope of the calibration to increase. Despite the differences in how the gauges were installed and operated in Sept. and December, the difference in the calibrations is quite small (7%). Other experiments (not show) showed similar calibrations. While more work is needed, it appears that a fairly universal calibration equation can be obtained for a given gauge design and probe insertion depth.

Figure 8 compares the gravimetric measurements of transpiration to the calibrated sap flow results for the September and December greenhouse studies. Recall, two gauges were attached to the same stem in both cases. Results showed that gauges tracked transpiration very well and typically agreed with the scale to within 3 % when integrated over 24 h. There was also excellent agreement between the two gauges attached the same stem, suggesting very minimal effect of gauge construction or installation. The gauges could also track dynamic changes in flow caused by partly cloudy conditions as demonstrated on September 28 (Fig. 9).

The gauges tended to overestimate velocity at low flow rates; thus, data below 20 g/h were eliminated from the calibration. Other researchers have also found the Tmax method is unreliable a very low flow rates (i.e., night or severe water stress). However, most corn production is under irrigated conditions or in regions with adequate soil moisture where about 90 % transpiration occurs during the day at flowrates greater than 20 g/h. Thus, the gauge is well suited for studying water consumption of corn in a typical agricultural applications.

Velocities and thermal properties measured by the side temperature probe (tangential) were also evaluated. The idea was that the side probe might be a good way to estimate V during low flows when the downstream probe proved inadequate. Recall the side probe is closer to the heater and detects a larger and more distinctive heat pulses at low flows (Fig. 1). However, results showed that calculating V using the side probe (Eq. 5) produced a very noisy result and was not any more reliable than the downstream probe at low flows. However, the side probe did seem to produce stable measurements of k_y, suggesting it might be useful in detecting water stress if thermal properties are a reliable surrogate for stem water content. Research on this topic is still underway.



