2021 Technology Research Review

December 3, 2020

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CONTINUING PROJECT REPORT **YEAR**: 1 of 3

Project Title: Modeling orchard effects on meteorological measurements

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Cooperators: METER Group, Pullman, WA

Total Project Request: **Year 1:** $60,025 **Year 2:** $62,916 **Year 3**: $65,113

Percentage time per crop: Apple: 100% Pear: Cherry: Stone Fruit:

Other funding sources: **None**

WSU: Information not provided.

Item	2020	2021	2022
Salaries	$13,245.75	$40,693	$42,321
Benefits	$4,517.25	$14,223	$14,792
Equipment	$36,150	$0	$0
Travel	$6,000	$8,000	$8,000
Total	$60,025	$62,916	$65,113

[1] Salaries include 2 months of postdoc time at AgWeatherNet in year 1 and 4 months in years 2-3, 1.5 months of research associate time in the Kalcsits lab (years 1-3), 1 month of field meteorologist time at AgWeatherNet (years 1-3), and 1.75 months of systems analyst/programmer time (years 1-3).

[2] Benefit rates are budgeted for 35%.

[3] Equipment includes 8 weather sensors, 8 soil moisture sensors, and 2 instrument towers.

[4] Travel budgeted for travel to field sites, meetings with collaborators and presentation of results at industry winter meetings in Washington State.

OBJECTIVES

1) Measure the effects of irrigated orchard canopies on meteorological measurements relative to standard unobstructed, unirrigated meteorological sites.

2) Construct statistical models that estimate the magnitude of orchard effects on air temperature, relative humidity and wind speed as a function of weather conditions and irrigation.

3) Develop and implement algorithms in AgWeatherNet to dynamically correct for orchard effects and support orchard-specific delivery of weather data, forecasts and decision-support tools.

Progress on objectives was consistent with the timeline reported in the proposal submitted in fall 2019:

Year 1 –
Goal: Identify paired sites, acquire instruments, initiate field measurements for both paired Atmos 41 stations and met towers. Restructure database as needed to secure Tier 3 station data.
Progress: Deployed 8 sets of paired ATMOS-41 stations in early summer 2020 which continue to operate. Completed two weeks of met towers observations at Sunrise research orchard in early August 2020. Completed database restructuring to support Tier 3 station data.

Year 2 –
Goal: Complete full year of field data acquisition, initiate modeling, code framework required to implement transformation models.
Updates: We have now acquired 4+ months of field data. We are making some adjustments to field deployments based on lessons learned in year 1 (described in methods section). Initiation of modeling remains on track to begin in year 2.

Year 3 –
Goal: Continue field data acquisition as needed, complete modeling, complete coding to automate model implementation in the AWN system.
Updates: No change to year 3 goals.

SIGNIFICANT FINDINGS

1) Microspray irrigation events are readily detectable in research-grade weather sensors as an abrupt reduction in temperature (up to 10 °F) and increase in humidity (up to 20%).

2) Paired inside-/outside-orchard ATMOS-41 observations confirmed several hypothesized orchard effects:
    a. Air Temperature (TEMP) is 2 °F cooler inside orchards on average.
    b. Relative Humidity (RH) is 35% higher inside orchards on average.
    c. Wind speed (WIND) is 2.7 mph lower inside orchards on average.

3) New standards for in-orchard station installations will be implemented moving forward based on experience gained in 2020. Consistency is necessary to isolate orchard effects from station placement effects.

METHODS

Methods from the original proposal submitted in winter of 2020 are summarized below. Changes to the methods are summarized at the end of each objective.

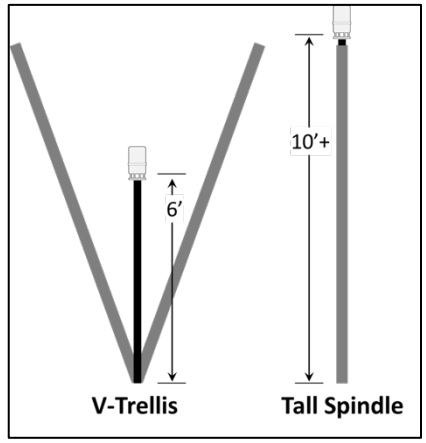

Figure 1: Proposed in-orchard installation standards.

Objective 1 – Observations

Standard meteorological observations

AWN has begun collecting observational data under a variety of orchard conditions in order to build a long-term database of in-orchard stations paired with nearby non-orchard AgWeatherNet (AWN) stations. The construction of this database is an essential foundation for modeling the orchard effect (Objective 2) and implementation (Objective 3). Increasing the number of stations in the classification database, particularly from grower-participants, remains a priority because the ability of the data to predict in-orchard conditions in orchards without a weather station will be strengthened with a longer period of record and more stations in the system.

As noted in the initial proposal, quality paired site selection remains the primary challenge this part of the project. It is critical to generate good participation from tree fruit producers so that AWN can select 20-30 quality paired sites from a larger pool of candidate sites.

Changes for 2021:

- AWN will continue to solicit additional grower participants to reach the stated goal of 20-30 paired sites.
- Consistent standards for paired station installation will be implemented in all new deployments moving forward, particularly the location of the in-orchard station within the trellis (Figure 1). Rationale for this change is to more directly measure weather conditions in the canopy when possible to simply the transfer equations (see Objective 2).

Meteorological tower observations

To further address key details of the differences between trellis, reference, and canopy locations, AWN is supplementing paired weather station comparisons by measuring vertical temperature, humidity and wind speed gradients within and adjacent to selected orchards with in-orchard weather stations. As planned, two portable 6 m (20 ft) instrument towers have been purchased and configured with shielded and aspirated temperature and humidity sensors and sonic anemometers at three heights: below, within and above the canopy. One deployment (Figure 2) was completed in summer 2020.

The purpose of the towers is multi-fold. First, measurements acquired by a trellis-mounted weather station may differ from actual conditions within the canopy due to the weather station being at a higher, more exposed level. By recording temperature, humidity, and wind at both the trellis and canopy level this height effect can be quantified. Second, the 15-minute time resolution of the weather station may not fully capture the dynamic effects of irrigation or wind gusts. The towers recorded at 10 second resolution to fully resolve variability on short time scales.

Changes for 2021:

- The 2020 portable tower deployment resulted in excellent data, but tower logics made it difficult to collect data in commercial orchards.
- In-orchard hardware will be reconfigured to attach to trellis poles so as not to restrict orchard operations.
- Additional sensors will be purchased to make pair-wise temperature comparisons at 3 orchards simultaneously.

Figure 2: Sunrise orchard deployment in summer 2020.

Objective 2 -- Statistical Modeling

AWN will construct three statistical models for each target variable (temperature, humidity, wind speed). These models will have both continuous and categorical predictors and it may be necessary to construct separate models for different seasons or synoptic meteorological conditions. The general framework of these models is given below. All three models will be examined for consistency between transformation pathways.

- ***Trellis post station -> reference station***
- ***Trellis post station -> canopy conditions***
- ***Reference station -> canopy conditions***

Ultimately, we want to run models and decision-support tools using weather conditions within the canopy. For orchardists who install weather stations on trellis posts, this requires construction of models that estimate within canopy conditions using trellis post measurements.

Changes for 2021:

- No major changes anticipated.

Objective 3 -- Implementation

Database modifications:
In October 2020 AWN released the AWNFarm app that will be used to deliver site-specific weather data, forecasts and decision-support tools to tree fruit producers. Additionally, AWN has now established an in-orchard station "type" designation in the existing database, ensuring that data from producer-owned stations is secure, and only available to the station owner unless they opt to make their weather data (and associated weather-driven tools) public. AWN is also continuing to develop additional site-specific metadata fields in order to collect and store information from in-orchard station owners on crop type, irrigation systems, training systems, and sun shading where relevant.

Moving forward, AWN will also need to incorporate Tier 3 stations into the current maintenance database, which could require substantial modifications to accommodate a different maintenance tracking program.

Model implementation

All three models from Objective 2 will be coded into the AWN system. First, any data acquired from an in-orchard station will be transformed using the trellis-to-reference model for implementation of station comparison QA/QC procedures. This transformed data will also be used to train machine-learning based forecast models as these are built upon physical atmospheric models that assume meteorological standard ground station data. Forecast predictions will subsequently be back transformed for site-specific delivery using the reference-to-trellis-to-canopy model. Current weather data will be directly transformed to estimate within-canopy conditions. Within canopy weather data and forecast estimates will be used to drive AWN (and potentially DAS) models and decision support tools.

When an in-orchard station isn't available, orchard managers can select and weigh up to three AWN stations to estimate site-specific weather conditions, and the reference-to-canopy model will be used to transform reference data for site-specific delivery of weather conditions, forecasts and tools.
The new AWN app will include clear indications when transformed data is being used, and allow users to easily compare with raw in-orchard station data or reference station data.

Changes for 2021:

- None proposed.

RESULTS AND DISCUSSION

In year one we installed paired inside- and outside-orchard ATMOS-41 all-in-one weather stations at eight partner orchards. In 2021, this database will be used to construct the statistical models proposed in Objective 2.

