Applying an Improved Heat Ratio Method Sap Flow Sensor to Almonds to Test for In-Field Variation in Water Use

Project No.: **15-HORT21-Gilbert**

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Objectives:

1) Our objective is to develop and apply a tool that can answer applied types of questions
2) Development of new sap flow sensors "combined sap flow sensors"
3) Validation and calibration of new sensors for almonds
4) Field application and evaluation in a commercial almond orchard

Interpretive Summary:

The core objective of this project has been to develop and evaluate a new sap flow sensor for use in measuring almond water use. We envisage the sensor being used in two manners: as a *quantitative* measure of almond water use, i.e. in units of gallons per tree per day, or acre feet; and as a *qualitative* measure of almond water use to diagnose stress conditions and schedule irrigation i.e. a relative measure over time. To evaluate the new sensors, 12 trees at Nickels Soils Lab (the mature pruning trial) were instrumented with between two and 10 sensors each and have been monitored since April 2016. Separately a weighing lysimeter was used to measure the water use of a tree using an independent method to verify the sap flow sensors.

The sensors and datalogging system were successfully installed and have run for four months, demonstrating the potential for the system to work in commercial orchards. A number of issues were encountered that make it difficult to use the system broadly for *quantitative* measures of almond water use: 1) almond trunks are very variable in the thickness of sap wood (water conducting tissue) and thus adjacent sap flow sensors may measure different values; the significance is that many sensors around the tree and at different depths are necessary to be representative of a tree; 2) it was found that parallel sensor installation was difficult for the thin drills used with the almond wood; the significance is that the spacing of temperature sensors affects the calculation of sap flow, but zero flow corrections were successful in accounting for this issue.
The Combined sap flow method proposed here was successful in measuring sapflow rates in almonds. The observed rates were highly correlated with transpiration measured by weighing.

The Combined method consists of the combination of two alternative methods, heat ratio method (HRM) and compensation heat pulse method (CHPM). The individual methods, HRM and CHPM, did not work well at high flow rates and low flow rates, respectively. The Combined method used the advantages of each and was able to measure the full range of flow rates observed in an almond orchard. The Combined method illustrated a number of useful *qualitative* features of sap flow such as: 1) decreases in tree transpiration due to soil drying in between irrigation cycles, 2) association with stem water potentials, 3) subtle variation in transpiration due to clouds, hot days, and transpiration at night. Thus, the Combined sap flow method appears to be a useful *qualitative* technique that could be generally used by a broad range of people including growers if a packaged system was available. The remaining data from this past season, and 2017 will help fully evaluate the method in relation to other common measurements such as ETo, stem water potential, and soil moisture. The Combined sap flow method appears to be a useful *quantitative* tool for researchers able to install comprehensive arrays of sensors in a few trees.

Materials and Methods:

Sensor production
Sensors were produced using thin stainless steel tubing equivalent to hypodermic needles of sizes 18 and 27 gauge. A precision temperature sensor, a thermistor (E322D103.CA from QTI Thermistors, USA), was placed within the tubing (18 gauge) to measure temperature. A delrin block drilled to the size of the tubing held the tubing securely and sealed the tubing when the two were epoxied together (**Figure 1i**). The epoxy also secured the thin thermistor wire to thicker extension wire that could be attached to a datalogger. A heater was made similarly, but with a coil of manganin wire inserted into the tube instead of the thermistor. The manganin wire was coiled around a 27-gauge tube and inserted into an 18-gauge tube. The coil length was varied to result in a 17-ohm resistance through the heater. A thorough pictorial guide to the manufacture of the sensors is being produced and will be publically available. Each sap flow sensor consisted of three tubes with thermistors, and one heater. Some sensors were built with one thermistor at 28mm depth, and others were built with four sensors at 8, 18, 28 and 38mm depths to explore sap flow variation with depth into the trunk.

Sensor installation
Sensors were installed using an involved process (**Figure 1**) designed to drill parallel holes at spacings of -7.5mm +7.5mm and +22.5mm relative to a fourth hole for the heater (+ indicates downstream or higher in the tree relative to the heater). The hard wood and thin, long drill bits used were not ideal, and future work may productively use thicker needles/tubes and drill bits to result in more parallel drill holes. Thicker needles would have the expense of a greater effect on the tree, and greater artifacts due to wounding.

Field arrangement
Twelve trees were instrumented with sap flow sensors in the pruning trial at Nickels Research Station (6 trees in one pruning treatment, 3 in another and 3 in a further block). Nine of the trees had sap flow sensors placed in the east and west sides of the trunk at a single depth (28mm). Three of the trees had further sensors installed in the north and south sides of the trees at a single depth (28mm) and sensors installed in the east and west side with four depths (8, 18, 28, 38mm). Thus, a total of 42 sap flow sensors were installed or a total of 124

temperature sensors. The trees selected for measurement were six Nonpareil, three Aldrich, two Monterey and one Carmel. The biased arrangement towards more Nonpareil was due to two trees falling over in a strong wind, necessitating reinstallation in adjacent Nonpareil. The trees fell over due to rotting at the base – unrelated to the current experiment.

