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Measuring and Modeling Transpiration in Relation to Citrus Tree Size using Sap Flow Sensors

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The water requirement of citrus trees changes with tree growth and seasonal evapotranspiration. Therefore, estimation of actual water usage by citrus trees at different times of the year is crucial for accurately scheduling irrigation. The relationship between water loss via transpiration and stem sap flow was evaluated for young and mature citrus trees. Actual transpiration was measured with the heat balance method using Dynagage sap flow sensors (Dynamax, Inc., Houston, TX) attached to the tree trunks or branches. Different sized sensors corresponding to stem or branch size of the trees were installed four times in a year (Nov. 2009, Feb. 2010, May 2010, and Sept. 2010). The sap flow data collected from sensors for 15 days were used to estimate the tree water usage. Canopy volume of each branch or the whole tree was measured and weather data (reference crop evapotranspiration, solar radiation, air temperature, and relative humidity) were downloaded from the Florida Automated Weather Network (FAWN) website. The correlation analyses showed that diurnal and seasonal tree water usage were strongly related to the tree canopy volume and weather parameters. Tree canopy volume and reference crop evapotranspiration (ETo) were used to develop predictive models for tree water usage using multiple regression and partial least squares (PLS) regression analyses. The predictive models could explain more than 80% of the variation in the tree water usage for different time periods of the year, suggesting that tree canopy volume and ETo can be successfully used to estimate water usage by citrus trees of any size for accurately scheduling irrigation.

As Florida's urban population increases, the demand for fresh water also increases. This places a burden on the agricultural sector. Irrigation is essential to producing high quality citrus yield; however, with decreasing water supplies, growers must find ways to become more efficient with their use of water. There are several ways for a grower to increase water use efficiency, namely through more precise timing and application of irrigation. Several methods have been identified, such as the use of water budgets, irrigation based on allowable soil water depletions, and irrigation scheduling (Morgan and Obreza, 2008). While these methods are effective at increasing water use efficiency for mature trees, they are not generally calibrated to young citrus trees. As disease becomes more prevalent, more grove blocks are being completely replanted, so the need for more precise irrigation recommendations for young trees is essential.

The objective of this research was to 1) measure the transpiration of various size trees throughout the dry portions of the Florida citrus growing season; 2) identify correlations between the measured values and weather data collected simultaneously; and 3) use these correlations to create a water use prediction model. One way of estimating young tree water use is through the use of sap flow sensors. These sensors are installed on the trunk of small trees and measure the transpiration of the tree by the stem heat balance theory (Dynamax, Inc., 2005). Using the daily transpiration of the trees we can accurately predict the amount of water used by the trees, and only apply that targeted amount of irrigation to the tree. The use of drip irrigation has a nearly 100% water use efficiency; therefore, with the use of an accurate prediction model, we aimed to accurately apply the amount of water needed by a tree on a daily basis, reducing the amount of water applied while not detrimentally affecting tree growth and yield.

Materials and Methods

Four separate data collection times during typical periods in Florida's dry season (October–May) were used. Young trees were selected for use on the campus of the Citrus Research and Education Center in Lake Alfred, FL. During the monitoring of tree transpiration, local weather was also monitored using the Florida Automated Weather Network (FAWN). Specifically, we used the 15-min observations of the air temperature (2 m height), dew point temperature (2 m height), solar radiation, and wind speed. These values were used to calculate the hourly and daily evapotranspiration (ETo) values using the Hourly Reference Evapotranspiration Calculator, developed by R.L. Snyder at the University of California, Davis (Snyder and Eching, 2001). Five to six trees were selected based on trunk size suitability with sensors. The system used for measuring sap flow was the Dynagage Sap Flow System using the Dynagage sensors SGA10 (9.5–13 mm trunk) and SGA13 (12–16 mm trunk) and SGB 19 (18–23 mm trunk), SGB25 (24–32 mm trunk), SGB35 (32–45 mm trunk), and SGB50 (45–65 mm trunk) (Dynamax, Inc). Before installing sensors, canopy volumes and trunk diameters were measured for analyses with the sap flow data. Each sensor was installed following the manufacturer's instructions and data was collected for at least three full weeks. After installation, an initial adjustment period was allowed for the stabilization of the sensors. For consistency, 15 consecutive days of measurements per installation period were used for analyses. A correlation matrix, linear regression, multiple regressions, and partial least squares (PLS) regression analyses were completed using SAS (SAS Institute, Inc., 2003).

