FINAL PROJECT REPORT

Project Title: Development of economical wifi-connected open-source sap flux probes

PI: Stephen Good
Organization: Oregon State University
Telephone: (541) 737-2118
Email: Stephen.good@oregonstate.edu
Address: 200 Gilmore Hall
Address 2: Oregon State University
City/State/Zip: Corvallis, OR 97331

Co-PI (2): Chet Udell
Organization: Oregon State University
Telephone: (541) 737-4043
Email: udellc@oregonstate.edu
Address: 234 Gilmore Annex
Address 2: Oregon State University
City/State/Zip: Corvallis, OR 97331

Co-PI(3): Nik Wiman
Organization: Oregon State University
Telephone: (541) 250-6762
Email: Nik.wiman@oregonstate.edu
Address: 4109 ALS
Address 2: Oregon State University
City/State/Zip: Corvallis, OR 97331

Cooperators: Oregon State University Experiment Farms

Percentage time per crop: Apple: 25% Pear: 25% Cherry: 25% Stone Fruit: 25%

Other funding sources: None

Total Project Funding: $86,320

Budget History:

Item	**Year 1:**	**Year 2:**	**Year 3:**
Salaries	$26,745	$27,379	
Benefits	$5,978	$6,218	
Wages			
Benefits			
Equipment			
Supplies	$7,500	$7,500	
Travel	$2,500	$2,500	
Plot Fees			
Miscellaneous			
Total	$42,723	$43,597	**No-cost extension**

Project Justification

In order to maximize orchard productivity while minimizing costs, tree fruit producers require accurate information about water use, particularly crop transpiration rates. This information is necessary to evaluate crop status and determine irrigation requirements. Often, water use information is obtained from estimated evapotranspiration rates from regional weather station networks such as AgWeatherNet (https://weather.wsu.edu) and AgriMet (https://www.usbr.gov/pn/agrimet/). However, orchard-level crop water use estimates may provide a poor representation of evapotranspiration when weather stations are not located within orchards. A common solution to this problem is to install meteorological sensors on-site at specific orchards. Highly accurate techniques such as surface renewal or eddy covariance systems are capable of measuring evapotranspiration rates locally. Yet these systems can be very costly to obtain and complicated to run. When estimates of local water use are based on simpler meteorological data from local stations (such as temperature and humidity), complex meteorological models (e.g. FAO56 [1]) are needed that are prone to errors in evapotranspiration estimates.

The most direct way to measure orchard-level water use is through sap flux probes, which are inserted into the trunks or stems of trees to monitor the vertical flow of water. These sap flux probe systems can provide direct estimates of the water passing through the stem/trunk of individual plants. Sap flux measurements can be made at high frequency (e.g. every half hour) to evaluate how water use varies throughout the day, or integrated over longer periods to determine total water use by an individual tree at daily or weekly timescales. Currently, these systems are very costly and often difficult for end users to implement effectively.

In this project, we proposed to develop an economical, open-source, wifi-connected sap flux measurement package. These new sap sensors are based on previously developed approaches for measurement, logging, and calculations of sap flux that have been recently published in academic journals. The development of this sap flux instrumentation has occurred at the Openly Published Environmental Sensing Laboratory (OPEnS Lab: http://www.open-sensing.org) at Oregon State University, which is devoted to developing similar low-cost 'internet of agriculture' technology solutions. It is expected that as a result of this proposal we will make available to tree fruit growers in the Pacific Northwest, and elsewhere, an alternative method for monitoring orchard water use that commercial growers can implement economically and effectively. The final objective of this project is the publication of a technical publication, with an associated computer program, that describes how to build, install, and operate a sap flux monitoring network with little prior experience in electronics or computer programing.

Project Objectives

This project consists of three objectives:

(1) Develop low-cost alternatives to commercially available sap-flux monitoring systems. These probes will be based on published designs recently made available in academic/research literature that are not accessible to typical tree fruit producers.

(2) Develop wi-fi connectivity protocols that will allow these new sap-flux probes to be monitored remotely via the world-wide web. Measurements will be converted to tree and stand level evapotranspiration measurements and placed online for end users.

(3) Make available, as extension publications and online, both the probe design and wi-fi connectivity protocols in a format where users with little technical experience can construct/create their own networks with minimal effort.