Paired meteorological observations

				ATMOS-41		Outside - Inside Difference		
Station	**Install Date**	**Orchard Type**	**Trellis**	**height (in)**	**Days**	**TEMP (F)**	**RH (%)**	**WIND (mph)**
AMT	2020-Jun-9	drip	V	71	142	2.1	-33%	4.8
Clark	2020-Jun-5	drip	spindle	71	146	1.3	-45%	2.0
Dietz	2020-May-29	drip + spray	spindle	141	153	0.6	-35%	1.1
Fir	2020-Jun-5	drip	V	68	121	3.4	-44%	2.0
O-Road	2020-Jun-5	drip	V	72	145	2.6	-40%	3.5
Quincy	2020-Jul-17	drip + netting	V	91	105	1.4	1%	3.1
Vanderbilt	2020-Jun-11	drip + spray	V	72	140	1.6	-50%	2.3
Average						**1.9**	**-35%**	**2.7**

Table 1: Metadata and summary statistics from paired station deployments.

Table 1 shows metadata and summary statistics from AWN paired station deployments in 2020. The Sunrise orchard is also operational but not included. Orchards included both spindle- and V-trellis,

two orchards with microspray, and one with overhead netting. At this time there is not enough data to determine how much the differences in orchard configuration are contributing to the temperature and

RH effects shown in Table 1. In 2021 we hope to increase the number of paired stations to 20 and to standardize the heights of our spindle- and V-trellis installations (Fig. 1).

More details of the orchard effect can be seen in the outside-inside timeseries comparison in Figure 3. Key findings are as follows:

- TEMP effects peaked in Aug-Sept at most sites.
- Surprisingly, RH effects were greater in autumn.
- WIND effects were generally greatest in early summer.
- The lack of an RH effect at Quincy (with netting) is considered questionable pending further analysis.

Dependence on the diurnal cycle (not pictured) was also noted. TEMP effects were fairly consistent through the day, RH effects were greatest at night, and WIND effects were greatest during the afternoon.

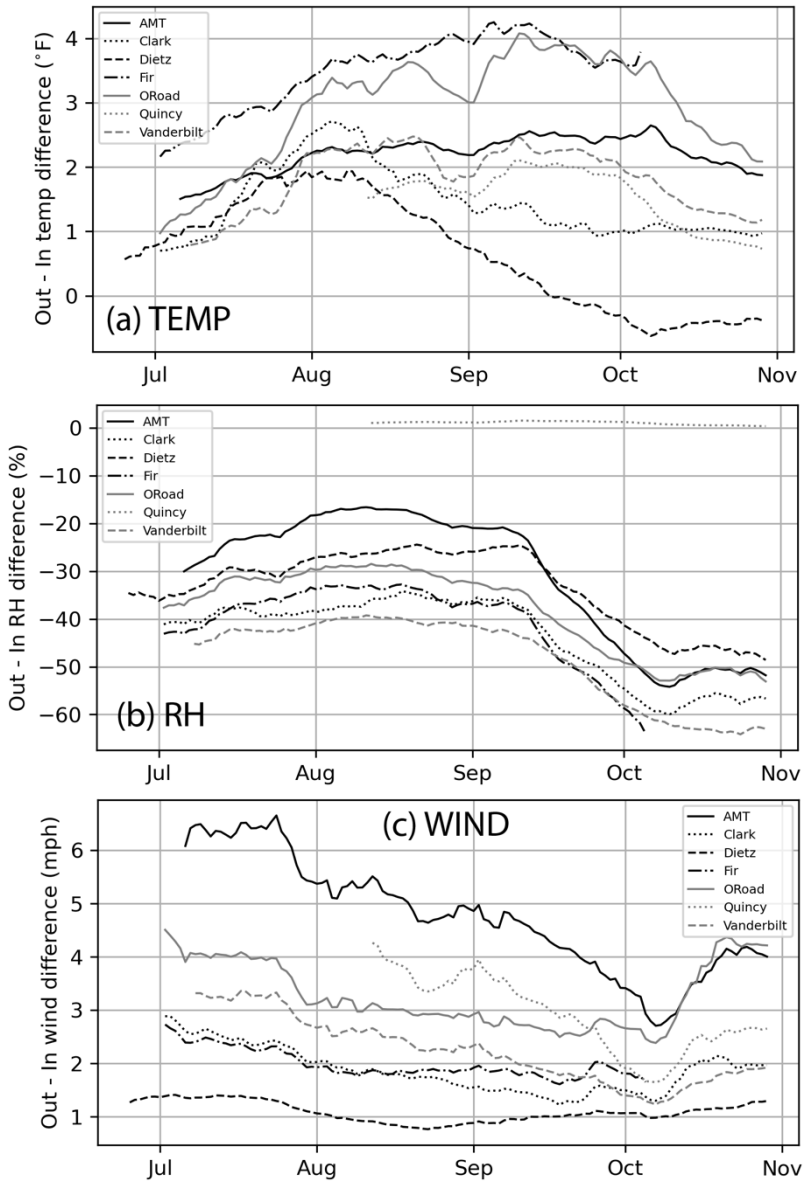

Figure 3: Timeseries (28-day rolling average) of (a) temperature; (b) humidity; and (c) wind speed at the seven paired sites described in Table 1.

Research tower observations

More detailed observations of orchard effects were obtained by deploying paired research towers at the Sunrise orchard for two weeks in August 2020. The towers are pictured in Fig. 2 and timeseries data of TEMP and RH at one-minute resolution is shown in Fig. 4.

Key findings from the research tower are as follows:

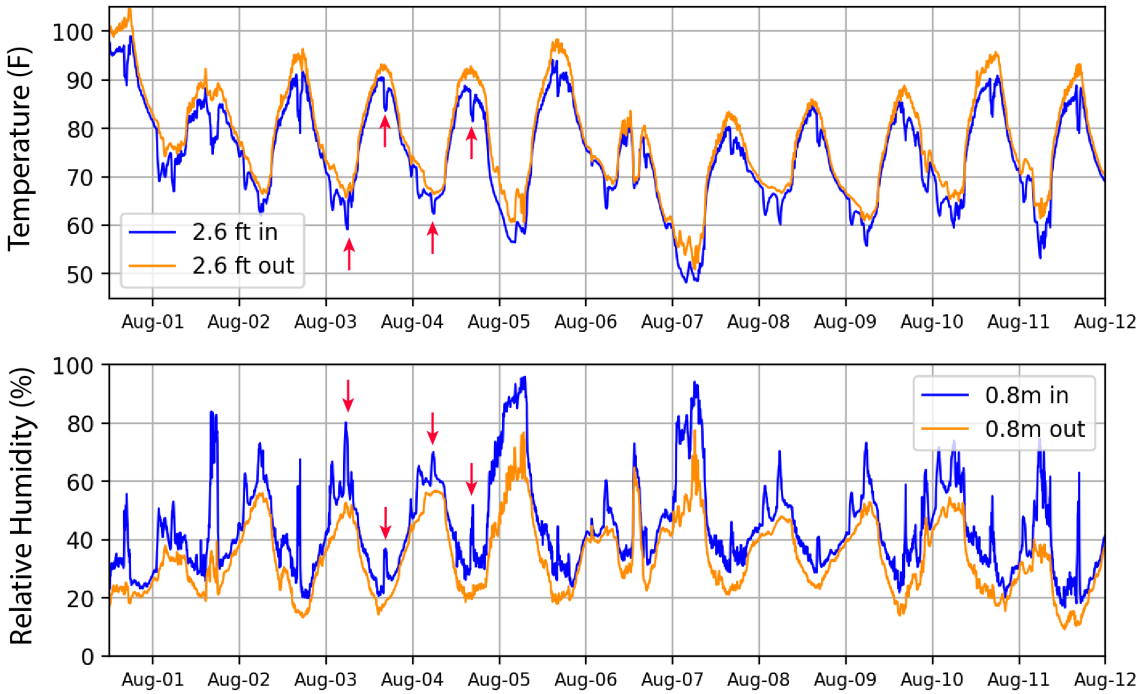

Figure 4: Sunrise research tower inside/outside temperature (top) and humidity (bottom) at 2.6 ft (0.8 m) height. The timeseries is averaged to one-minute time resolution. Arrows indicate examples of irrigation "spikes".

Similar to the paired met observations (Fig. 3), a 3 °F cooling was observed on average in the canopy relative to the same height (2.6 ft) outside of the orchard.

- Irrigation 'spikes' are clearly seen at one-minute time resolution which result in a temporarily enhanced orchard effect for approximately one hour.
- A more subtle orchard effect was also observed at 7.5 ft and 16.4 ft heights (not pictured).

Discussion

From the first year of results, it is clear that we need more paired Atmos 41 observations to model in- vs out-orchard differences. There is substantial variability in irrigation practices, cooling practices, training systems, etc… While it will not be possible to model every possible variation, effect sizes should be quantified for as many different situations as possible. That said, across the diverse orchards instrumented in 2020, ***the direction and general magnitude of temperature, wind and relative humidity orchard effects were consistent across diverse sites.***

Very precise, micrometeorological research-grade sensors will be the key to modeling vertical gradients within orchards. With an Atmos 41 station at the top of a tall spindle trellis post, Atmos 14 sensors can be used by growers to capture within-canopy temperatures but solar gain and resultant positive bias of these passively shielded sensors makes them less than ideal for research. The deployment of more micrometeorological research instruments for longer durations can also be used to provide gold standard, precise, temporally resolved reference measurements needed to model the effects of specific irrigation events as detected by the Atmos 41 stations (with 15 minute aggregation intervals.)