Each instrumented tree was paired with soil moisture sensors (10HS sensors, Decagon Devices, USA) at two depths (20 and 60 cm; 8 and 24 inches). A weather station was installed 2 meters above the canopy on a tower. Each of the three blocks were measured by a CR1000 datalogger and AM16/32 multiplexers (Campbel Scientific, USA), and each was powered by a 20W solar panel connected to one 12-amp hour sealed lead acid battery.

Figure 1. Installation of sap flow system in orchard at Nickels Soils Lab: smoothing of bark with chisel (panel a to b), installation of steel manifold for drilling of holes at specific spacing (c), drilling holes using 90º frame (d) four holes for a sap flow sensor (e), temperature sensors and heater installed for one sap flow sensor (f), wiring boxes (with ten sap flow sensors four wiring boxes were needed for this tree, typical trees would have one wiring box; g), Reflectix weather proofing added to tree and datalogger box in line with the row, trees across the row had cables installed at 8 inch depth below soil to avoid tractor entanglement (h), illustration of one temperature sensor, the metal needle is 1.5 inches in length and epoxied into a delrin (black) base (i).

Data analysis
The sap flow data were analyzed using a program written in the free data analysis program *R*. Briefly, the analysis consisted of: 1) conversion of the mV thermistor measurements into temperatures, 2) calculation of temperature transients for each heat pulse applied, 3) calculation of the HRM sap flow value using the two lower temperature sensors in each sap flow sensor, 4) calculation of the CHPM sap flow value for the highest and lowest sensors, 5) calculation of the Combined method sap flow value. These data were then adjusted for zero flow conditions to account for variation in the distances between each sensor (non-parallel geometry). All of the calculations were performed as per Burgess et al. (2001), Bleby et al. (2004) and Marshall (1958). The Combined method was defined as follows for simplicity. The motivation was to be able to use the Combined method as an easy-to-program sap flow output directly from a datalogger, and thus useful for growers. Alternative definitions for the Combined method would involve statistical analysis and be better suited for post hoc data analysis by researchers.

IF $V_{\mathrm{CHPM}} > V_{\mathrm{HRM}}$ and $V_{\mathrm{HRM}} > 5\ \mathrm{cm\ hr^{-1}}$
THEN $V_{\mathrm{Combined}} = V_{\mathrm{CHPM}}$
ELSE $V_{\mathrm{Combined}} = V_{\mathrm{HRM}}$

Where V_{CHPM} is the heat pulse velocity, proportional to the water flow velocity using the CHPM method; V_{Combined} and V_{HRM} are the equivalent velocities for the proposed Combined method and HRM method. The data analysis program is available to the public upon request.

Results and Discussion:

Quantitative scaling sap flow up to tree water use
Sap flow measurements must be representative of the tree to be useful in scaling up sap flow to a tree or orchard level. The variation in sap flow with direction around the trunk and with depth in the trunk were investigated to evaluate how many sensors are necessary to be representative of the water use for a tree.

Tree cross sections were evaluated where the trees had fallen during strong wind events (**Figure 2**). Typical almonds had considerable variation in the depth of sap wood varying between 0 and 2 inches in depth – the wood that conducts water. Thus, in order to accurately scale sap flow measurements up to the tree, the cross sectional area of sap wood will be difficult to measure in intact trees. To adequately do this, researchers would need to install in each tree at least four sensors with multiple sensing depths. The current experiment was designed to do this, and found that the direction that the sensor was inserted from played a variable role in the measured sap flow rates (**Figure 3**). Similarly, sensor depth resulted in varying sap flow rates (**Figure 4**). Little consistent pattern is evident, but as a general rule for future work, it appears that sensors sometimes are too shallow or deep, being outside of the sap wood. Thus sensors should be placed at between 15 and 30mm depth. The majority of sensors in this study were at 28mm and thus were representative of the main flow region in the trunk.