Significant Findings

Project Accomplishments

This project was successfully able to construct and validate a low-cost sap flux probe. Key successes of our probes' configuration are:

- Employs a cost microcontroller: 'Adafruit M0 Feather' and thus no additional datalogger are needed
- Has a flexible printed circuit board (PCB) probe so depth can be easily adjusted
- Uses the heat ratio methods (RHM) to directly solve for the sap flow and is much more accurate than the empirical thermal dissipation probe (TDP) approach
- Includes a custom amplifier to provide improved precision at low cost
- Total system cost is $302, which includes the enclosure, printed circuit boards, electrical comports, and battery (this is a significant reduction over commercially available options).
- Open source design and source files are freely available for anyone to use
- The root mean squared error (RMSE) of this probe relative to a corrected Dynamax TDP system is 11.7 liters per day when integrated over a 24hr period, with an r^2 of 0.90.

Relevance for Pacific Northwest Tree Fruit Producers

This project directly addresses a number of key priorities for technology development in the tree fruit production. Our objectives are designed in a manner so as to be directly beneficial to tree fruit growers in the Pacific Northwest.

It is expected that the direct, accurate, and low-cost monitoring of orchard-level water use obtained through the development of these probes will allow growers to reduce production costs while ensuring premium quality fruit is grown for the consumer. This is because accurate water use monitoring will allow for precision application of required water at the stand, or individual tree, level. Effectively, growers will be able to adjust irrigation rates to achieve desired transpiration rates.

Furthermore, accurate water use monitoring will allow for direct surveillance of orchard blocks, and fruit trees that are in danger of drought damage can be identified remotely. When individual or stand transpiration rates fall below critical thresholds, this signals that trees in these locations are not growing properly and should be investigated in person.

Finally, because transpiration, as directly measured in the sap flux probes, occurs only when leaf stomata are open during photosynthesis, transpiration rates can be related to biomass accumulation via photosynthesis. Sap flux measurements can be integrated as the growing season progresses to provide estimates of how much carbon has been assimilated by each individual tree or stand. These can then be translated in to yield predictions for the final end of season harvest.

Results

Probe Design and Fabrication

Our design makes use of the commonly used Adafruit M0 LoRa Feather Microcontroller. There are three custom PCBs used in our design. The three custom PCBs are shown in Figure 1. On the physical probe itself, there is the flex probe PCB which contains three RTDs (Resistance Temperature Detectors)

