Improved installation and validation of sap flow sensors on maize plants.

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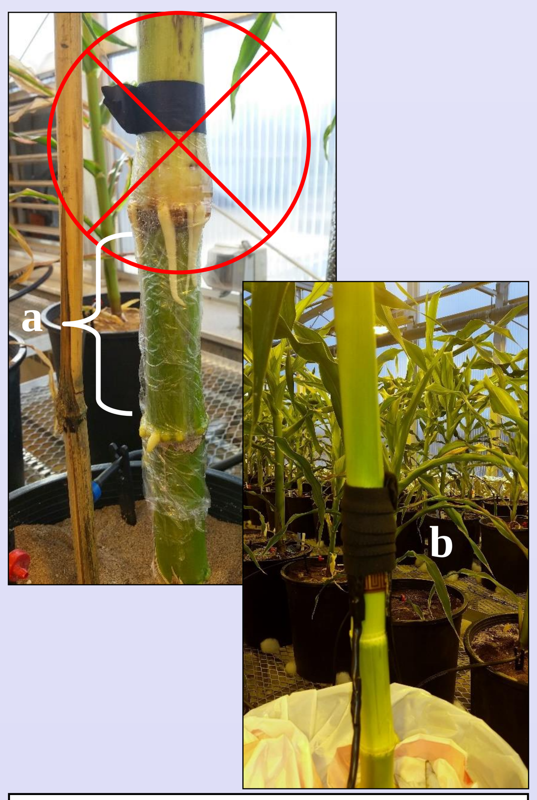
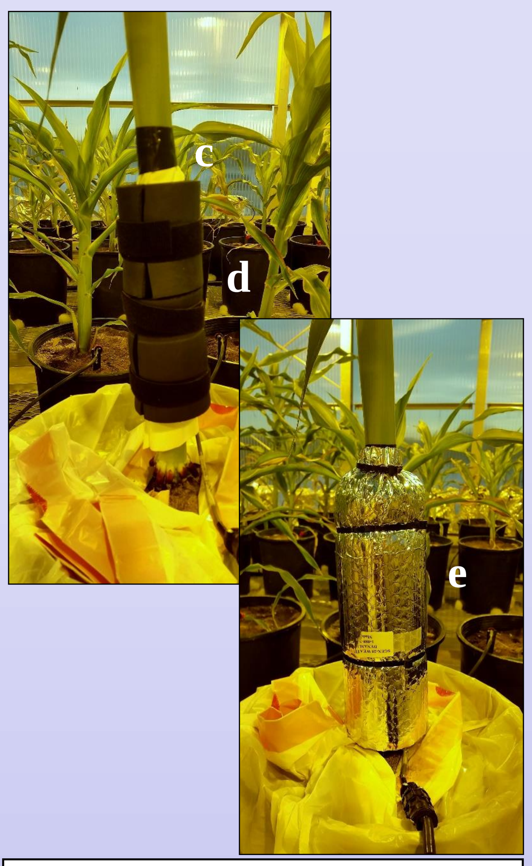
Introduction.

Over the last 3 years a considerable effort has been implemented to upgrade heat-balance type sap flow sensors and simplify installation for plants with high stem transpiration, such as maize. A new style of sensors makes the installation on maize efficient and can eliminate additional issues, including moisture accumulation and adventitious root production in the vicinity of the sensors. Sap flow sensors were installed on maize plants placed on continuously logging scales in the greenhouse. The tops of the pots were sealed between the pot rim and the plant stem with plastic garbage bags. Transpiration measured by sap flow sensors was compared to that gravimetrically-determined from the weight loss of pots. Greenhouse along with field data suggests that the ability to install and leave sensors on stems without maintenance can be increased from 2 weeks to 4 to 6 weeks or longer, depending on the stage of growth at the time that sensors are installed, with accurate results.

Methods.



Sap flow sensor installation on stems with plastic wrap and stretch Velcro to exclude moisture.



Gore-tex fabric, foam and foil bubble wrap around sap flow sensors to exclude moisture and moderate temperature shifts.

Experimental set up.

Dekalb 54-38RIB (104 RM) was planted in a greenhouse in Fort Collins, CO in 13.6 L pots filled with fritted clay (Profile Greens Grade, IL, USA) in November 2015. Plants were given continuous fertigation of 200 ppm N of Grow More soluble 20-20-20 fertilizer and 14 hr supplemental lighting from high pressure sodium lights. Greenhouse temperatures were set for a maximum of 27C daytime and minimum of 13C nighttime. The experiment was run ca. 8 weeks after emergence.