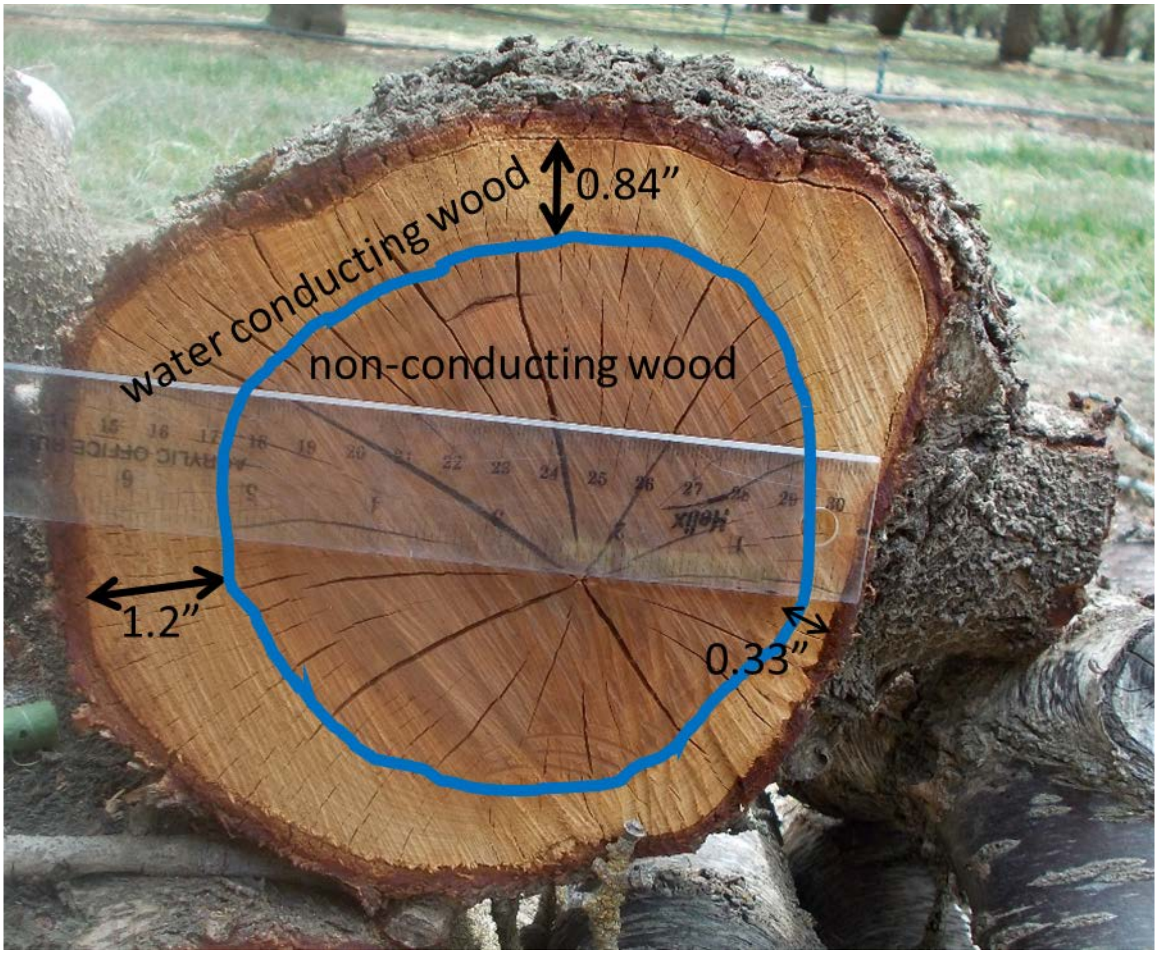

Figure 2. Typical variation in thickness of water conducting sap wood around a Nonpareil almond trunk. In other trunks, sap wood thickness can be zero in some directions. Quantative scaling of sap flow measurements up to tree water use are dependent upon knowledge of total sap wood area in the trunk, and the sensor placement relative to the sap wood depth.

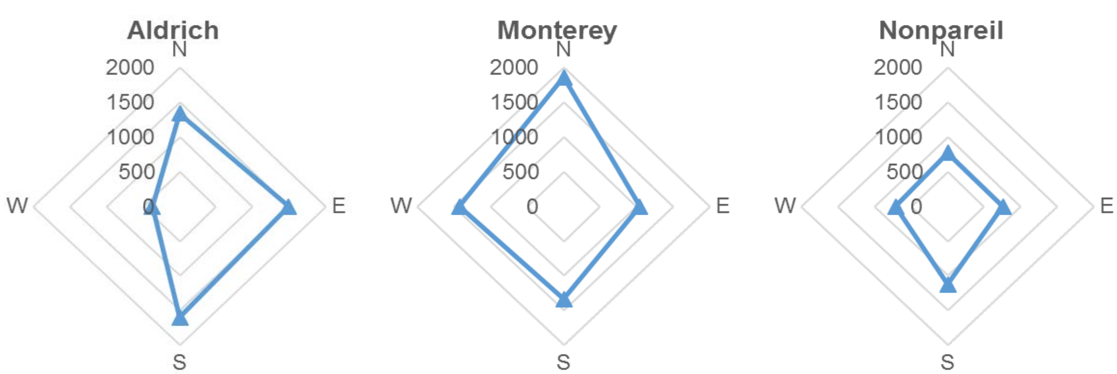

Figure 3. Illustrative cumulative daily flow rates (cm hr^{-1}) for three trees of three varieties showing different sap flows with direction in tree. The variation partially reflects the variation in water conductive sap wood thickness around the tree. These data represent one tree per almond variety, and thus are not representative of that variety.