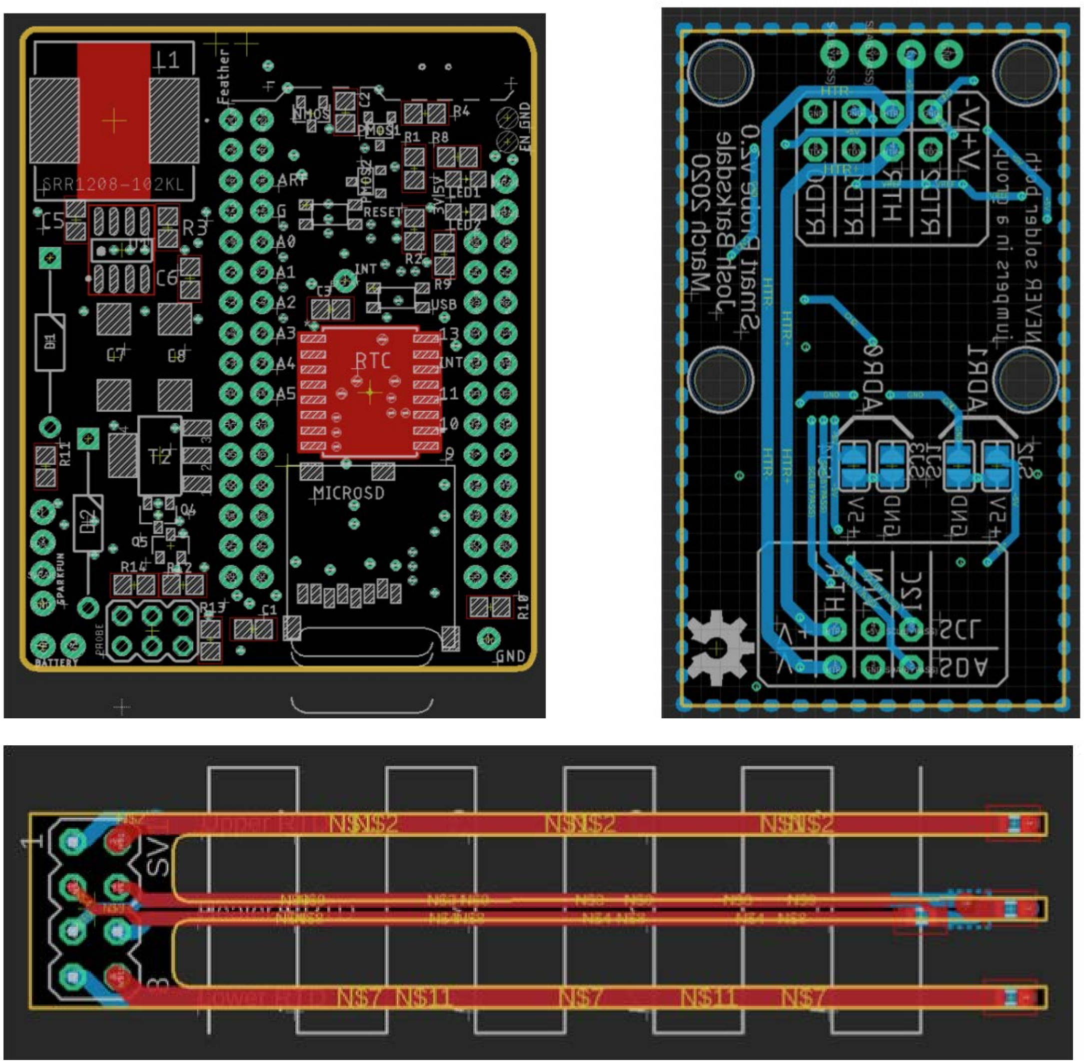


Figure 1: The three custom PCBs developed as part of this project. The Sap Flux Wing (upper left) connects to the Smart Prob PCB (upper right), which connects to the flex prob (bottom)