Whole plant transpiration.

Whole plant transpiration was measured on three plants with SGEX ExoSkin stem heat balance type sap flow gages (Dynamax, Inc., TX, USA). Gages were installed with a new designed to minimize the water trapped inside maize stems and inside the sensors that would expedite the longevity of sensors on maize. The bottom 2-3 leaves were removed. Stem internodes ('a' in picture) were wrapped with plastic wrap (e.g. Saran Wrap). Caution was taken to avoid nodes to prevent stimulation of adventitious roots. The heater on the sensor and thermocouples were coated with a thin layer of G4 (electrical silicone compound) and installed over the plastic wrap with stretchable Velcro wrap (b). A Gore-Tex barrier (white fabric) was wrapped over the Velcro and fixed to the stem at the top with electrical tape (c, open at bottom). The assembly was then insulated with foam (d) and foil bubble wrap (e).

Whole-pot evapotranspiration (±1 g) was also monitored by placing plants on digital balances (Adam CBK 70A, Adam Equipment Inc., Oxford, CT, USA) and recording mass continuously with the tops of pots sealed to the base of the plant stem with plastic garbage bags and duct tape. Holes on the bottom of pots were sealed on the sides of the pots but left open for drainage on the bottom. The diurnal drift for each scale was removed by weighing an inamemant object for several days to quantify the drift and subtracting the diurnal pattern.

Ksh setting.

The average value of the thermopile radial heat loss factor (Ksh) is established daily when there is low to zero flow and is required to solve the energy balance of the system. The Ksh is calculated as the "apparent" KshApp= (Pin-Qv)/Ch. The Pin is the power input computed with the heater voltage squared divided by the heater resistance, Qv is computed according to the literature on the conducted heat, Ch is the signal (mv) coming from the radial thermopile that indicates the loss of the heater power to ambient conditions. The zero set was computed each day as an average of the three hours from 1:30 to 4:30 am. This value is the average of the KshApp during this low flow period (rather than the minimum value) and is then set to the Ksh-in-use at 5 am. For the remaining part of the day the power equation computes the Qr=KshInUse*Ch. The Sap Flow heat flux for the remaining part of the day is Qf=Pin-Qv-Qr.

Since the formula for the KshApp depends on Qf equal to zero at the time the sensor equation is zeroed, there is a small error if there is some transpiration from 1:30 to 4:30 am. The scale loss was inspected and during that time, and the actual weight loss was an average of 3.7 g h^{-1} during the three hours over 12 days. If we assume the weight loss was from transpiration and not evaporation from the pot, the computed power for 4 g/hr is about .004 W. The total power loss for a 25 mm stem sensor is about .250 W, so the error in power from Ksh error is about 1.6 %, and negligible.

Results and Discussion.