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Results and Discussion

After the first measurement period, hourly data were analyzed. The hourly sap flow measurements (Fig. 1) were observed to be visually correlated with the hourly ETo values and the solar radiation intensity (Fig. 2). A correlation matrix was used to quantify this observed correlation (Table 1). Each tree's observed hourly sap flow was significantly correlated to the observed weather conditions, including ETo, air temperature (T), solar radiation (Rs), and dew point air temperature (Td).

A visual correlation was also observed between the daily sap flow values (Fig. 3) and the ETo and solar radiation values (Fig. 4). A correlation matrix was performed on the daily sap flow observations (Table 2). The data showed all the daily sap flows were correlated significantly with the ETo and solar radiation values. Results for the other three sampling dates showed similar significant results (Fig. 5 and Table 3).

Regression analyses between canopy volume and sap flow (Fig. 6a) and between ETo and sap flow (Fig. 6 b and c) showed that the sap flow can be successfully predicted using these two parameters. Canopy volume was able to account for 80% of the variability in sap flow and the sap flow variability explained by the ETo was greater than 60% for different sensors.

In order to find a model that could be used to estimate the water needs of a citrus tree, PLS regression analyses were performed. The PLS regression analysis was performed using several parameters, such as, ETo, canopy volume, trunk diameter, solar radiation, air temperature, and dew point temperature. The final prediction model, the model with the fewest parameters and the highest R^2, was selected, resulting in ETo and canopy volume parameters, that were found to be the best predictors of sap flow in citrus trees. The prediction model used a pooled data set of all of the daily means for ETo and the measured canopy volumes (CV) for the trees over the four time periods. The regression estimates for the intercept and ETo × CV were used for developing a final model equation. The final equation developed by the model, below, uses transpiration flow (L/tree/day), ETo (mm/day) and canopy volume (CV; m^3).

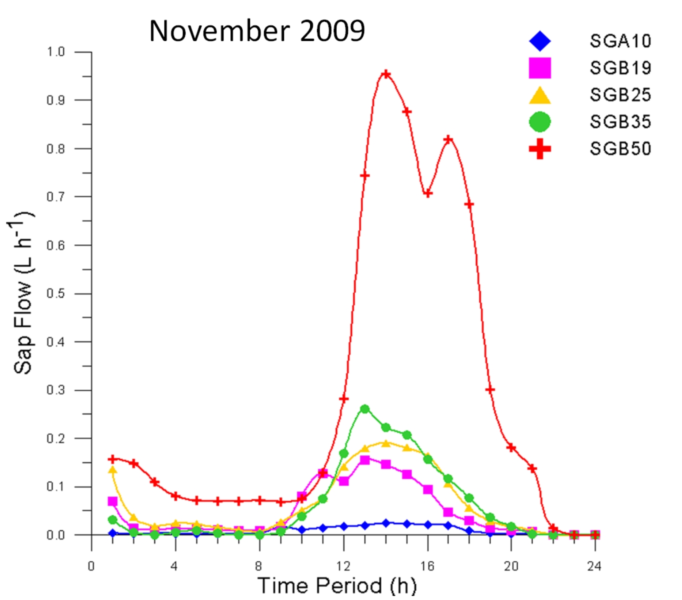

Fig. 1. 27 Nov. 2009: Hourly transpiration for a typical sunny day during this measurement period. SGB10–50 are the different trunk sensor sizes.