CONTINUING PROJECT REPORT **YEAR**: 1 of 3

Project Title: Decision Support Tool for Precision Orchard Management

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Cooperators: Dave Allan (Allan Brothers Fruit Co)

Total Project Request: $222,500 **Year 1:** $73,569 **Year 2:** $77,335 **Year 3:** $71,596

Percentage time per crop: Apple: 100% Pear: Cherry: Stone Fruit:

Other funding sources: None

WTFRC budget: None

Budget 1
Organization Name: Oregon State University/Agricultural Research Foundation
Contract Administrator: Charlene Wilkinson
Telephone: (541) 737-3228 **Email address:** Charlene.Wilkinson@oregonstate.edu

Item	2020	2021	2022
Salaries[1]	$31,331	$32,271	$26,622
Benefits	$8,311	$9,206	$8,162
Wages			
Benefits			
Equipment			
Supplies[2]	$2,986	$4,000	$4,000
Travel[3]	$3,000	$3,000	$3,000
Miscellaneous			
Plot Fees			
Total	$45,628	$48,477	$41,784

[1]Salaries includes a Graduate Research Assistant on a 12-month, 0.49 FTE appointment in years 1 and 2, and a 9-month, 0.49 FTE appointment in year 3. Salaries also include 0.25 months per year for Joe Davidson and Cindy Grimm.
[2]Leaf samples are included in the supply budget.
[3]Travel budget is requested to support mileage and lodging for data collection and field experiments.

Budget 2

Organization Name: Washington State University **Contract Administrator:** Katy Roberts

Telephone: 509-335-4564 **Email address:** katy.roberts@wsu.edu

Item	2020	2021	2022
Salaries	$17,840	$18,554	$19,296
Benefits	$5,101	$5,304	$5,516
Wages			
Benefits			
Equipment			
Supplies	$4,000	$4,000	$4,000
Travel[1]	$1,000	$1,000	$1,000
Plot Fees			
Miscellaneous			
Total	$27,941	$28,858	$29,812

[1]Travel budget is requested to cover the mileage for field experiments.

OBJECTIVES

This continuing report summarizes research progress for the performance period of July – November 2020. Table 1 shows the project's objectives, major research activities, and current schedule (an **X** marker indicates an activity in progress). We have focused most of our efforts this year on tasks for Objective 1. In the following sections, we briefly review the goal of each task, present significant findings, and describe methods to be employed during the upcoming year.

Table 1. Original project objectives and schedule**.**

Objective	Research Activity	Year 1		Year 2		Year 3	
1	Develop methods & algorithms for tree trunk detection	X					
	Discussions with experts and N data collection (e.g. leaf samples, physical measurements, N applied)	X					
	Map the orchard block with RTK-GPS	X					
	Develop methods & algorithms for vehicle localization	X					
	Develop methods & algorithms for N sensing: geometric, color, and spectral characteristics	X					
2	Create a collaborative decision-making framework for recommending fertilizer plans						
3	Design and develop a variable rate, proof-of-concept sprayer						
	System integration with limited field trials demonstrating variable rate N application						

Objective 1: Orchard Mapping & Nitrogen Sensing

This objective concerns the development of the standalone components that are prerequisites for the integration of a precision nitrogen (N) application system (Objective 3). Over the summer, we tagged 199 trees with identifying seals at a Jazz plot (Yakima Valley Orchards, Prosser, WA) for long-term monitoring. We then completed multi-day experiments at the orchard in July and October to collect the datasets needed to develop computational algorithms and methods.

<u>Task 1 - Tree trunk detection (OSU lead, WSU participant)</u>

Objective 1 / Task 1 involves detecting tree trunks from a standard RGB-D camera feed. Initially, our goal is to create a baseline map of the test plot represented by semantic features, which in this case are tree trunks. Detecting pixels in images of the environment which correspond with a tree trunk will enable us to identify individual trunks and, combined with depth information and GPS coordinates of the vehicle (Task 2), estimate their locations in the environment. Ultimately, we also want to use this network to detect and identify individual trees in real-time during nitrogen application.

Our work in this area has focused on evaluating the feasibility of using machine learning techniques for trunk detection. First, we obtained several minutes of footage from the orchard by walking down several rows while scanning with an Intel RealSense D435 RGB-D camera. We then manually labelled

the data with masks indicating which pixels in the image corresponded with a tree in the row closest to the camera. We then tried several different architectures for detecting these pixels, including Faster R-CNN (which produces a bounding box) and a convolutional encoder-decoder framework. A sample result from the encoder-decoder framework is shown in Fig. 1, with the detected mask overlaid with yellow on top of the corresponding image.

Figure 1. Output of a convolutional encoder-decoder for detecting tree trunks.

Findings:

- Initial results indicate that segmenting out tree trunks in the foreground is feasible with relatively simple neural networks.
- In general, while there is some noise in the detection (especially with occasional detection of trees in the background) the network is able to accurately identify foreground trunks.

Methods: There is still much work to be done in this area. First, we are evaluating other architectures such as Mask R-CNN, which have been shown to be useful for other semantic segmentation tasks. Mask R-CNN is actually an instance segmentation network, meaning that it will also distinguish separate instances of tree trunks in the image; this is another topic that we need to consider, since we would like to be able to track trees across multiple video frames in order to refine their position estimates and avoid double-counting. Finally, since the initial videos we took last winter had a fairly limited set of conditions – they were all taken on the same day with the same weather conditions – we collected a larger dataset of video footage of orchard scenes under a variety of conditions (July/October 2020). We will use this data to refine our networks during the upcoming year. Ideally, our system would be able to reliably detect tree trunks even with differing seasons and weather conditions.

Task 2 – Orchard mapping (OSU lead, WSU participant)

Objective 1 / Task 2 involves the creation of a semantic map indicating the locations of individual trees in the test plot. Completing the map requires two components: the tree trunk detection system described in Task 1, as well as RTK-GPS data, which provides a useful ground truth for accurately locating the trees in the environment. The primary difficulty with obtaining the RTK-GPS data is elevating the receiver above the vehicle to receive the data, as the tree canopy tends to block out the requisite number of GPS satellites needed to maintain RTK-GPS accuracy. To address this, we elevated the GPS receiver by mounting it to a pole attached to the utility vehicle (Fig. 2). We confirmed that we were able to reliably receive RTK fixes via this setup; even with the receiver on the vehicle fully lowered, we were able to receive an average of 7 satellites inside the rows (5 is sufficient).

Figure 2. RTK-GPS/vehicle system used for orchard mapping.

In October 2020, we collected raw data which will be used for orchard mapping. In addition to the RGB-D images collected for Task 1, we obtained Inertial Measurement Unit (IMU) data from the RealSense D435 camera as well as RTK-GPS data from the receiver. Each run consisted of driving the vehicle through the test plot and continuously recording the raw data; this data will be post-processed

to produce the desired orchard map of all tree coordinates. Figure 3 shows the locations of the 199 treatment trees within the plot. As a preliminary check on the accuracy of the GPS data, we performed two data collection runs 1 day apart and overlaid the GPS measurements on top to see if the runs were roughly consistent (Fig. 3, upper right).

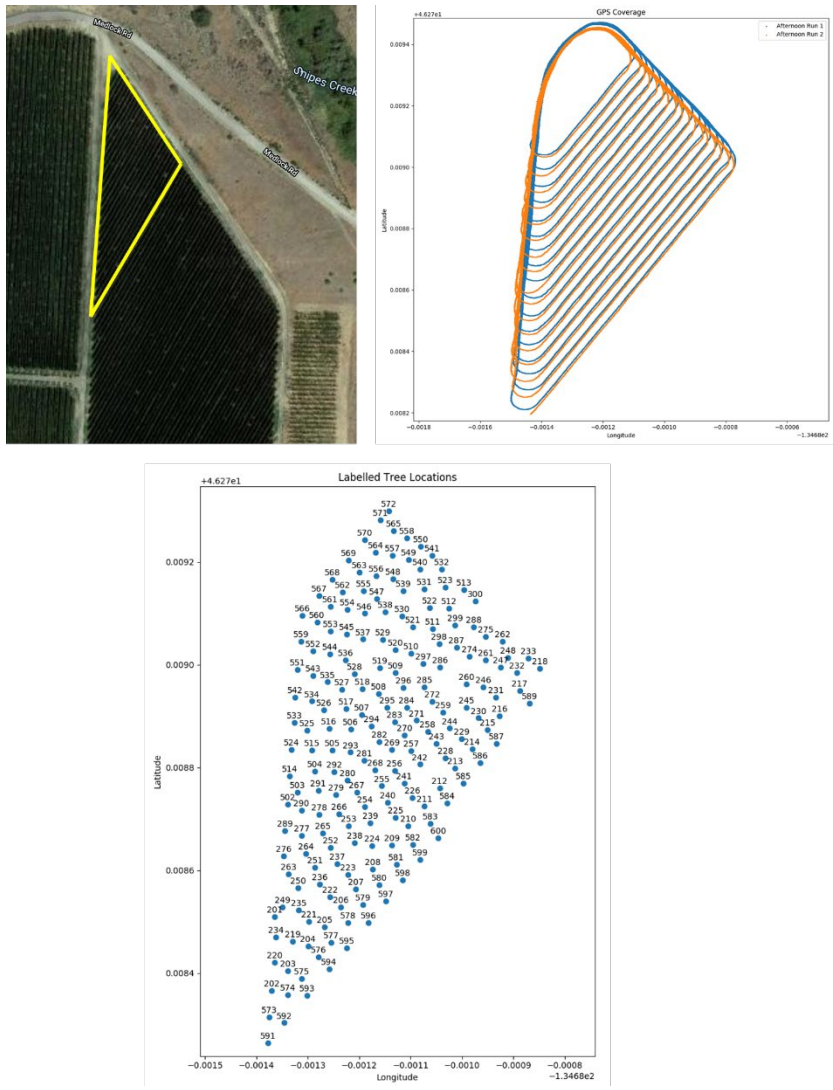

Figure 3. Satellite image of orchard rows selected for this study (*top left*); overlay of RTK-GPS data from two separate traverses through the orchard (*top right*); and GPS coordinates of the 199 trees tagged for this study (*bottom*).