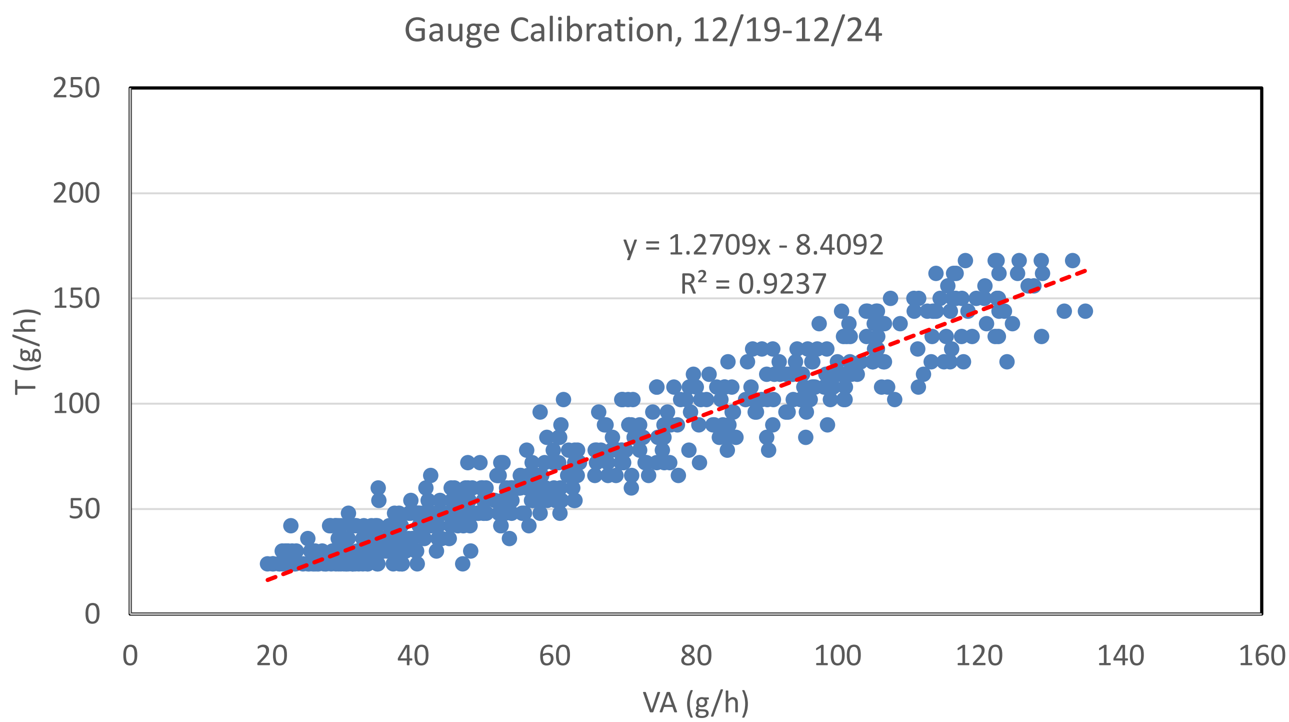
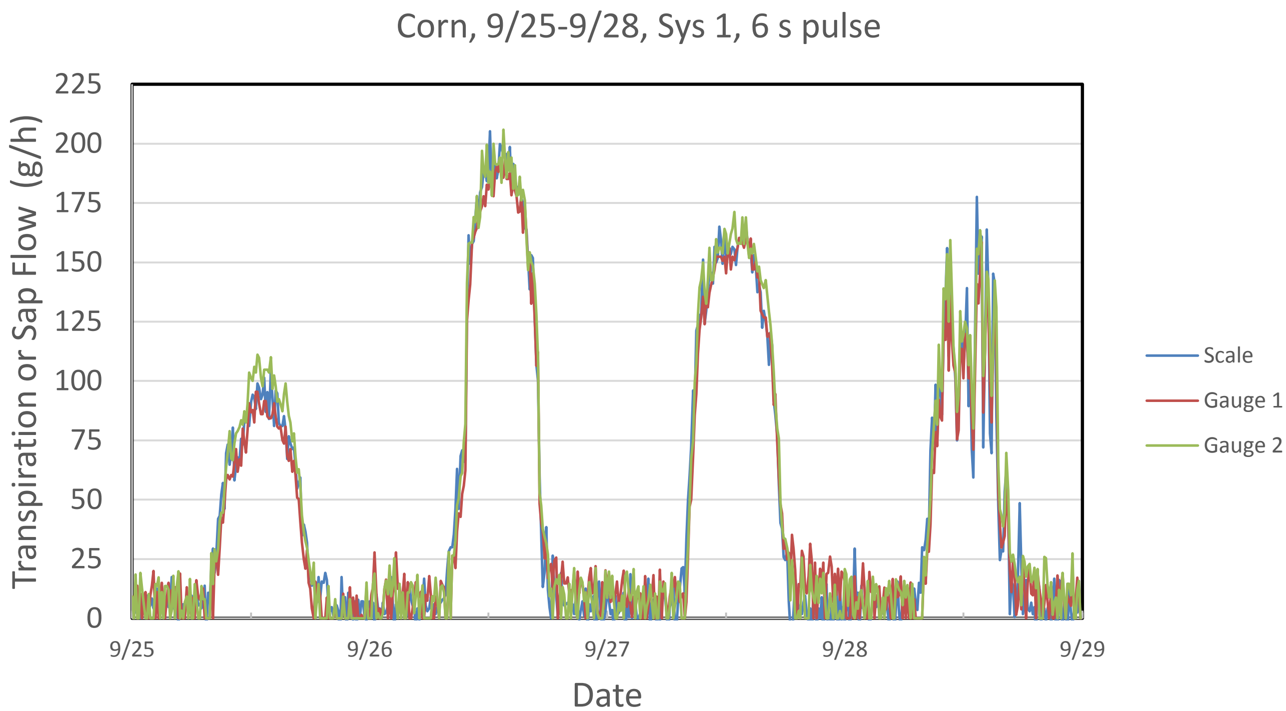


Figure 7. Relationship between whole plant transpiration (T) measured gravimetrically to the product of sap velocity and stem cross-sectional area (VA). Data are shown for two different experiments