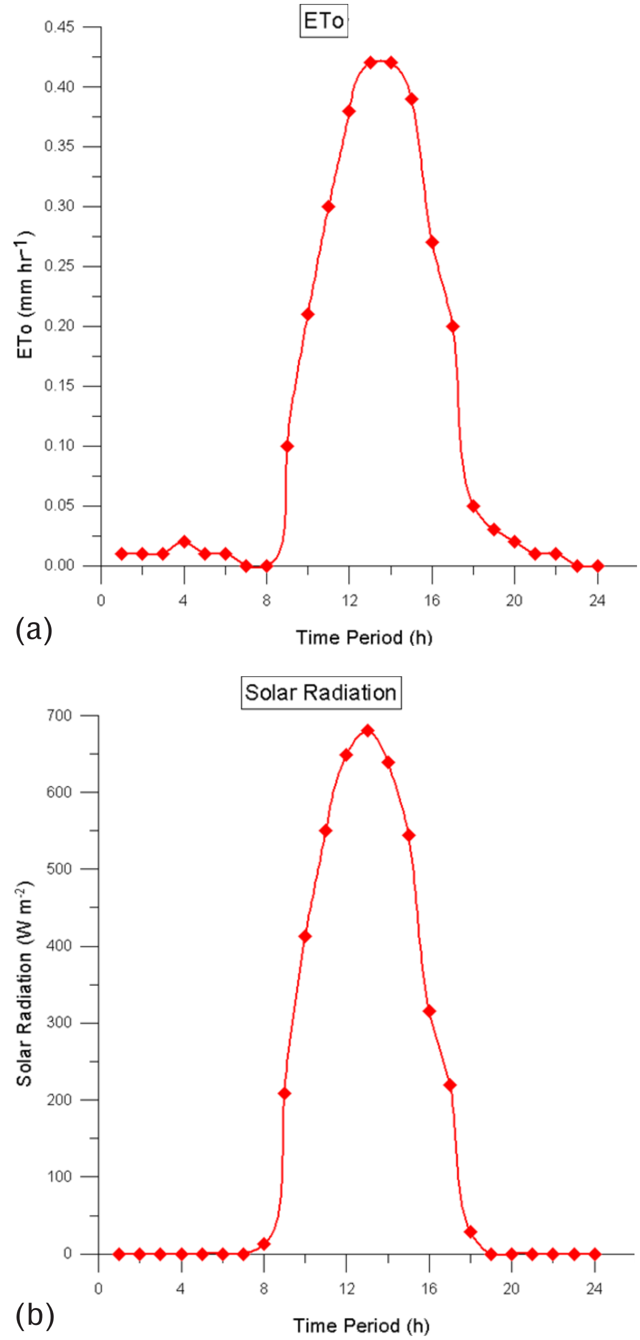

Fig. 2. 27 Nov. 2009: Hourly (**a**) ETo and (**b**) solar radiation for a typical sunny day during this measurement period.

Table 1. Correlation matrix of diunal sap flow and weather parameters for 27 Nov.

	Pearson's correlation (r) and significance			
Sensor	ETo[z]	T	Rs	Td
SGA10	0.93***	0.84***	0.88***	–0.77***
SGB19	0.95***	0.77***	0.94***	–0.59***
SGB25	0.87***	0.85***	0.81***	–0.57**
SGB35	0.93***	0.88***	0.87***	–0.70***
SGB50	0.72***	0.89***	0.60**	–0.67***

[z]ETo = reference crop evapotranspiration; T = air temperature; Rs = solar radiation; Td = dew point air temperature.

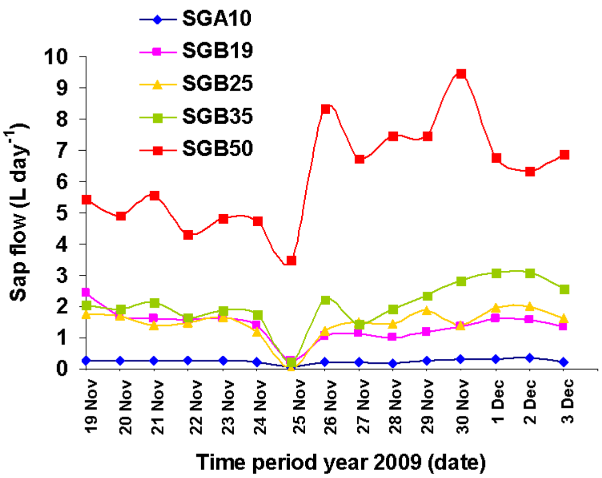

Fig. 3. Daily sap flow for different sap flow sensors (SG10-50) during the experiment.

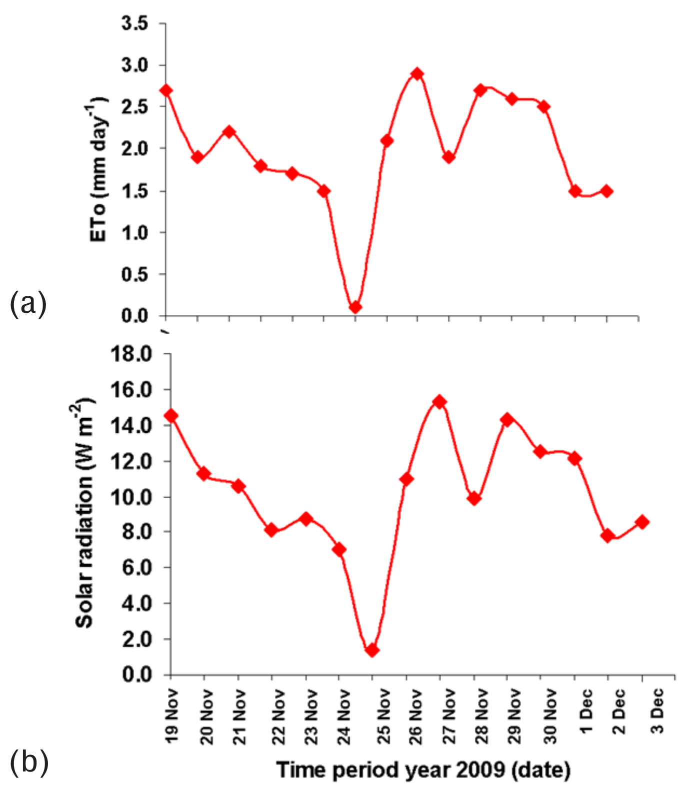

Fig. 4. Daily (**a**) reference crop evapotranspiration (ETo) and (**b**) solar radiation during the experiment.