<u>Findings</u>:

- Generally, the RTK-GPS data is very high quality (<10 cm accuracy), showing few sudden jumps in position that are characteristic of regular GPS measurements. However, the two runs were slightly offset from each other. We suspect this may have been caused by a minor difference in setup of the RTK-GPS base station between the two days. Additional studies are needed to determine if this is the case, as well as to ensure sure that our mapping/localization algorithms are robust to this sort of error.

<u>Methods</u>: Our next steps are to manually post-process the video footage from the RGB-D sensor to populate the map with all trees contained within the plot (i.e. a person observes the video, identifies a tree, and then records its GPS coordinates). We will then use the manually created map and raw video

footage to evaluate the performance of our autonomous tree trunk detection network. An accurate orchard map is critical for vehicle localization during precision nitrogen application (Objective 3).

Task 3 – Nitrogen measurements and non-contact sensing (WSU lead, OSU participant)
We will assess leaf nitrogen content and tree growth annually each year for all 199 trees selected for this study. In early August, we collected 50 leaves from the middle of the current year's branch growth of each treatment tree. Leaf mineral nutrient content was measured at Ward Labs Inc. (Kearney, Nebraska) using the combustion analysis method. Tree growth measurements are also planned for November 2020. Additionally, our grower collaborator collected yield data from each of the treatment trees during the recent harvest. Yield data was not yet available at the time of report submission.

For non-contact sensing, we developed a framework for collecting both canopy color and multispectral images and associating it with each tree. We attached two sensors, an RGB-D sensor and a multispectral camera, to a vehicle pointed towards the canopy of each tree. As the vehicle drove down the row, we stopped at each treatment tree and acquired 5 images, each one a distinct spectral band. An example of the variations in appearance between spectral bands for a single tree can be seen in Fig. 4. We collected this data during the summer in July, as well as in the fall at the end of October. Due to a premature frost, the leaves on the tree failed to change color as expected, which we were counting on for the multispectral analysis. We will evaluate the collected data to see if it can still be useful for nitrogen assessment.

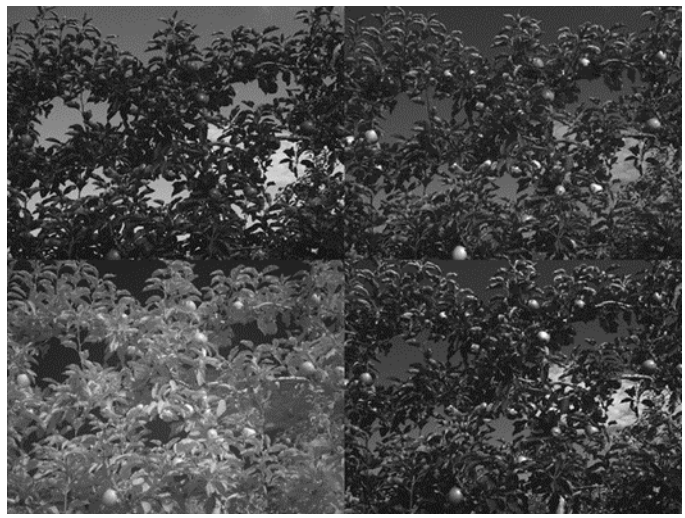

Figure 4. Variations in spectral bands for a single tree.

Findings:

- Results from leaf nutrient analysis indicate that of the 199 treatment trees, 8 were nitrogen deficient and 92 had excess nitrogen (using Stiles and Reid (1991)).

Methods: Due to the multispectral camera design, which has 5 separate staggered lenses each corresponding to a single spectral band, the multispectral images are not perfectly aligned. We are currently working to see if the images can be properly registered to each other, which would allow us to compute various important indexes such as the NDVI (Normalized Difference Vegetation Index), GNDVI (Green Normalized Difference Vegetation Index), and DGCI (Dark Green Color Index). Another critical activity for the upcoming year will be to use parameters from the color images in a multivariate analysis to estimate plant nitrogen status, and then compare the estimated status with leaf nutrient results and tree growth measurements.

Objective 2: Decision Support Tool (WSU/OSU joint lead)

For Objective 2, which we will start during the upcoming year, we will develop an automated decision-making system for precision nitrogen application. Our approach is to create a collaborative decision-making algorithm using rules to represent precision fertilization plans recommended by horticultural domain experts. An interactive human-machine learning algorithm will enable this decision-making system to interpret the sensed nitrogen status and nitrogen stress trends of plant canopies under different

nitrogen application schemes stored in the database, and tune the application strategies to determine the optimal rate of nitrogen.

Specifically, there will be two levels of decision-making incorporating feedback mechanisms for learning and improvement over time. First, an open loop mechanism will be used to develop a recommended rate for nitrogen application integrating various canopy parameters and human experts' interpretations and decision-making rules. Second, a closed loop feedback mechanism will be implemented at the higher level, which will track the historical application level to individual trees and the final outcome at the end of the season in terms of major plant parameters including shoot growth (this parameter was also used as the input in the decision-making process), fruit yield, and quality.

Objective 3: Variable Rate N Application

This objective includes the demonstration of a proof-of-concept method for variable rate N application. While most of Objective 3's research activities are planned for year 3, we have started preliminary studies of various techniques for localizing the spray vehicle in the orchard map. As we only intend to use the RTK-GPS to populate the baseline map, a key functional requirement is low-cost, self-contained navigation. We are currently incorporating inertial sensors and wheel odometry with an Extended Kalman Filter (EKF), an algorithm commonly used for localization. Our goal for the upcoming year is to integrate the trunk detection system (Objective 1) with inertial sensors mounted to a test vehicle. If results from row traversing indicate that the Extended Kalman Filter is not a robust method for vehicle localization, then we will consider Particle Filter techniques.

DISCUSSION

During the first year of this project, we focused on establishing a test plot with treatment trees, completing horticultural measurements (e.g. leaf nutrient analysis), and collecting sensor datasets (e.g. RGB-D, IMU, multispectral, and RTK-GPS). Our current focus is developing computational frameworks for trunk detection and vehicle localization. During year 2 of the project, we will concentrate on non-contact sensing for assessing N status and the Decision Support Tool. While we will make the datasets and algorithms open-source and freely available to the community, we anticipate that the Decision Support Tool will have the most long-term value to the industry.

FINAL PROJECT REPORT

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

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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)