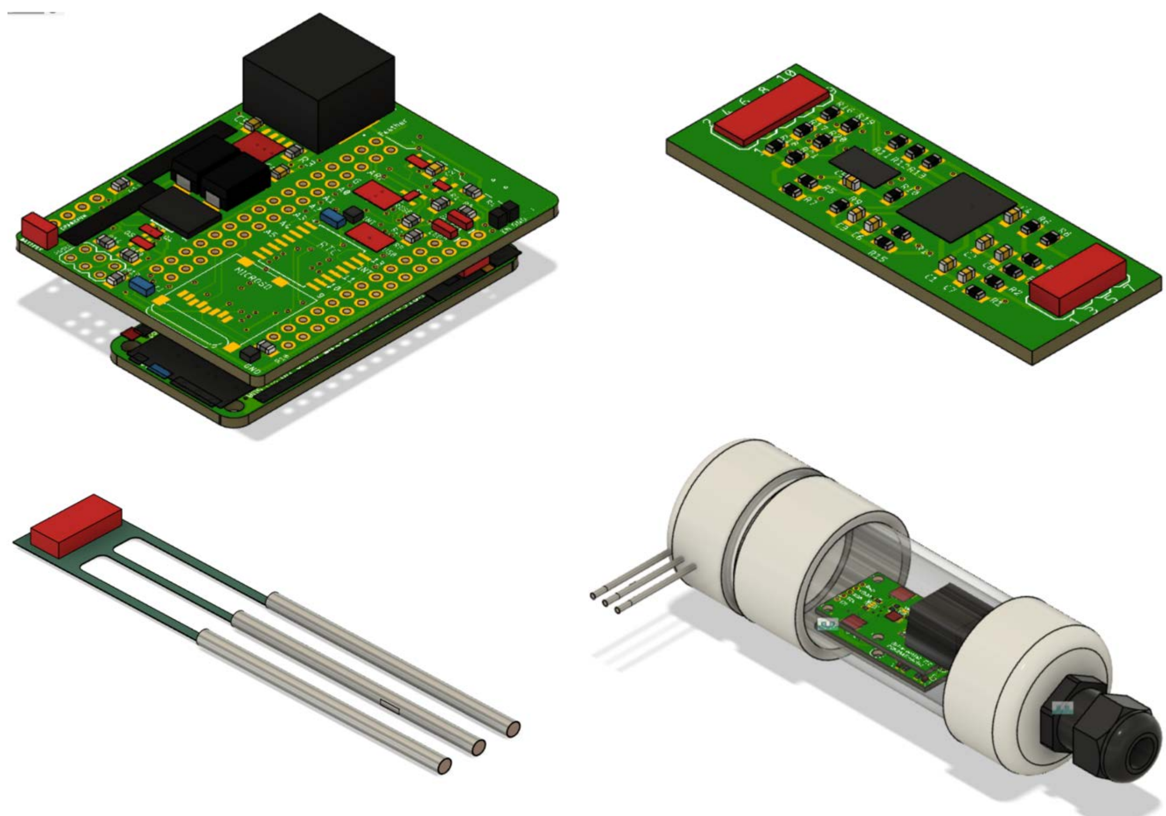


Figure 2: 3D Fusion renders of the Sap Flow Wing (upper left), the smart probe PCB (upper right), the flex PCB (lower left) and assumed probe (bottom right).

and a heater resistor for the heat pulse sap flow calculation. The Flex probe PCB connects to the Smart Probe PCB which contains a filter and an ADC (analog to digital converter) for converting the RTD values into binary values. The Smart Probe connects to the Sapflow wing over a CAT5 (Ethernet) cable. This part of the design makes use of two SparkFun Differential I2C Breakouts to send the sap flow data over a CAT5 cable using the I2C communication protocol. This data is received. The most complex is the Sapflow wing, which contains a micro sd slot, a real time clock as well as the micro controller. 3D Fusion renders of the developed electronics are shown in Figure 2. The flex PCB and Smart Probe PCB are housed within readily available PVC tubing. For ease of installation and to ensure good thermal contact between RTDs and the tree itself, the flex probes are inserted into steel tubing and filled with thermal paste.

Design files are hosted on the OPENs website at Oregon State University. The URLs to download these files are listed in Table 1. In total 9 files are avalible. These include **flex_probe.brd**, which details the PCB layout for FlexProbe PCB; **flex_probe.sch,** which details the schematic for FlexProbe PCB; **sapflow_v4.brd** which details the PCB layout for SapflowWing PCB; **sapflow_v4.sch** which details the schematic for SapflowWing PCB; **smart_probe.brd** which details the PCB layout for SmartProbe PCB; **smart_probe.sch** which details the schematic for SmartProbe PCB; **better_header.libr** which details the PCB Library with improved header pin footprints; **sapflow.libr** which details the PCB Library containing several components used in the project; **MCP3424-E_SL.libr** which details the PCB Library containing footprint for ADC IC. The sapflow bill of materials is very large and will officially be linked with Open Science Framework (OSF). Currently we provide a URL to a Google Sheets document containing everything used in the last field deployment (https://docs.google.com/spreadsheets/d/1jbjz2JIk6myMRL4v5k-S3q_fC6cAR19Av14QS87rkHA/edit?usp=sharing). Total cost of this system is $302 dollars. This includes everything needed to create a functioning probe.

Design file name	File type	Location of the file
flex_probe.brd	PCB CAD	https://github.com/OPEnSLab-OSU/PCB/tree/master/Sapflow/flex_probe
flex_probe.sch	PCB CAD	https://github.com/OPEnSLab-OSU/PCB/tree/master/Sapflow/flex_probe
sapflow_v4.brd	PCB CAD	https://github.com/OPEnSLab-OSU/PCB/tree/master/Sapflow/sapflow_v4
sapflow_v4.sch	PCB CAD	https://github.com/OPEnSLab-OSU/PCB/tree/master/Sapflow/sapflow_v4
smart_probe.brd	PCB CAD	https://github.com/OPEnSLab-OSU/PCB/tree/master/Sapflow/smart_probe
smart_probe.sch	PCB CAD	https://github.com/OPEnSLab-OSU/PCB/tree/master/Sapflow/smart_probe
better_header.libr	PCB Library	https://github.com/OPEnSLab-OSU/PCB/tree/master/Sapflow/smart_probe
sapflow.libr	PCB Library	https://github.com/OPEnSLab-OSU/PCB/tree/master/Sapflow/smart_probe
MCP3424-E_SL.libr	PCB Library	https://github.com/OPEnSLab-OSU/PCB/tree/master/Sapflow/smart_probe

Table 1: Design Files and their URLs

Probe Installation and Operation

The probe installation approach is detailed in table 2. No specialized tools are required beyond a hand drill. Hydrogen peroxide is used to maintain sanitary conditions and is easily obtained at pharmacy.