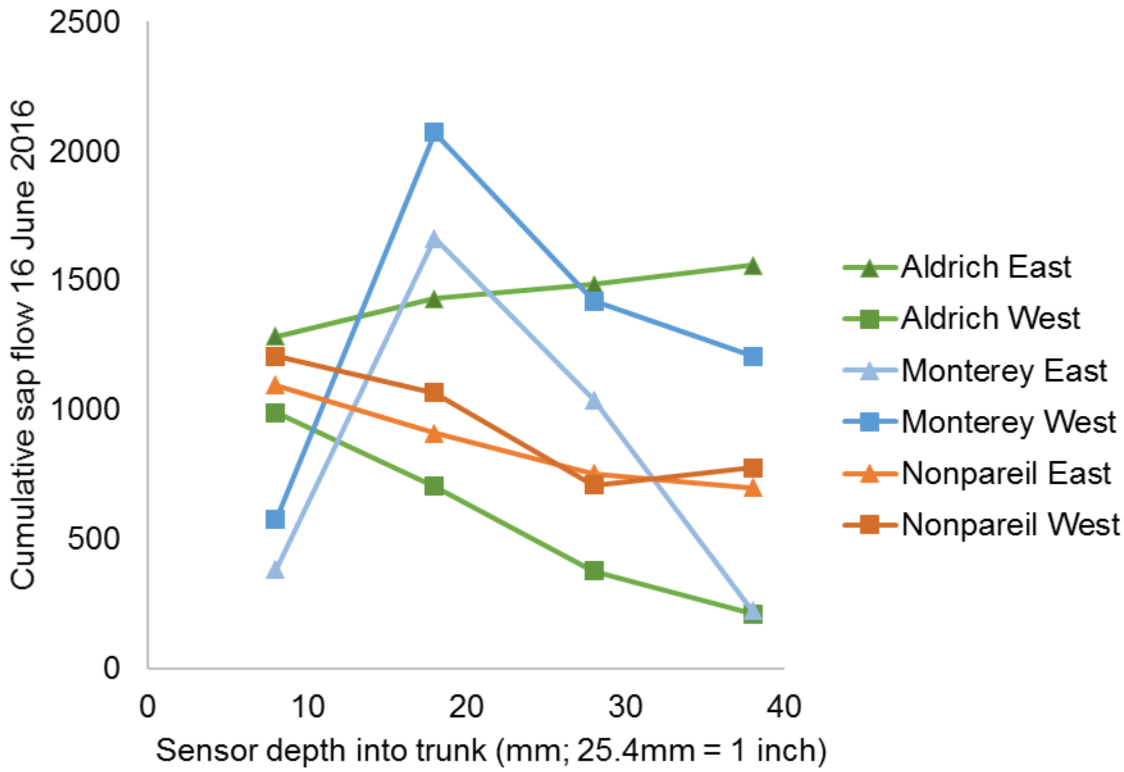

Figure 4. Variation in sap flow with depth of the sensor into the trunk for three varieties and in two directions. The variation partially reflects the variation in water conductive sap wood thickness around the tree. These data represent one tree per almond variety, and thus are not representative of that variety.

Can sap flow sensors be used to quantitatively measure tree/orchard water use?
The large variation in trunk sap wood thickness found for almond makes it difficult to quantitatively scale up sap flow measurements from just one or two sensors per tree. Thus it is recommended that quantitative scaling of sap flow to orchard water use is limited to researchers who are able to install and run an intensive array of sensors (10's per tree). This conclusion is general for sap flow sensors of any technology and all available commercial sensors. HRM, CHPM, Granier-type and Combined method sensors would all operate in a generally similar manner requiring measurements in multiple directions around the trunk and at multiple depths to be quantitatively representative. Heat balance sensors are slightly different as they do not measure trunks of almonds greater than about 3rd leaf, and thus are limited to smaller branches on older almonds. Thus heat balance sensors have a similar problem to the others – they must measure multiple branches to be representative of the tree.

These considerations do not preclude the use of sap flow technology for qualitative measurements of sap flow over time, as explored next.