➢ Diurnal plant water use from sap flow and scales

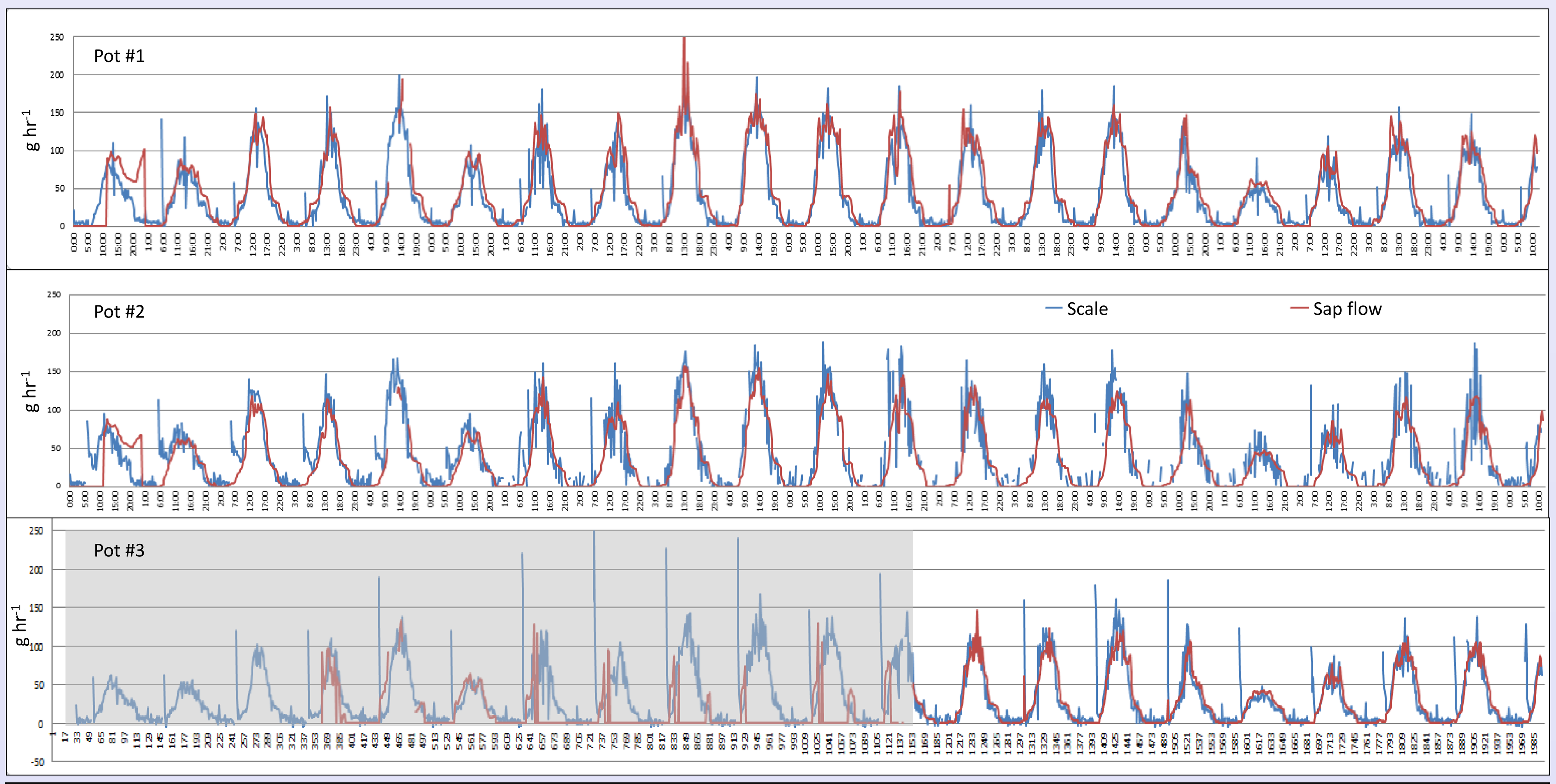


Figure 1. Diurnal plant transpiration measured gravimetrically by scales (blue) vs sap flow (red) on three plants over 21 days. White areas of the graph show when SGEX ExoSkin sap flow sensors were installed. Data from scales shows a spike at 5 am when between 0.9-1.1 L of irrigation was supplied to each pot. Scale data stabilizes approximately 30 min after the irrigation percolating from the bottom of the pots ceases (ca. 6 to 6:30 am).

Transpiration measured by sap flow and scales closely matched, both showing similar magnitude and shapes of diurnal responses across the different plants on days with high and low plant water use. Data from sap flow was substantially smoother than that from scales, likely due to fans circulating air in the greenhouse and moving plants around. In the scale data, typically a large weight loss gathered in one period as a spike is followed by another period with a dip in weight loss, cancelling the error. There is a small amount of night time transpiration that was captured by the scales (ca. 18.5 g d^{-1} on average) that was not captured by the sap flow sensors).