Step 1: Use the drilling jig to start drilling the three holes. The drill bit used should be 2mm in diameter, the size of the holes in the jig	

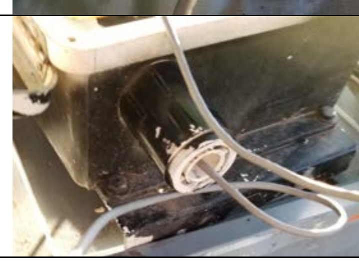
Step 2: Change out the drill bit for one that is slightly larger than the 2mm probes. This is a somewhat subjective process. Drill again in the same holes.	
Step 3: Flux out the holes with hydrogen peroxide. A simple syringe is used to inject the hydrogen peroxide into the drilled holes	
Step 4: Now that the hole is drilled, insert and secure the probe.	
Step 4: Twist the grip on the bottom of the probe to close off any openings and to hold the cord firmly in place	
Step 5: Feed the CAT5 cable into the enclosure. Verify connections. The Cat5 cable should be connected to a sparkfun breakout which makes I^2C and heater connections with the sap flow wing board.	

Table 2: Installation approach.

Data from the SapFlow system is logged directly to an SD card. Reconfiguration with a LoRa wireless technology is also possible though not implemented in the current design.

Sap flow is calculated following Burgess et. al. [2] using the heat ratio method. The heat pulse velocity (V_h) is calculated as

$$V_h = \frac{k}{x} \ln\left(\frac{v_1}{v_2}\right) 3600$$

where k is the thermal diffusivity of green wood (2.5×10^{-3} cm^2 s^{-1}), x is the distance between the heater and either temperature probe and v_1 and v_2 are the increases in temperature from baseline conditions measured at each RDT. In our configuration probes are spaced (x) at 0.5cm above and below the heater. After installation of the probes nonconducting wood forms around the site of installation. The corrected heat pulse velocity (V_c) is calculated as

$$V_c = bV_h + cV_h^2 + dV_h^3$$

where b = 1.8558, c = -0.0018, and d = 0.0003 [2]. Finally, the corrected heat pulse velocity is translated into a sap velocity (V_s) as

$$V_s = V_c \frac{\rho_w}{\rho_s} \frac{(c_w + m_c c_s)}{c_s}$$

where ρ_w and ρ_s are the densities of wood and sap respectively. The density of cherry wood is used and taken to be 451.2 kg/m^3 [3], while the sap density is taken to be 997 kg/m^3 (from water). The specific heat capacity of wood, c_w = 1200 J kg^{-1} C^{-1}, and of sap c_s = 4182 J kg^{-1} C^{-1} [2] and the water content of sapwood, m_c is 237.3 kg/m^3 [3]. Finally, the sap velocity is converted into the total water use by multiplying the velocity by the conducting area.

Discussion

During Fall 2020 we conducted a number of tests of our probe against a commercially available option. We used the Dynamax TDP30 for these comparisons. Trials were ran on a test tree at Oregon State Universities Urban Horticulture Center in Corvallis Oregon. The test tree was a cherry tree with a circumference of 121cm. Dynamax probes estimate the sap flow velocity through an empirical relationship between a dimensionless 'flow index' (K) and the sap velocity. In their manual [4], Dynamax suggest calculating sap flow velocity as $V_s = aK^b$, where a and b are empirical constants. Note, that the values of a and b were originally estimated based on sap flow velocity in Douglas Fir trees. Accordingly, since the value of a is not expected to be applicable to hardwood fruit trees, we scale Dynamax probes by new value of $a' = a$*0.32, with the scaling coefficient estimated by matching OPENs probe measurements to the TDP30 measurements.