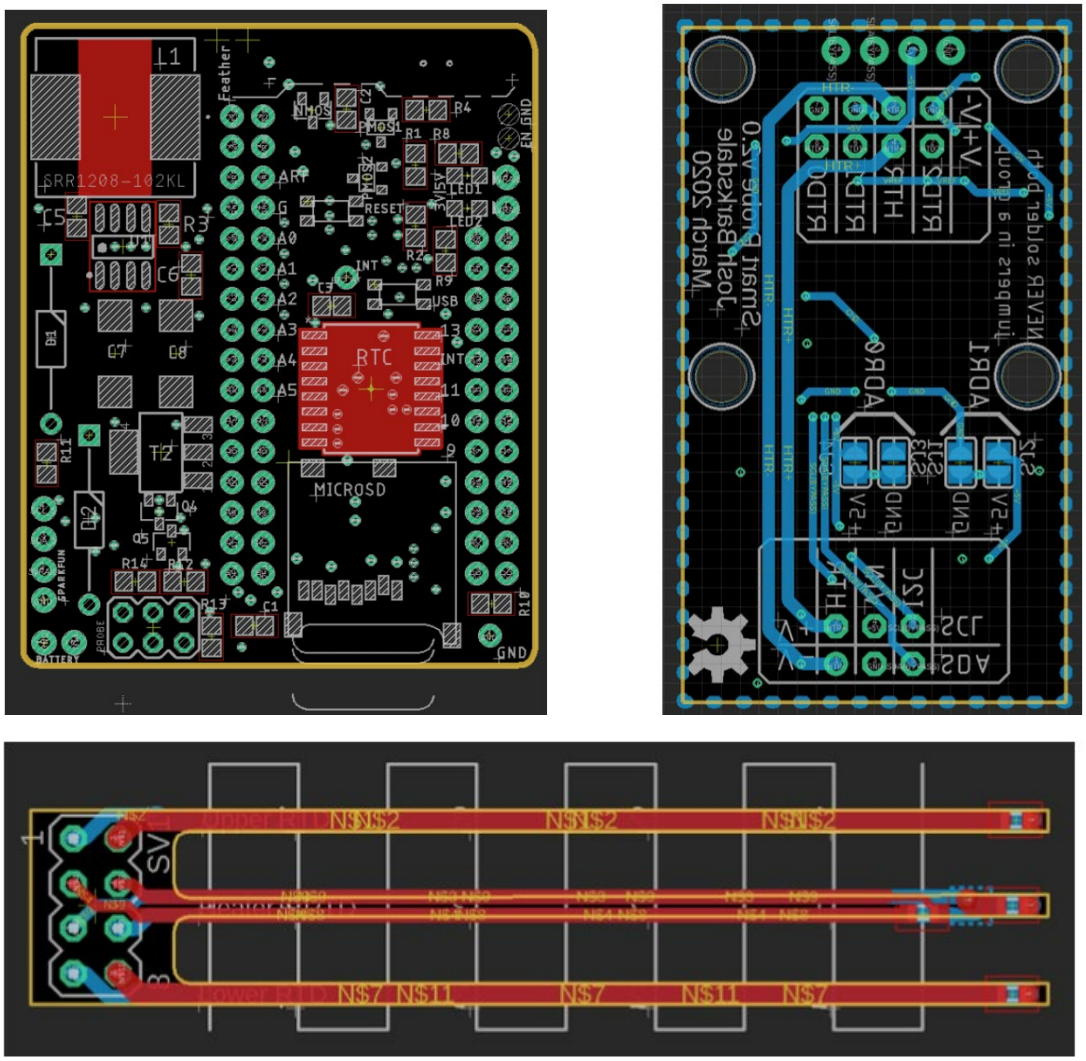


Figure 1: The three custom PCBs developed as part of this project. The Sap Flux Wing (upper left) connects to the Smart Prob PCB (upper right), which connects to the flex prob (bottom)

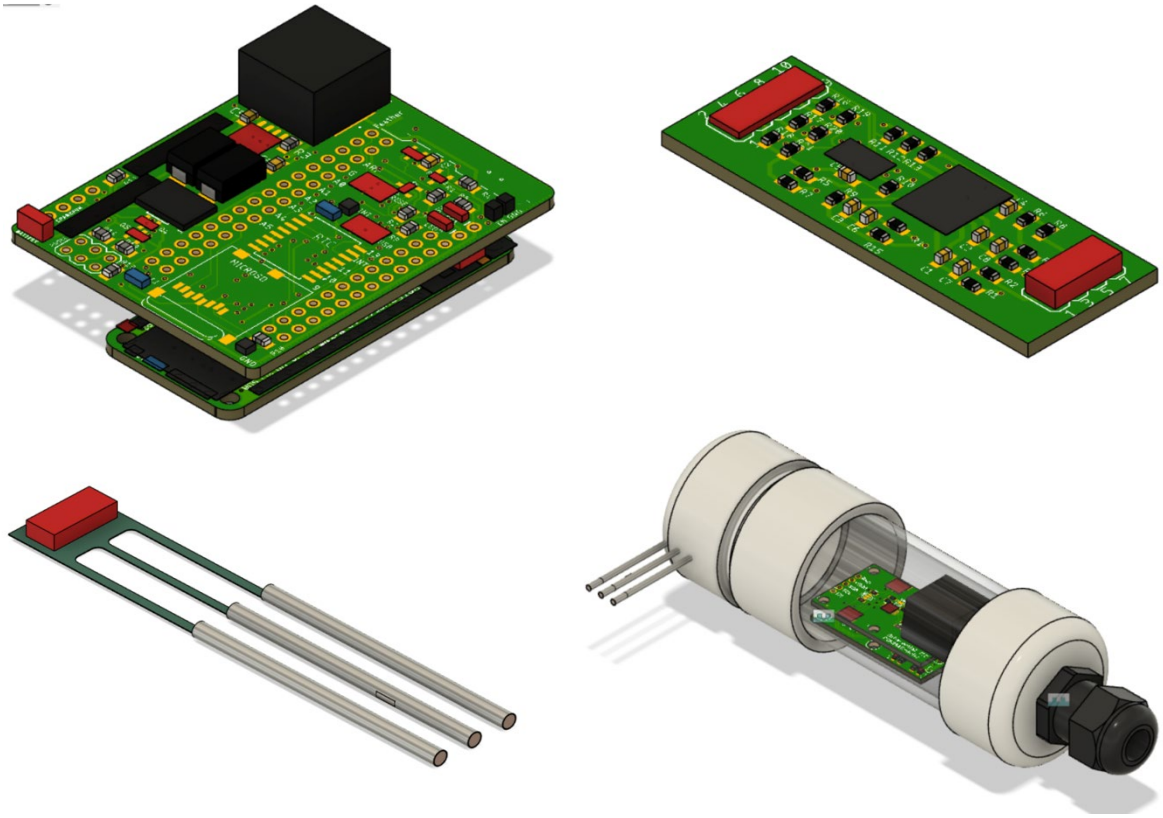


Figure 2: 3D Fusion renders of the Sap Flow Wing (upper left), the smart probe PCB (upper right), the flex PCB (lower left) and assumed probe (bottom right).

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	

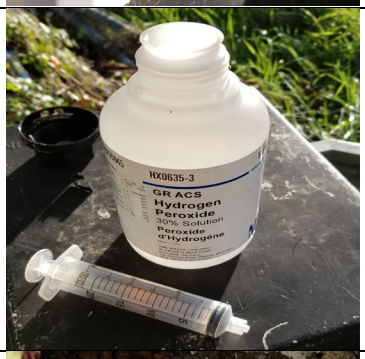
Step 2: Change out the drill bit for one that is slightly larger than the 2mm probes. This is a somewhat subjective process. Drill again in the same holes.	
Step 3: Flux out the holes with hydrogen peroxide. A simple syringe is used to inject the hydrogen peroxide into the drilled holes	
Step 4: Now 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.

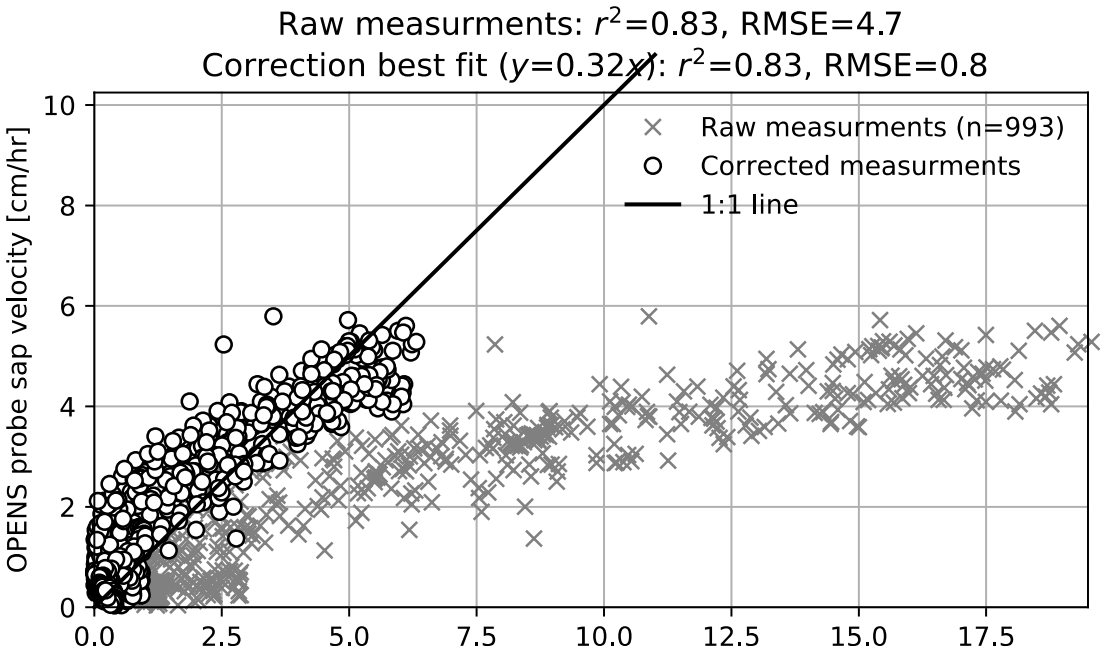


Figure 3: Comparison of OPENs estimated sap velocity with Dynamax probes. After rescaling Dynamax probes.