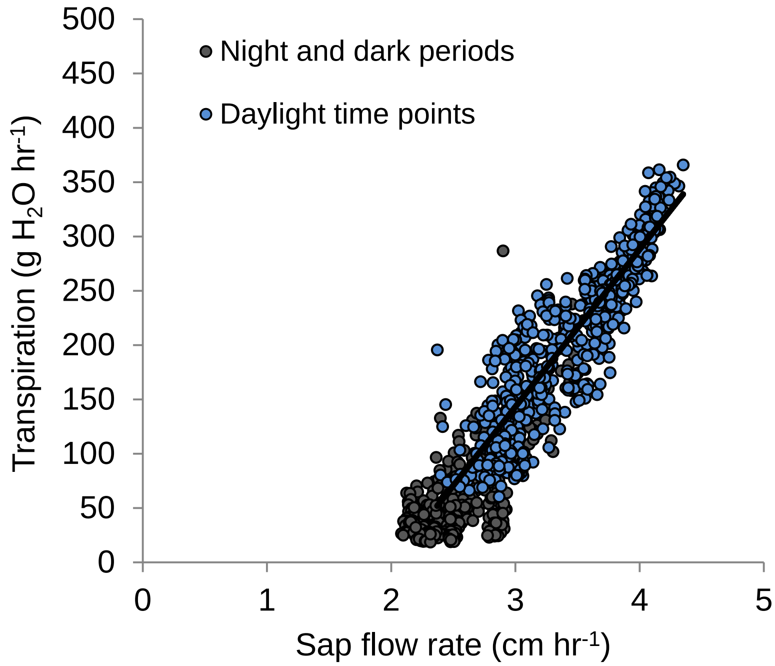

Figure 5. Correspondence of weighing lysimeter measurement of transpiration, and sap flow measurement. These data represent a two-week period during which measurements were made every 15 minutes. A zero flow correction was not performed for this tree, meaning that non-parallel temperature sensors resulted in the prediction of 2 cm hr^{-1} flow rate at a measured transpiration of zero.

Performance of the Combined sap flow method: lysimeter

Sap flow sensors were installed in a 3rd leaf almond situated in a large pot on a 200-pound load cell. The intention was to evaluate the Combined method relative to the independent measure of transpiration through weighing the pot. However, the lysimeter tree displayed signs of stress, and did not have high enough sap flow rates to adequately evaluate the Combined method (**Figure 5**). The Combined sap flow rate was well correlated with weighing based transpiration (R^2 = 0.82), but the majority of measurements were at flow rates where the HRM technique was preferred over the CHPM technique – an unideal situation for the evaluation of the Combined method which used both the HRM and CHPM. Thus, little further analysis was attempted for the lysimeter data. However, the strong correlation found for the small range of sap flow values is a good sign that the sap flow sensors were performing well.