Comparisons between the OPENs probes and the Dynamax probers were very good. Figure 3 shows both raw and corrected Dynamax measurements of sap velocity at 15 minute intervals compared with the OPENS probe measurements. A coefficient of determination, r^2=0.83, between OPENs and Dynamax probes is demonstrated (note that correcting the Dynamax in this way will not influence the coefficient of determination). As also shown in Figure 4, the two probes are highly consistent throughout the diurnal variations during the study period. Finally, the tree's total daily water use was estimated by scaling sap velocity by conducting area and integrating over 24hr periods. As shown in Figure 5, the OPENs probe is able to capture days of high and low water use similar to the Dynamax probe. Integrated to the daily scale the room mean squared error between the commercially produced probe and our OPENS probe is 11.7 liters per day.

References

[1] R. G. Allen, L. S. Pereira, D. Raes, M. Smith, and W. Ab, *Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56*, vol. 300, no. 56. 1998.

[2] S. S. O. Burgess *et al*., "An improved heat pulse method to measure low and reverse rates of sap flow in woody plants," *Tree Physiol.*, 2001.

[3] A. J. Molina *et al.*, "Effect of irrigation on sap flux density variability and water use estimate in cherry (Prunus avium) for timber production: Azimuthal profile, radial profile and sapwood estimation," *Agric. Water Manag.*, 2016.

[4] Dynamax, "TDP Thermal Dissipation Probe User Manual," 1997.

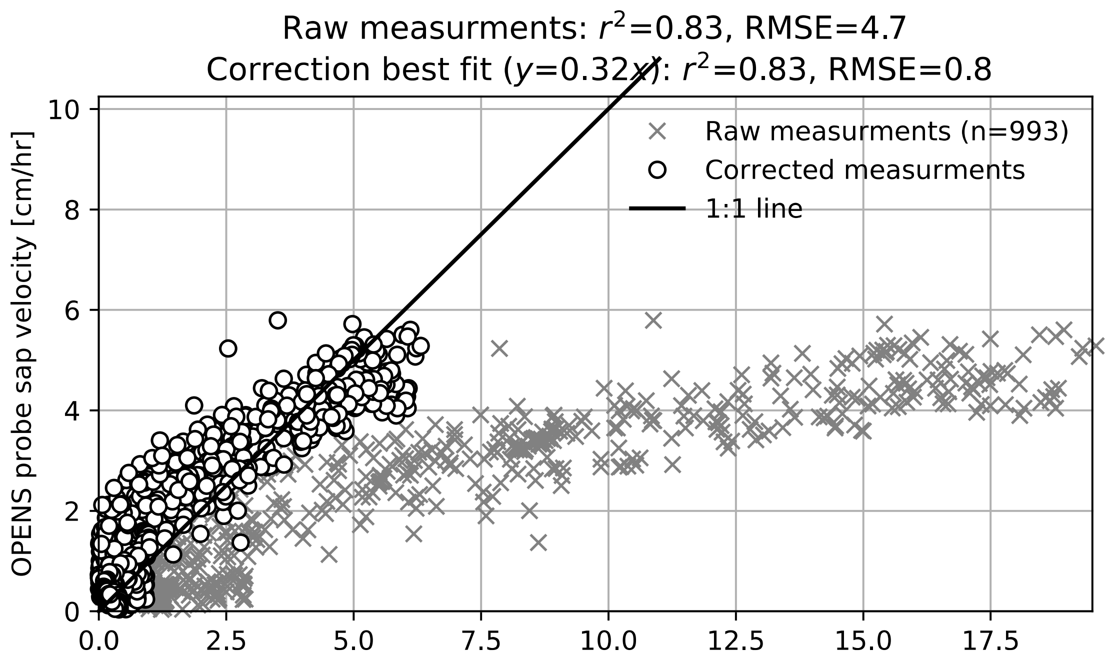


Figure 3: Comparison of OPENs estimated sap velocity with Dynamax probes. After rescaling Dynamax probes.