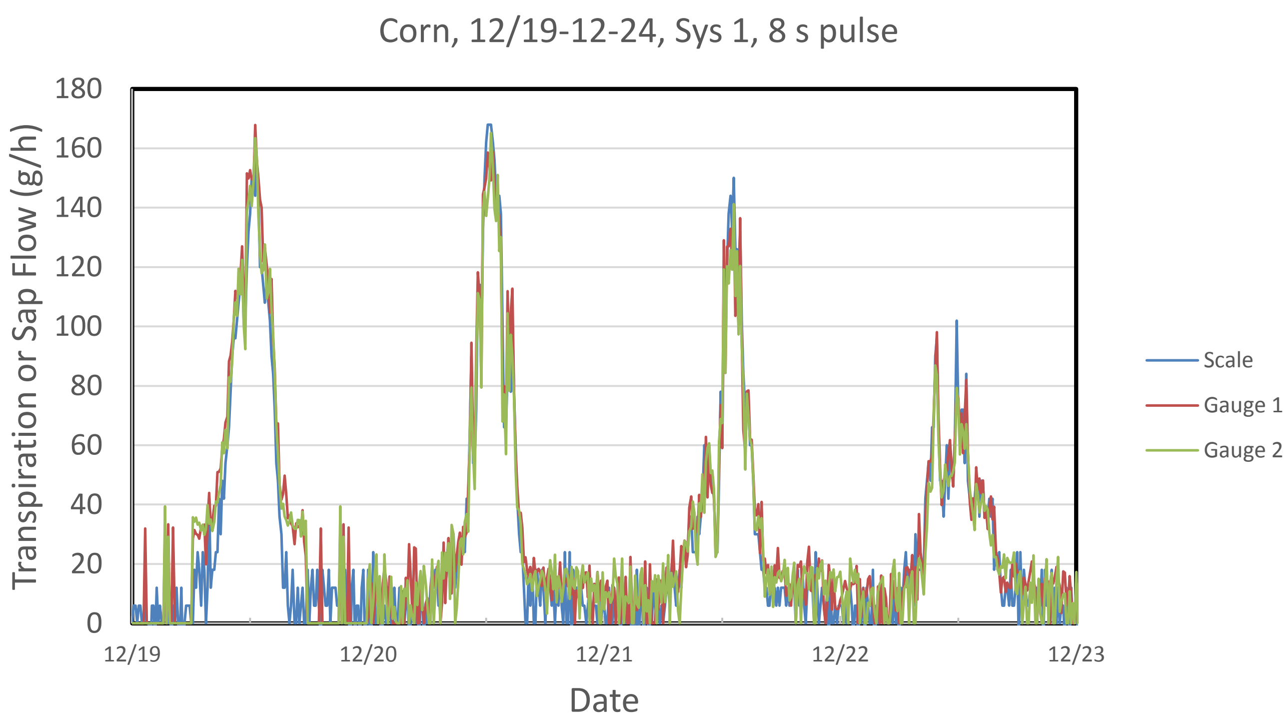


Figure 8. Comparison of gravimetric measurements of transpiration to sap flow measured by two gauges attached to the same corn stem. Velocity was calculated with equation 2 using only data from the downstream temperature probe.