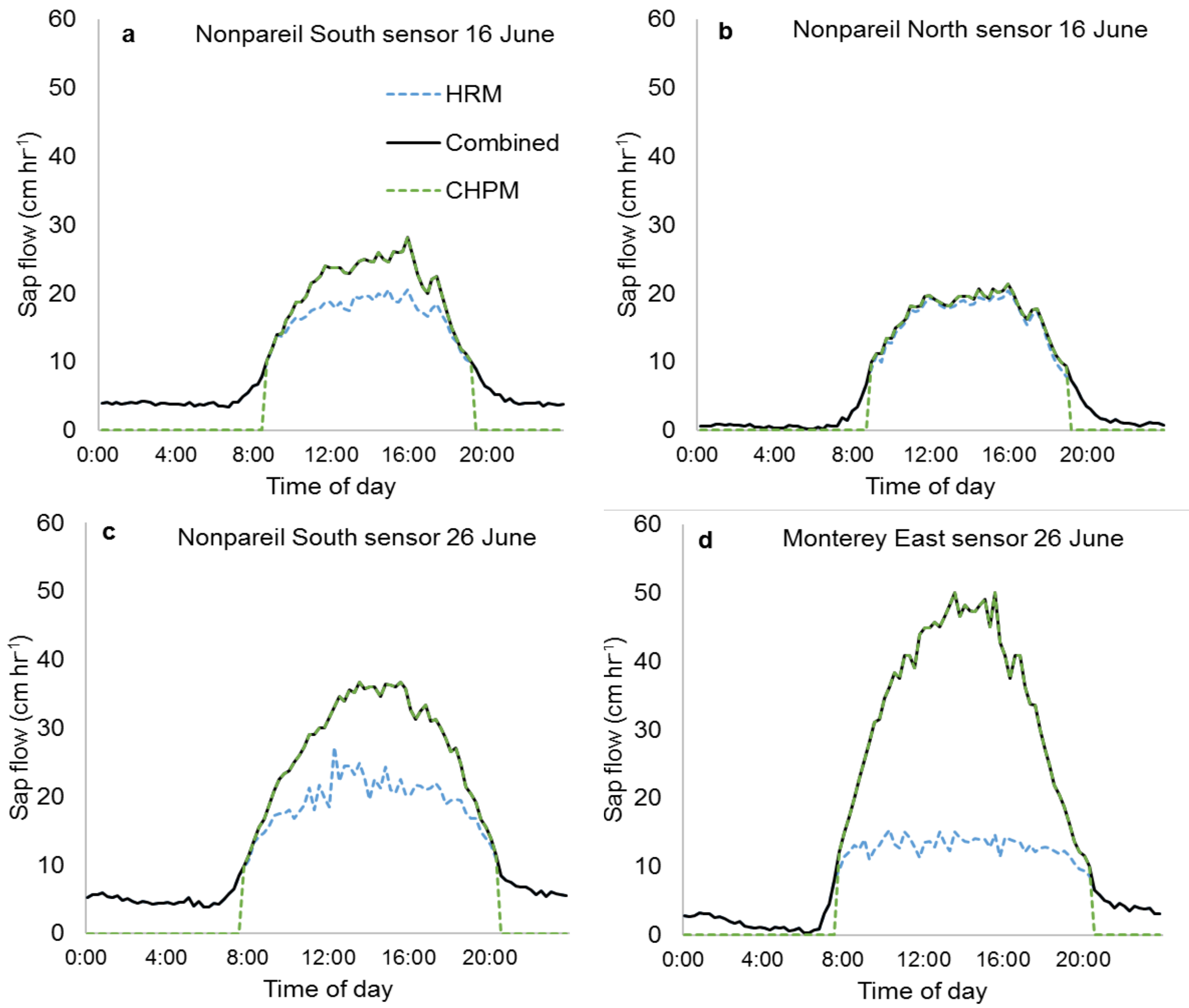

Figure 6. Comparison of the HRM sap flow method with the CHPM method and the Combined method shown here. The Combined method uses the HRM method at night and during days of low evaporative demand (panel b), when that method is most sensitive and CHPM does not work, but switches to the CHPM method when flow rates are high during the day (panel c and d). These data represent a low evaporative demand day (16 June) and a high evaporative demand day (26 June) for typical trees. Rates shown here were measured every 15 minutes (144 measurements per day).

Performance of the Combined sap flow method: commercial orchard

The Combined method calculates the sap flow rate from the greater of the HRM or CHPM estimates of sap flow (**Figure 6**). Illustrative sap flow rates for the 16th and 26th of June are shown, days of low and high reference evapotranspiration (ETo). For typical low sap flow rates on low ETo days the HRM technique can underestimate sap flow (panel a), while some sensors show that the two methods are comparable at low flows (panel b); on high ETo days HRM method can be noisy (panel c) and underestimate sap flow by up to three fold (panel c and d). Thus, the combination of the two methods in the Combined method functioned well under a broad range of circumstances and seems a substantial improvement over either of the HRM or CHPM methods. For instance, use of just the HRM method, a common commercial sensor, would miss a considerable amount of transpiration that occurs in the middle of the day, and thus not be representative of almond peak water use.

Previous calculations suggest that the HRM method can function up to sap flow rates of 36 cm hr^{-1} using the sensor spacing used here (Burgess et al. 2001). Considerable periods of the year had sap flow rates in excess of the 36cm hr^{-1} (e.g. **Figure 6d**), lending theoretical support to our findings. Closer spacing of the sensors would allow the HRM method to measure higher flow rates. But closer spacing would increase the sensitivity of the method to non-parallel geometry, which was a big problem in almonds even with the wider spacing used here. Thus it seems theoretically and practically difficult to use the HRM sensor alone for measuring almond sap flow.