Table 2. Correlation matrix of daily sap flow and weather parameters during the November–December sampling period.

	Pearson's correlation (r) and significance			
Sensor	ETo[z]	T	Rs	Td
SGA10	0.80***	0.84***	0.72***	0.30 NS
SGB19	0.74***	0.84***	0.69**	0.36 NS
SGB25	0.82***	0.70**	0.78***	0.09 NS
SGB35	0.73***	0.69**	0.65**	0.20 NS
SGB50	0.80***	0.42*	0.74***	–0.14 NS

[z]ETo = reference crop evapotranspiration; T = air temperature; Rs = solar radiation; Td = dew point air temperature.

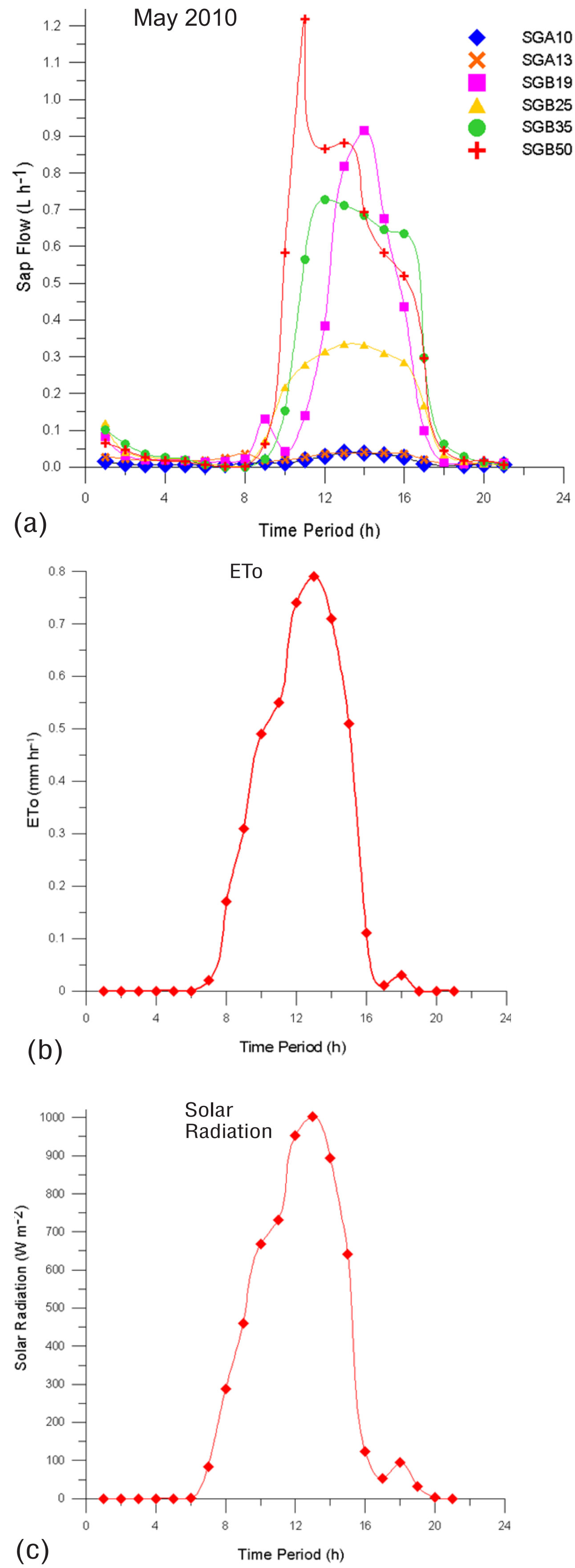

Fig. 5. Daily (**a**) sap flow, (**b**) ETo, (**c**) and solar radiation values for a typical day in May 2010.