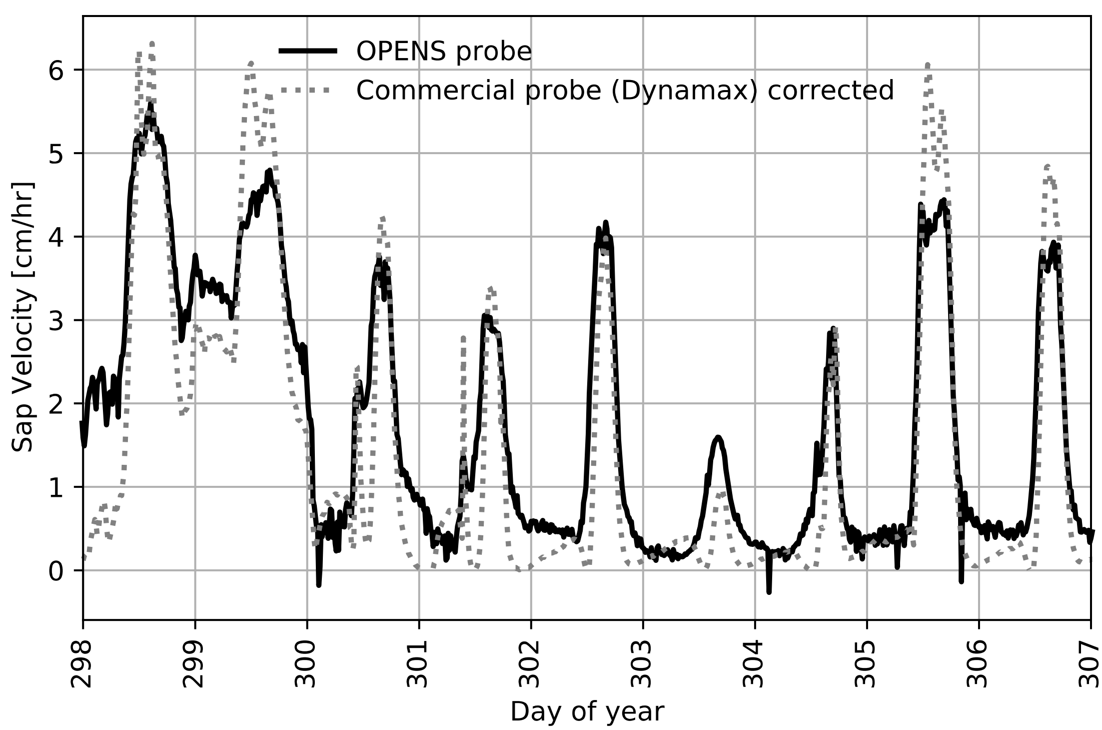


Figure 4: Time series of OPENS probe and the corrected Dynamax probe during the trial at Oregon State University in fall of 2020.