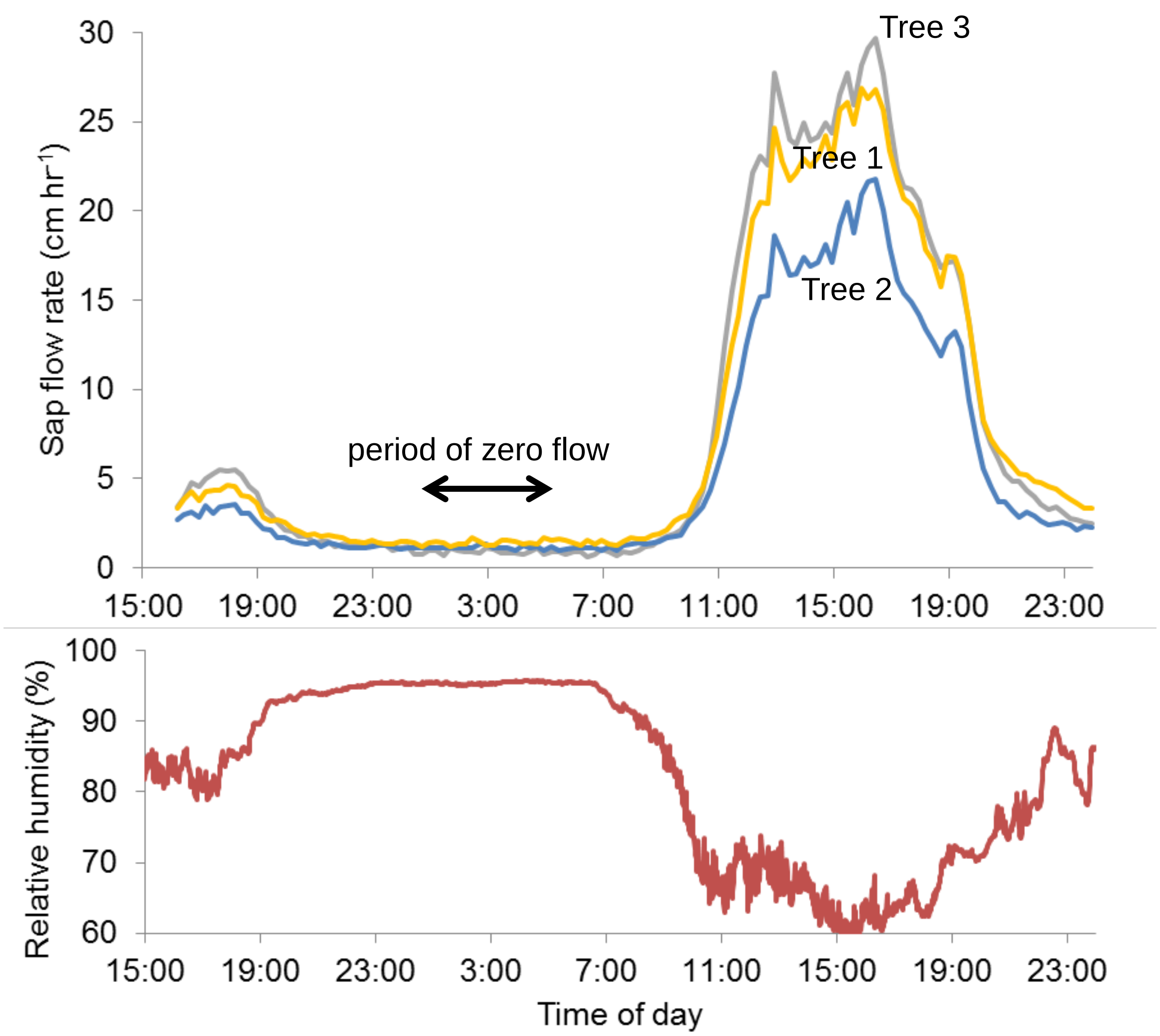

Figure 7. Illustrative sap flows measured during period of zero flow – a rainy night. The sap flow rates shown above are for the Combined method where the sensor spacing was calibrated for zero flow.

The major effect of non-parallel sensors is the apparently elevated rates of flow that occur under conditions of very low flow. Thus, a necessary step for the use of the HRM method or the Combined method is to calibrate the sensors under conditions of zero flow (**Figure 7**). Specifically, a period with no transpiration must occur, in the case of this study a rainy night where relative humidity reached >95% for more than 5 hours. The spacings of the sensors are then adjusted to result in the observed sap flow rates reading zero under these conditions. The issue of non-parallel sensors is not ideal, and the zero flow must be performed, necessitating the early installation of sensors while the tree either has no leaves, or early in the year before a period of light rain. While this is a limitation to the application of the method, the calibration did work well when performed.

The Combined method was able to measure sap flow under a wide range of conditions (**Figure 8**) and illustrates its use as a qualitative measure of plant water status. Sap flow was sensitive to cloud conditions that would affect evapotranspiration (the depression in solar radiation on the 23 May was associated with a large decrease in sap flow; **Figure 8**). The initial four days show decreasing soil water contents, but low reference evapotranspiration (shown here as its main components: solar radiation and air temperature). Consequently, the sap flow rates for each tree were low and apparently unaffected by the soil water deficit. The final four days represent greatly increasing air temperature (approaching 100ºF) and fewer clouds, while the soil water content drops below the values before. The increasing reference evapotranspiration and soil water deficit result in varying responses, with tree 2 showing stress and decreasing sap flow the most, while tree 3 increases slightly. The variation in sap flow corresponds well to drops in stem water potentials – confirmation of stress in the two trees that decreased sap flow.