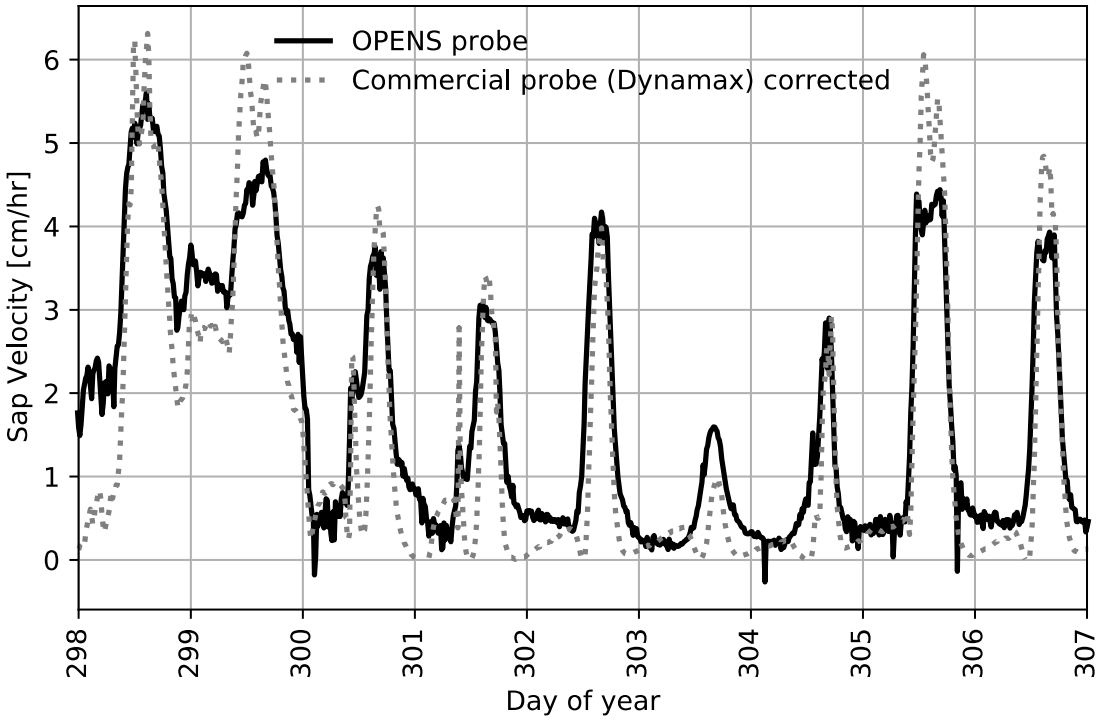


Figure 4: Time series of OPENS probe and the corrected Dynamax probe during the trial at Oregon State University in fall of 2020.

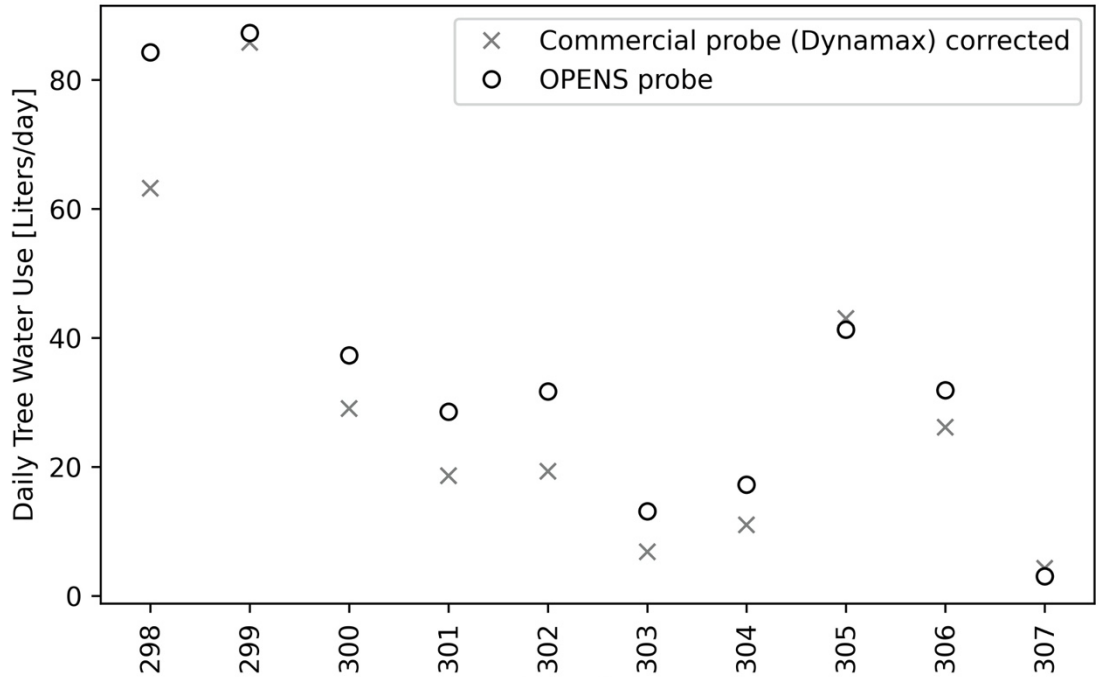


Figure 5: Comparison of Dynamax and OPENs sap flow probe estimated total daily tree water use during the study period.

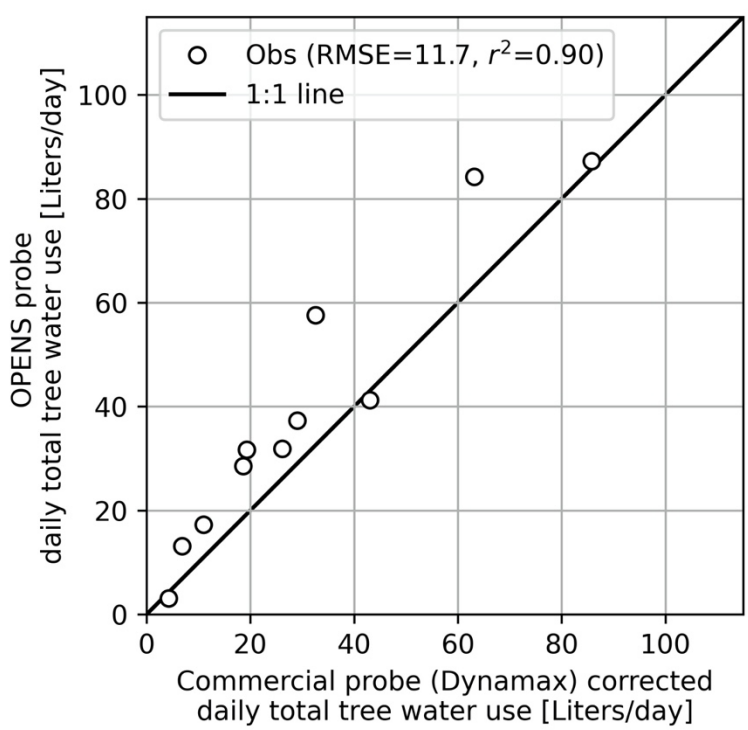


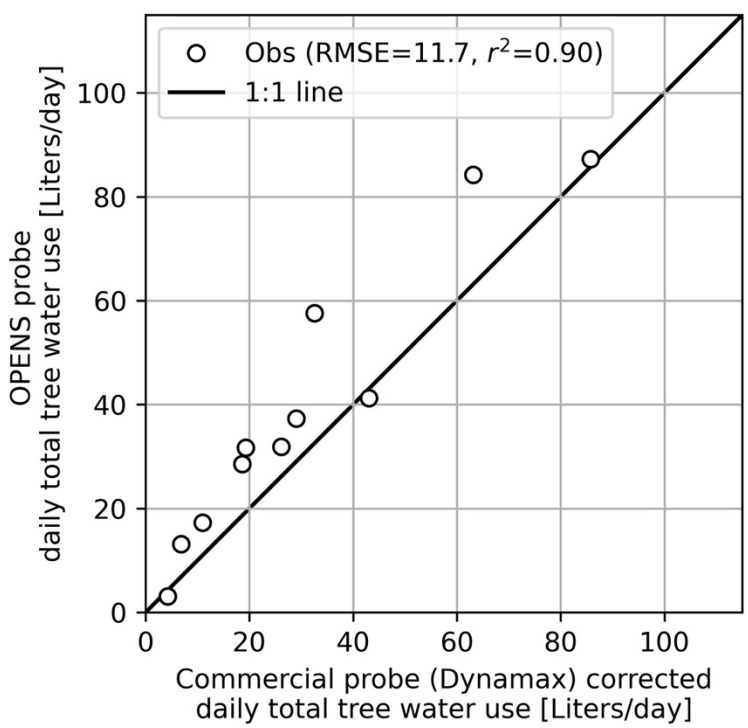
Figure 5: Cross comparison of tree total daily water use during the study period.

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.



FINAL PROJECT REPORT

Project Title: Developing and validating models for tree fruit

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Cooperators: Louie Nottingham, WSU-TFREC

Percentage time per crop: Apple: 40% Pear: 50% Cherry: 10% Stone Fruit: 0%

Other funding sources
Agency Name: WSU Extension
Amt. awarded: $ 198,268
Notes: This is the funding WSU Extension has committed to support maintenance of WSU DAS and implementation of new models.

WTFRC Collaborative expenses:

Item	2017	2018	2019	2020 (No-cost extension)
Salaries	6,000	4,000	4,000	0
Benefits	2,000	1,200	1,200	0
Wages/Benefits[1]	14,000	18,000	20,000	0
Supplies	0	0	0	0
Travel[2]	2,500	2,600	2,700	0
Miscellaneous	0	0	0	0
Total	24,500	25,800	27,900	0

Footnotes:
[1] Wages/benefits adjusted in years 2 and 3 to reflect new WA minimum wage schedule.
[2] In-state travel to research plots.

Budget 1
Organization: WSU-TFREC **Contract Administrator:** Susan Cao/Shelli Thompkins
Telephone: 509-335-4564/509-293-8803 **Email:** bentjen@wsu.edu /shelli.tompkins@wsu.edu

Item	2017	2018	2019	2020 (No-Cost Extension)
Salaries[1]	34,020	35,380	36,796	0
Benefits[2]	13,442	13,979	14,539	0
Wages[3]	8,000	8,320	8,653	0
Benefits[4]	216	225	234	0
Equipment	0	0	0	0
Supplies[5]	2,500	2,600	2,704	0
Travel[6]	4,000	4,160	4,326	0
Miscellaneous	0	0	0	0
Plot Fees	4,200	4,368	4,543	0
Total	66,378	**69,032**	71,795	0

Footnotes:
[1] Matt Jones (0.25FTE, T. Melton 0.45 FTE).
[2] 34.1% (Matt Jones); 48.3% (Melton).
[3] Student 40 hr/wk for 16 wks.
[4]2.7%.
[5]Includes lab and field supplies.
[6]In state travel.