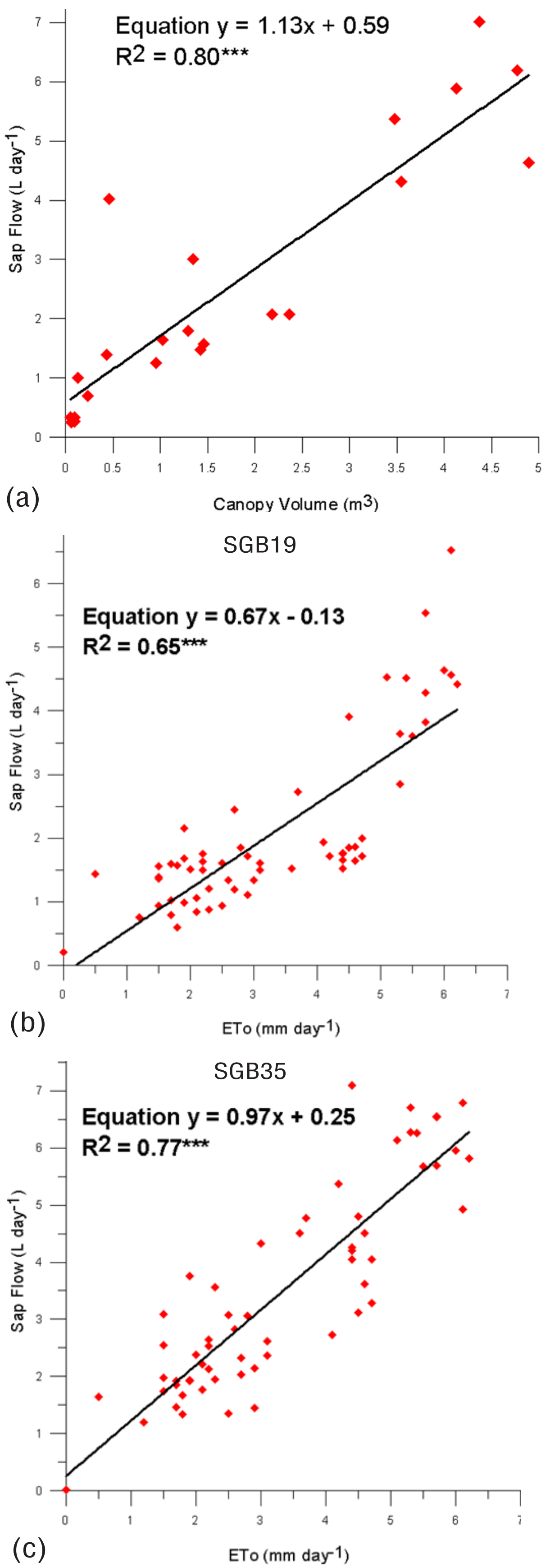

Fig. 6. Linear regression analyses for (**a**) the average sap flow vs. tree canopy volume, (**b**) daily sap flow vs. daily ETo for SGB19, and (**c**) daily sap flow vs. daily ETo for SGB35.

Table 3. Correlation matrix of daily sap flows for 16 May 2010.

	Pearson's correlation (r) and significance	
Sensor	ETo[z]	Rs
SGA10	0.84***	0.81***
SGA13	0.67**	0.65**
SGB19	0.78***	0.75***
SGB25	0.86***	0.83***
SGB35	0.81***	0.79***
SGB50	0.87***	0.86***

[z]ETo = reference crop evapotranspiration; Rs = solar radiation.

Table 4. Cross-validation of actual transpiration for the models developed by the PLS regression analysis.

Period	Sensor	Observed	Predicted
Nov–Dec	SGA10	0.24	0.42
	SGB19	1.34	1.19
	SGB25	1.42	1.63
	SGB35	1.94	2.02
	SGB50	5.91	5.20
Jan–Feb	SGA10	0.26	0.45
	SGB19	1.25	1.32
	SGB25	1.80	1.59
	SGB35	2.07	2.28
	SGB50	4.64	4.24
May	SGA10	0.37	0.57
	SGB19	4.13	2.98
	SGB25	3.12	2.94
	SGB35	5.65	6.04
	SGB50	6.24	7.07
OctSGA10	0.36	0.41	
	SGB19	1.75	2.10
	SGB25	1.64	1.90
	SGB35	3.74	4.50
	SGB50	8.03	7.02
	For all sensors	2.79	2.79
Observed vs. Predicted			
	R^2	---	0.85
	RMSE	---	0.89
	CV	---	31.9
	Significance[z]	---	***

[z]Significant at $P < 0.001$; n = 300. The values in the table are the mean values of 15 measurement days per time period.

The developed model was cross-validated using the 300 observed and predicted measurements (Table 4). This prediction model was able to explain up to 85% of the variation in a tree's water usage for the different time periods of the year. This value suggests that, using only the canopy volume and the daily ETo values, water usage calculated for citrus trees of any size could be used successfully for scheduling irrigation.

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