The combination of atmospheric sensors, measuring components of reference evapotranspiration (ETo), plant water status sensors (Combined method of sap flow). and soil moisture sensors leads to unique insights into the water dynamics in this orchard. It appears that irrigation during this period was not sufficient to hydrate the soil down to 24 inches, and that this lack of rehydration led to limited plant water availability under conditions of high reference evapotranspiration. The sap flow measurements also illustrate that different trees have widely different responses. In this case, the trees were three varieties. Future work on this experiment is focusing on using the intensive sap flow system to compare variety water use.

Acknowledgements:

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Research Effort Recent Publications:

A collaborative scientific paper on the new sap flow method used here is being drafted with the University of Sydney.

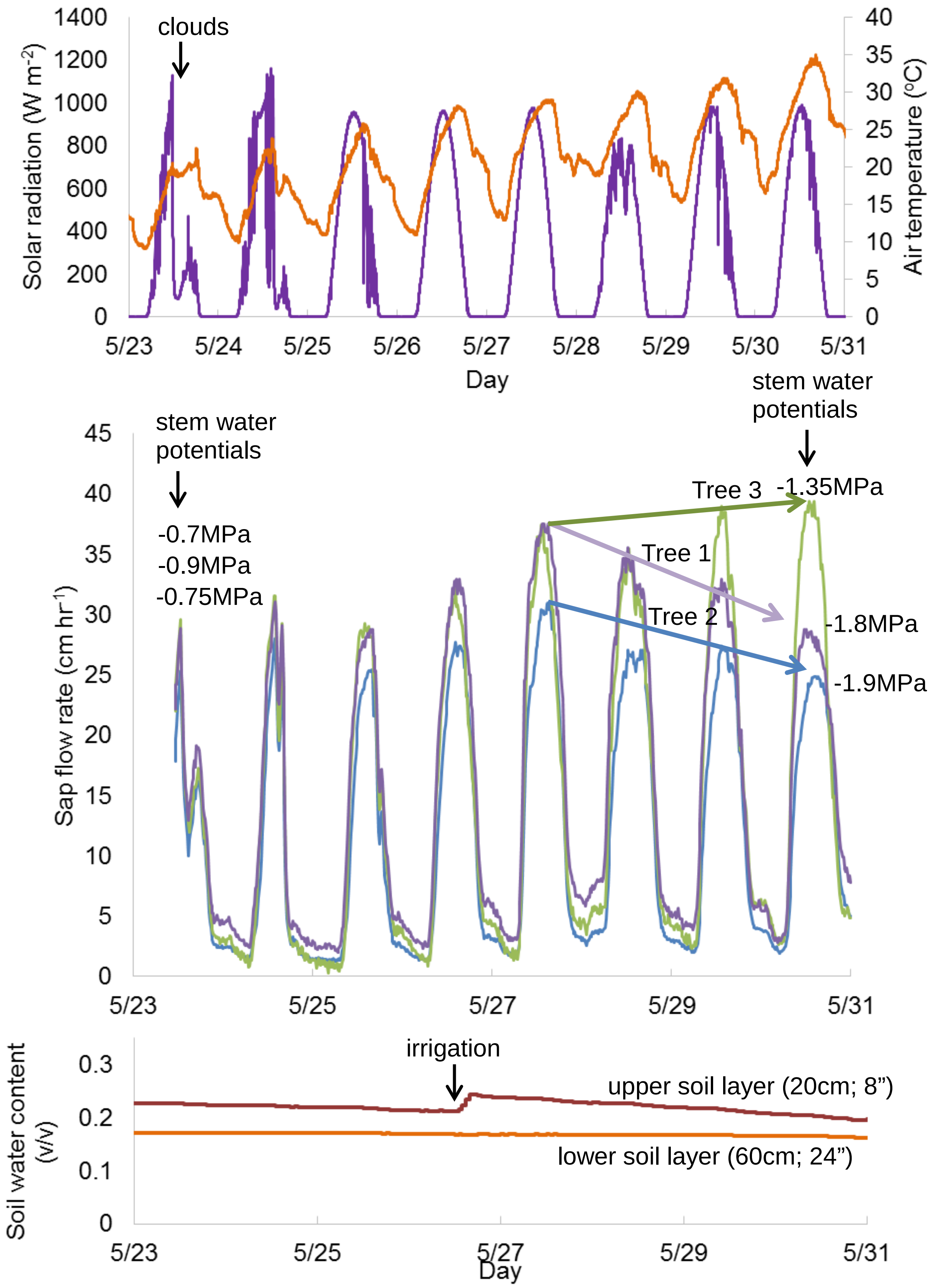

Figure 8. Illustrative sap flows during a hot period with one irrigation event. Volumetric soil water contents were average values for two depths across the orchard.

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