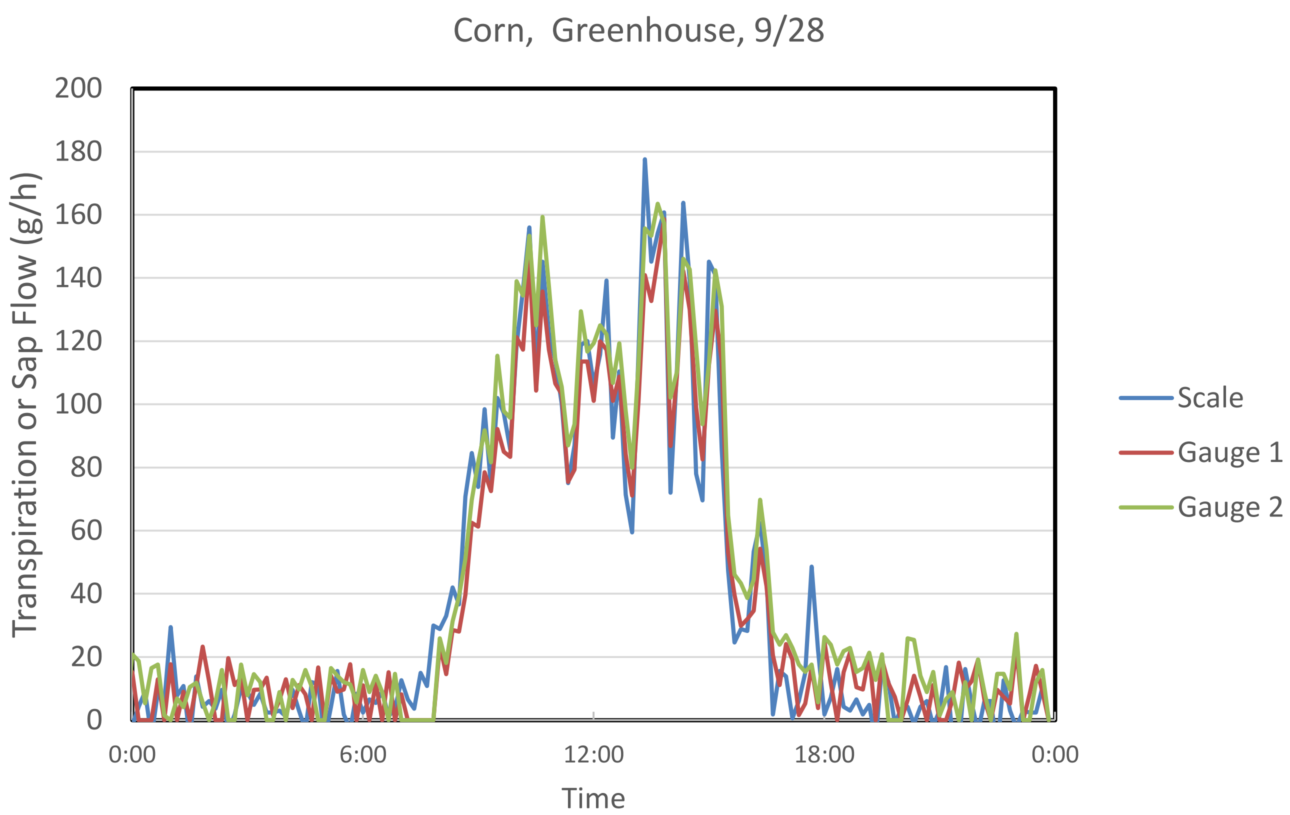


Figure 9. Comparison of gravimetric measurements of transpiration (scale) and sap flow measured by two gauges attached the stem. Data were collected on 9/28 under partly cloudy conditions which caused sudden changes in transpiration.

Field Results

Sap flow was measured on multiple plants in the field and scaled up to a land area basis using plant population (31,000 plants/acre, 7.6 plants/m^2). Significant plant-to-plant variation was observed even in a corn field that looked very uniform. In some cases there was a 20 to 30% difference in transpiration between plants less than 1 meter apart. This was likely caused by inherent differences in leaf area and interception of radiation among plants. However, excellent agreement (+/- 10%) was observed between the sap flow based estimates of canopy transpiration and reference crop ET calculated using ASCE tall crop formula (Fig. 10). For example, on August 8th the sap flow gauges predicted a daily ET of 10.8 mm while Reference crop ET was 10.1 mm. The field was well watered (%100 of reference ET irrigation) so relatively good agreement was expected. The sap flow gauges tended to overestimate flow at night or other periods when flow was less than 30 g/h. Thus, it may be advisable to discard the gauge data during these periods and use a gap filling strategy to fill in the low-flow periods (i.e., night). Nevertheless, the sap flow gauges are most accurate during the day when the majority of transpiration occurs. While more field studies are needed, the new sap flow gauges should be an excellent tool for estimating field or plot scale canopy transpiration if a sufficient number of gauges are deployed (e.g. 8 to 10 per plot). The system is very low power compared to heat balance techniques and can run for over a week on small lithium polymer batteries. Thus, the system tends to be easier to install and maintain in comparison to other methods.