Total Project Funding:

Budget History:

Item	Year 1: 2017	Year 2: 2018	Year 3: 2019	Year 4: no cost extension
Salaries	40,020	39,380	40,796	0
Benefits	15,442	15,179	15,739	0
Wages	22,000	26,320	28,653	0
Benefits	216	225	234	0
Equipment	0	0	0	0
Supplies	2,500	2,600	2,704	0
Travel	6,500	6,760	7,026	0
Plot Fees	0	0	0	0
Miscellaneous	4,200	4,368	4,543	0
Total	90,878	94,832	99,695	0

Objectives:

1. Develop and validate a demographic model for pear psylla to assess pesticide effects on population management.
2. Continue to collect validation data for demographic models for mites and aphids.
3. Development new fruit growth models for Honeycrisp, Fuji, and Golden Delicious.

Significant Findings:

- Psylla phenology is well defined at this point in time and the pesticide model has been developed and is available for testing and parameterization (pesticide efficacy and residual longevity) for our collaborator.
- A preliminary model for the pear psylla parasitoid, *Trechnites psyllae* was developed, but it needs to incorporate other data and be finalized next year.
- The phenology of pear bloom has been estimated for swollen bud, bud burst, green cluster, white bud, and bloom for the cultivars Bartlett, Bosc and D'Anjou.
- More extensive studies of the bloom period of the three pear cultivars showed that "rat-tailed" bloom is <3.5% of the total bloom.
- Analysis of rosy apple aphid and apple grain aphid phenology was completed, and we have implemented the models on DAS as well as pesticide-effects models also on DAS.
- Our two-spotted spider mite data shows that diapause coloration is not a good indicator of when reproduction starts in the spring; egg deposition occurs almost immediately in the spring.
- Predatory mites are found in large number in the ground cover during the spring and fall, but most appear to migrate up into the canopy in June and remain there until the start of August. Management of the ground cover during the spring or fall could thus disrupt integrated mite management in the current or following year.
- Work on the fruit growth models for Cosmic Crisp, Fuji, Jonagold, and Honeycrisp was completed and implemented on DAS.

Obj. 1. Develop and validate a demographic model for pear psylla to assess pesticide effects on population management.

Methods Pear Psylla. Phenology data for pear psylla were collected at five locations with low-intensity management; samples were taken twice a week from February until the end of October from 2016-2019. The number of adults (winterform and summerform), eggs, and immature stages (instars 1-3 and instars 4-5) was determined from beat samples and shoot samples. Shoot samples were visually inspected before leaves were developed, and subsequently processed through the mite brushing machine as the leaves became close to full size. In addition, unbaited sticky yellow cards were placed in each orchard (8/site) to catch more adults as well as the pear psylla parasitoid, *Trechnites psyllae*.

Weather data came from the high-resolution historical data provided by daymet which provides data at 0.6 x 0.6-mile resolution as well as from data loggers placed in the orchard from the period 2016-2019. Data was fit by maximum likelihood to five different statistical distributions and examined for the best overall fit across the range.

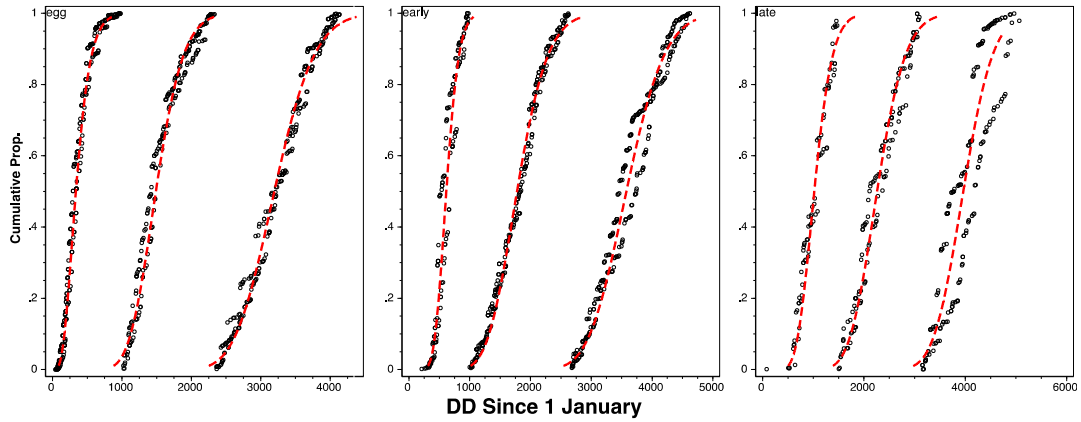
Methods Pear Bud Stage Development. Pear bloom phenology was evaluated at four locations with the cultivars Bartlett (3 locations), Bosc (1 location), and D'Anjou (2 locations). At each location we evaluated 60 fruiting buds (4 buds per tree from 15 randomly chosen trees – one bud per quadrant of each tree) and classified them as dormant, swollen bud, bud burst, green cluster, white bud, bloom, and petal fall. We visited each location twice per week to evaluate the clusters. Data analysis was done for each cultivar by using a maximum likelihood fit to one of five statistical distributions: (normal, lognormal, gumbel, gamma, Weibull).

Methods Bloom Progression

The second trial was run in 2020 which is called the bloom progression series. This one only considered the bloom period but used many more buds per tree. We used 10 trees per cultivar for each location and looked at as many buds as could be found on a branch. The numbers were counted initially on each tree and varied from about 30 to 100. We then came back 3x a week to evaluate how many blooms were open on each sampling date. This gave us up to 1000 buds per cultivar per location and the total numbers were from about 5500 to 9751 buds examined compared to around 1300-1600 for the bud stage studies. The result with the larger sample size is to catch more of the "rat tailed" bloom than the bud stages studies showed us.

Results and Discussion.

Fig. 1. Phenology of pear psylla egg, early instars (1-3) and late instars (4-5). Dashed line is model predictions, circles are observed.

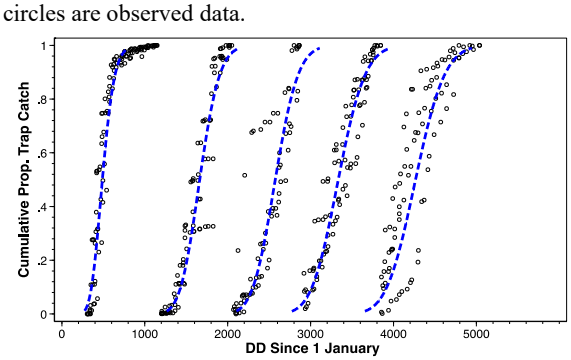


Pear Psylla Phenology. We completed evaluation of the pear psylla model for the winterform and summerform adults, eggs, early instars (1-3), and late instars (4-5) (Fig. 1). Our model shows that psylla begin laying eggs almost immediately – the adult and egg stages overlap almost completely when plotted on the same graph. We saw some variation in the late instars near the end of the season compared to the other stages, which was actually caused by a slight difference in DD between the sites at the end of the season. One of the changes compared to last year is that we found that the phenology was better estimated using a horizontal upper threshold for development.

We have also already finished the pesticide effects model for pear psylla. We have made this model available to Dr. Louie Nottingham and will work with him to evaluate the optimal control strategies for pear psylla.

We have also made a preliminary model for the pear psylla parasitoid, *Trechnites psyllae* (Fig. 2). The yellow panel data showed very large numbers of *Trechnites* present and we merged this with data collected by Drs. Dave Horton and Peter Shearer during the SCRI Enhancing biological control in Western Orchards grant. This data were combined with the same parameters for the lower threshold and type of cutoff as pear psylla and it allowed us to make the preliminary model just using the field data. However, when we did a literature search for information on *T. psyllae*, but there were no

Fig. 2. Phenology of trap catch of adult *Trechnites psyllae*. Dashed lines are preliminary model predictions, open circles are observed data.



laboratory data on developmental times which could be used to finalize the model. The status of this model is therefore unchanged as a preliminary model until validation of the thresholds.

Pear Bud Stage Development. This was the third year of collecting data on pear bloom for the three cultivars. The bud stage data was evaluated using not only the maximum likelihood estimates, but also simple summary statistics. We had reasonable numbers of all stages collected that allowed us to define the different stages and the variation associated with them at the different locations. We did not fit the distribution to the dormant stage, because we may have started a bit late in some cases and early in others so that you would get different distributions (since everything is in that stage until development starts). For the case of petal fall, we also did not run that fit because it would be easy to define as being "past bloom". For the maximum likelihood estimates for the different stages, the normal distribution was sufficient in most cases and for simplicity sake, we just used it for all the stages and cultivars (Figs. 3 & 4 shown for examples). These models are being incorporated into DAS and will be available next year.