➢ Daily plant transpiration determined from sap flow *vs* scales

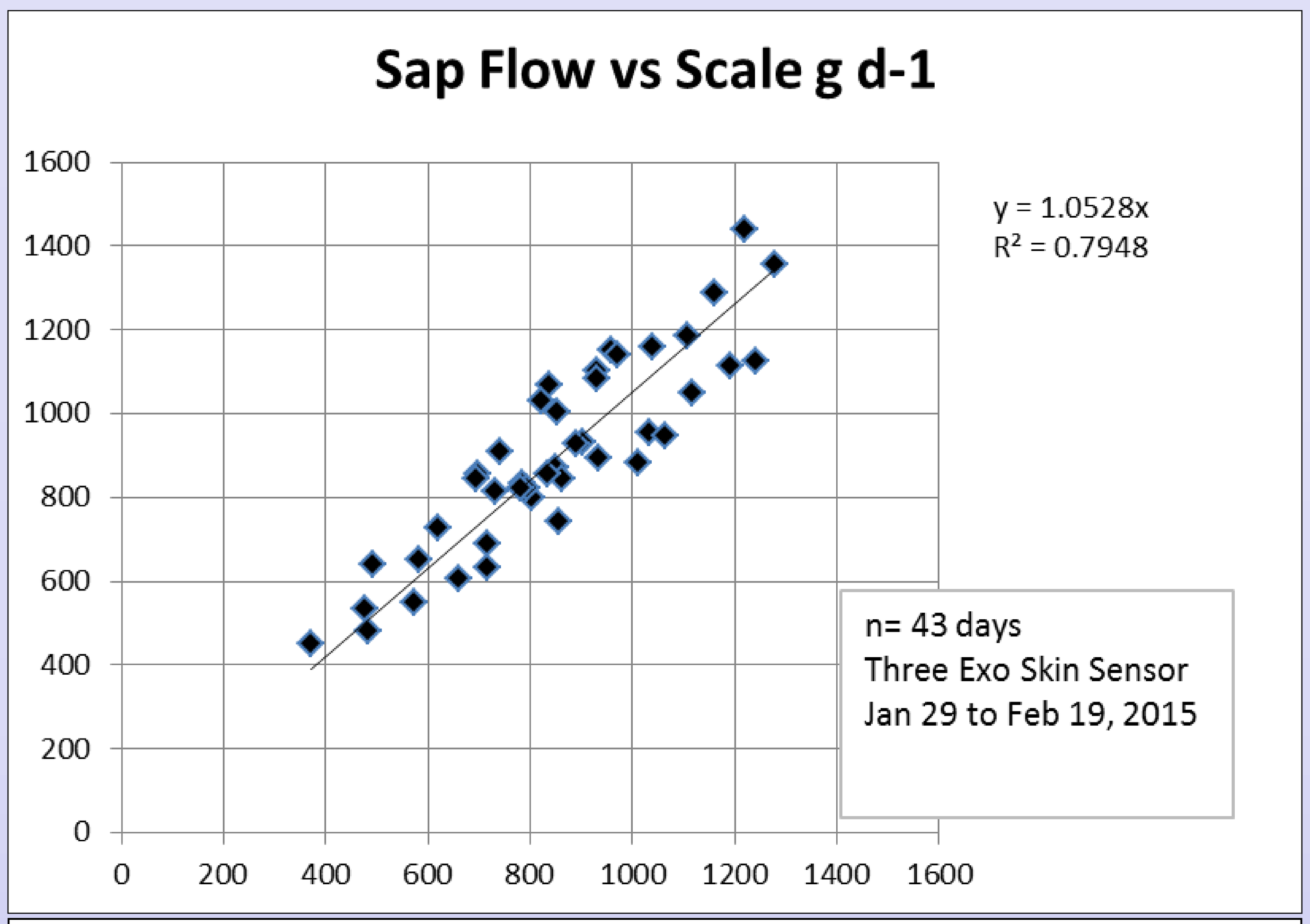


Figure 2. Plant transpiration (g d^{-1}) from sap flow sensors compared to that gravimetrically-determined from scales between 6:30 am to midnight over 43 days with complete data compiled across three plants.

The mean sap flow for the 43 days was 871 g d^{-1}, and the mean gravimetrical determination was 822 g d^{-1}. Sap flow was consistent with sap flow realized in the field, for stems from 19 to 25 mm diameter. The average error was 6% (49 g d^{-1}) and the error standard deviation was 103 g d^{-1}. Sap flow is 1.05 x the gravimetrical determination.

Conclusions.

Plant transpiration measured by sap flow closely matched transpiration measured gravimetrically with logging scales. The improved installation of sap flow sensors allowed for exclusion of moisture from sensors. The exclusion of this moisture prevented the growth of adventitious roots on nodes near the sensors and allowed for sap flow sensors to work continuously for longer than two weeks, which was a previous limitation.

The next step is to see how long sap flow sensors can be kept on plants in the field. So far, our use of sap flow sensors in the field suggests that sensors can be kept on plants 40-60 days as along as sensors continue to make contact with stems (e.g. plants under drought do not shrink away from sensors) and plants do not out grow sensors (e.g. if sensors are installed prior to full stem expansion).

Acknowledgements.

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