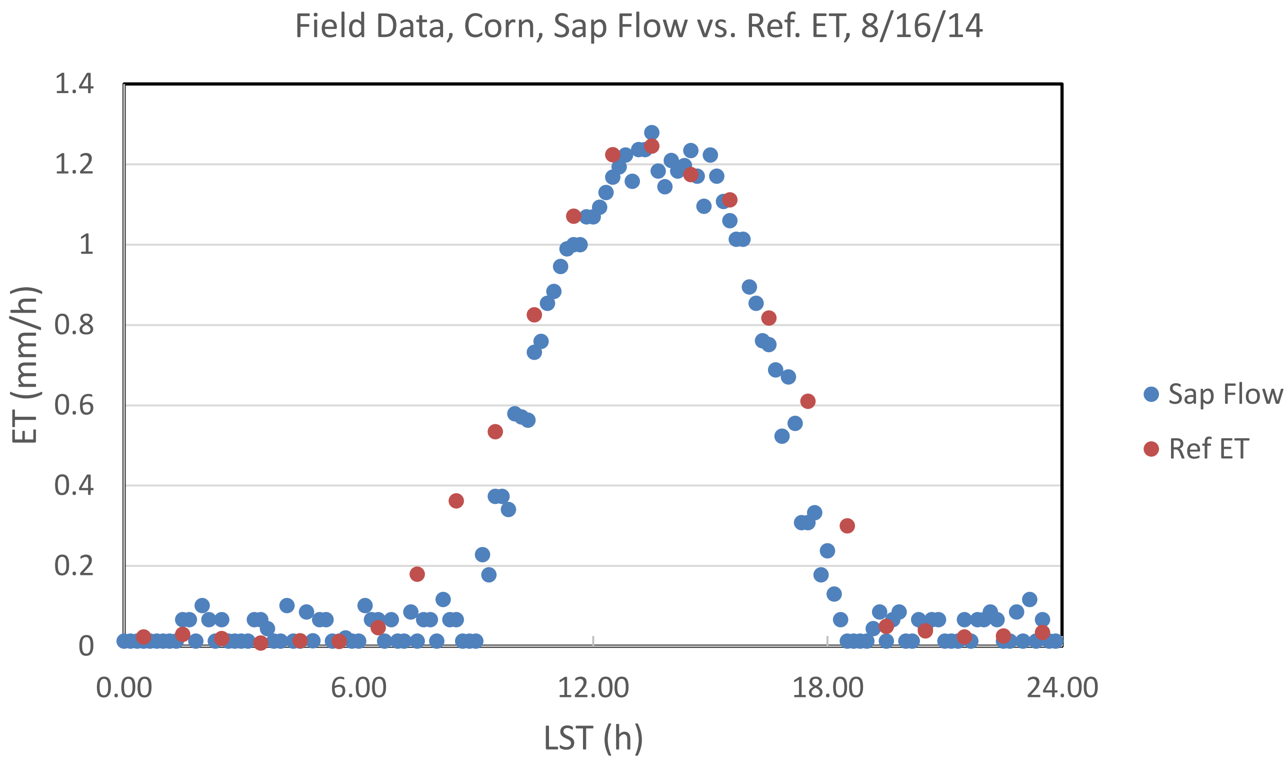


Figure 10. Field measurements of canopy transpiration measured by sap flow gauges compared to reference crop ET calculated from weather data. Sap flow was scaled up to a land area basis using plant population.

Conclusions

3D-Printing technology can be used to make research-grade heat pulse sap flow gauges for about $25 per unit - 6 to 10 times less than many commercial gauges.

The open-source Arduino microcontroller board can be used as data logging and control system for the gauges. These systems can be made inexpensively in the lab and open-sourced to accommodate a wide range of users. A system to read 4 sap flow gauges costs under $100. Thus, a 4-gauge sap flow system would only require about $200 in materials to fabricate.

The theory of Kluitenberg and Ham (2004) proved to be an excellent approach to calculate sap velocity form the heat pulse data. To our knowledge, this study was the first to experimentally evaluate thier equations for a non-instantaneous heat pulse.

Once calibrated for a given gauge design, the sap flow system ccan measure whole plant transpiration to within +/- 5 % in corn. Similar results were obtained in sunflower but are still being analyzed.

Because the cost of the system is so low, and the design instructions and software will be open-sourced for do-it-yourself fabrication, the new sap flow system will be very useful to those who need to deploy large number of gauges or have limited budgets. The technology could prove especially useful in studying the water use of corn in Colorado. While not yet evaluated, the gauges could like be used to study water consumption of riverine shrubs along riparian areas –another important issue in the state.

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