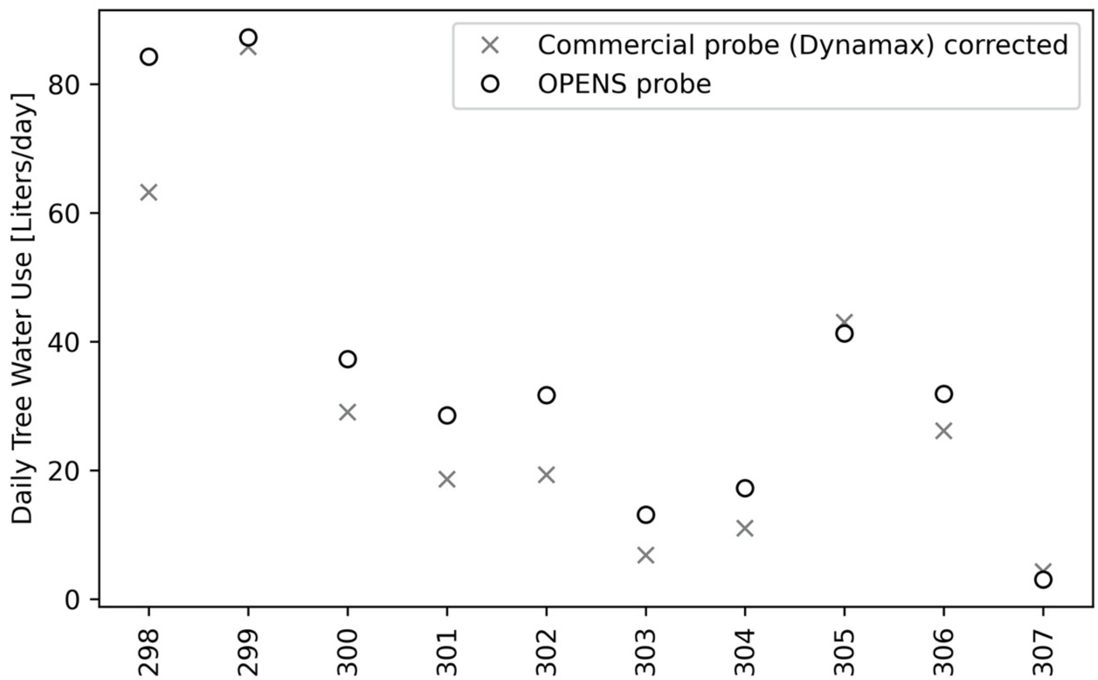


Figure 5: Comparison of Dynamax and OPENs sap flow probe estimated total daily tree water use during the study period.

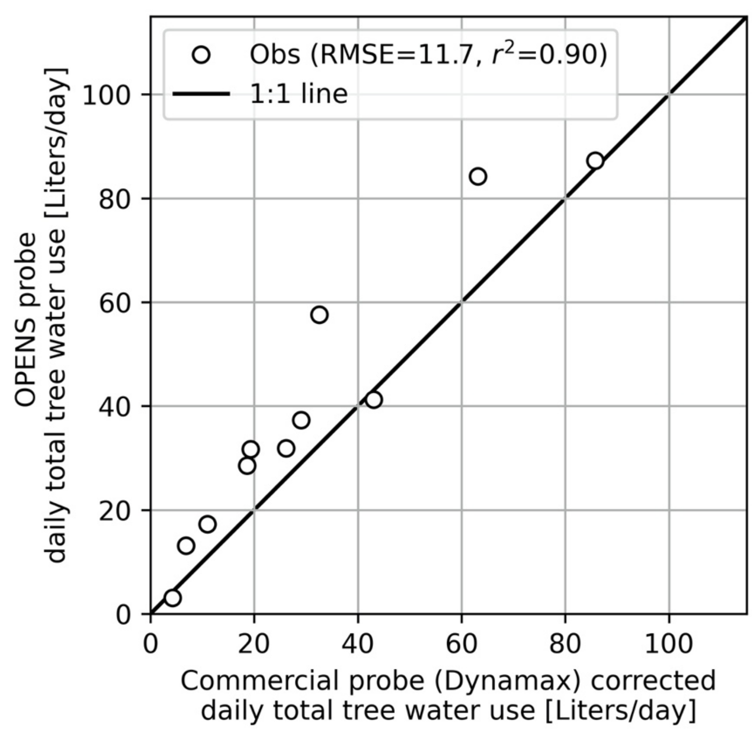


Figure 5: Cross comparison of tree total daily water use during the study period.

EXECUTIVE SUMMARY

Project Title: Development of Economical WIFI-Connected Open-Source Sap Flux Probes

Keywords: open-source, sap flow, heat-ratio method

Abstract: In order to maximize orchard productivity while minimizing costs, tree fruit producers require accurate information about tree water use, particularly crop transpiration rates. The most direct way to measure orchard-level water use is through sap flux probes, which are inserted into the trunks or stems of trees to monitor the vertical flow of water. These sap flux probe systems can provide direct estimates of the water passing through the stem/trunk of individual plants. In this project, we have developed an economical, open-source sap flux measurement package in collaboration with the Openly Published Environmental Sensing Laboratory (OPEnS Lab: http://www.open-sensing.org) at Oregon State University, which is devoted to developing similar low-cost 'internet of agriculture' technology solutions. Our design makes use of the commonly used Adafruit M0 LoRa Feather Microcontroller as well as other economically available electronic components, all of which are install onto three custom printed circuit boards. The OPEnS sap flux system can be built with $302 worth of components. Tests of the OPEnS probes against commercially available probes demonstrated accuracy at the 15-minute (r^2=0.82) and daily (r^2=.90) timescales. Results at the daily timescale for a test on a Cherry tree in fall 2020 are shown below. It is expected that as a result of this proposal we will make available to tree fruit growers in the Pacific Northwest, and elsewhere, an alternative method for monitoring orchard water use that commercial growers can implement economically and effectively. The final objective of this project is the publication of a technical publication, with an associated design and operating files, that describes how to build, install, and operate a sap flux monitoring network with little prior experience in electronics or computer programing.