Fig. 3. Bud stage distribution for D'Anjou fruit using the normal distribution

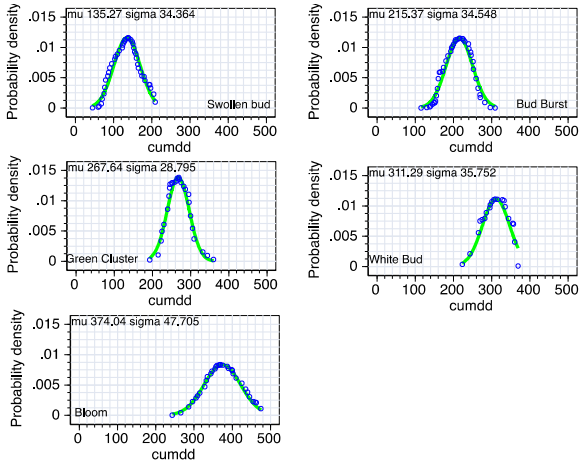
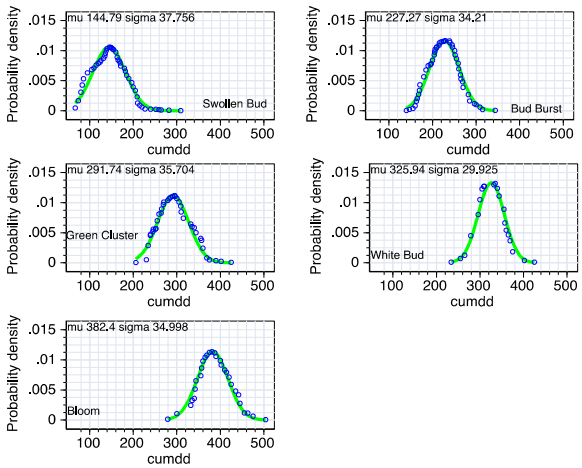


Fig. 4. Bud stage distribution for Bartlett fruit using the normal distribution



Pear Bloom Progression: The data for the bloom stage progression showed a much-extended period of what would normally be called "rat-tail bloom". The mean for the bloom period is not much different than the Bud Stages experiment values (max 10 DD difference), but the maximum time of any bloom occurring was about 335 DD longer than observed in the pear bud stage development experiment for the Bartlett and Anjou and only about 100 DD longer for Bosc. For Bartlett, only 3.5% of the 5598 bloom observations occurred after 550 DD, and 1.7% of the 9751 observations for D'Anjou. For Bosc, only 5 of 5645 observations occurred after 550 DD. In comparison to the Bud Stage data for bloom where the normal distribution provided a good fit, the data had a longer right tail which was better fit by the gumbel distribution. In reality, it probably doesn't make much difference except for the situation where fireblight is considered. In this case, the rat-tail bloom means that there is still a possibility for fireblight infection through a considerably expanded bloom period. However, it is still a very rare occurrence.

Obj. 2. Continue to collect validation data for demographic models for mites and aphids.

Methods. Phenology data were collected for woolly apple aphid (WAA), green apple aphid (GAA), two-spotted spider mite (TSSM), European red mite (ERM), and brown mite (BM). For GAA and WAA, four apple orchards were sampled twice a week from the end of March to mid-October. We sampled 100 shoots early in the year and 100 leaves later in the year (10 randomly chosen per 10 randomly chosen trees). The number of nymphs, nymphs w/ wing buds, wingless adults, and winged

adults was recorded for each aphid species.

Phenology data for ERM and BM were collected from six apple orchards, twice a week from start of April until late-October. Initially, when eggs started to hatch, double-sided sticky tape was placed tightly around 50 branches per site (1 per tree) to detect mobile immature stages. After leaves expanded, a total of 100 leaves from 20 trees per site were collected and run through the mite brushing machine. Mite numbers were recorded by species and stage. In addition to the canopy samples, we also collected mites from the ground cover. Our results from last year showed that common mallow (button weed) consistently had high numbers of TSSM, so all the ground samples focused on that plant.

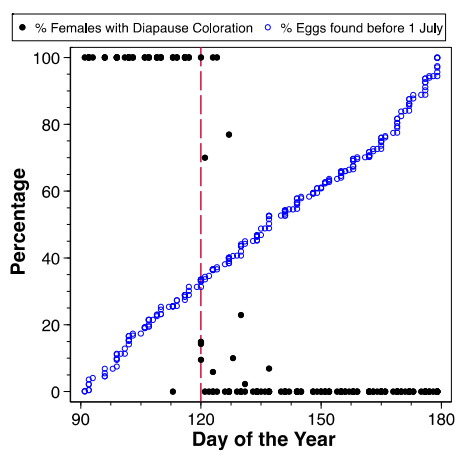
Results and Discussion

Rosy apple aphid & apple grain aphid. The phenology of rosy apple aphid and apple grain aphid from 2015-2019 were quantified and models were developed that allow to predict phenology and develop pesticide effects models (found at pesticides.decisionaid.systems). These models have been incorporated into WSU-DAS and were available for beta users this year. They will be available for all users next year.

Green apple aphid. Analysis of the green apple aphid showed no big drop off related to temperature as occurs with WAA. There is a significant reduction in immature survival during peak heat, but adults do not seem to drop off as much, so that recovery is quick once temperatures drop. Part of the problem with GAA is that populations in the orchards build up significantly before any heat-induced mortality and thus the populations stay high throughout the season. We were not able to quantify phenology to any significant degree as we have with the other aphid species because the generations overlap very quickly and they are present all season long (an average of >8 generations per year) – this makes it impossible to validate generation based models which are needed for the pesticide effects models. In comparison the RAA and AGA models have 3 and 2 generations/year, respectively.

Mites. Our work on mites has focused on both emergence times and whether we can develop a model that simulates what we observe in the field. We examined European red mite (ERM), Brown Mite (BM), and two-spotted spider mite (TSSM). TSSM analysis initially showed that the winter diapause-mediated color change (adult females turn orange when in winter diapause and return to greenish-tan when out of diapause) could be predicted by the daylength. The TSSM overwinters as adult females in reproductive diapause (if the temperatures are warm, they can feed or move about, but they are not reproducing until the temperatures & photoperiod rise above a certain level). Above 15.5 hours of light (roughly 1 May depending on site), we found the proportion of the adult female population switched relatively quickly to non-diapausing females (Fig. 4). However, we had also been taking leaf samples in the orchard and we found that eggs were produced at roughly the same rate per female when the female population was solely showing diapause coloration versus just after the female population showed no diapause coloration. Obviously, diapause coloration is not a true indicator of female reproductive status and cannot be used to guide management tactics for TSSM.

Fig. 4. Percentage of females showing diapause coloration and the percentage of the total eggs found before July 1 during the early season using data from 2017-2019.



During the studies of TSSM, we have examined both ground cover weeds (primarily button weed which is an excellent host) and sampled the canopy for all stages as well as for the presence of predatory mites. Our data for the predatory mites shows that we have a fast early season build up in the weeds from early April through the end of May, a drop off during the period of June through the first week of August, then a large build up until the end of the season. At first, we though the drop off in mid-season was related to high temperatures that start about that that time, but examining the canopy samples, that period is the same as when a large increase in predatory mites were collected in the canopy. This suggests there is a net migration upwards from the ground cover and that ground cover effects are key to making sure that predatory mites are available when spider mite populations in the canopy are peaking. Timing of weed control is therefore as critical with predatory mites as it is with TSSM.

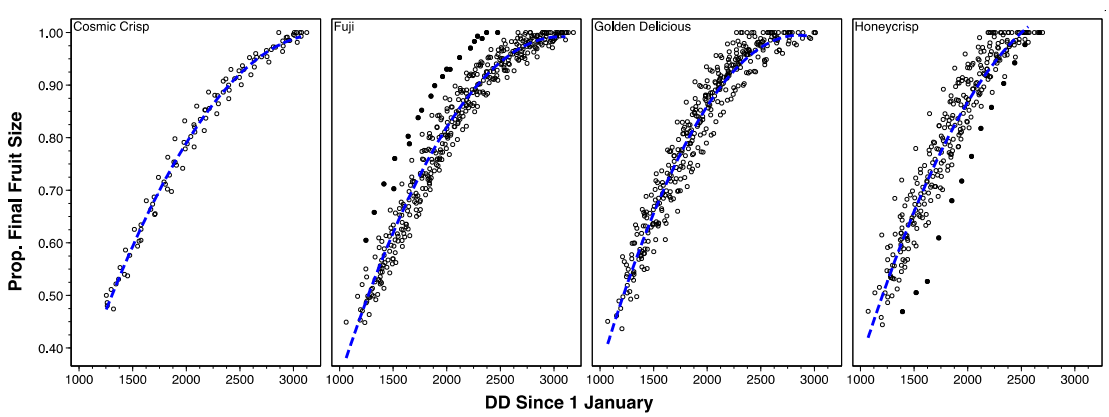
We had high hopes that we could develop a phenology model for the egg hatch of ERM and BM. However, collections done both before this grant started and during the grant period provided inconsistent data that could not be traced to time of collection in the field or to photoperiod that they were reared under. Both species exhibited very high variability with some years having and very low variability in others. Unfortunately, there was no consistent trend in emergence time related to the number of degree days and collection times in the field. The ERM data we collected reflects the sort of variation seen in the literature from a survey of six different studies. It is possible that some of the variation is just a natural adaptation to variable spring conditions, but the data we had is just not appropriate for developing a management model for ERM or BM.

Obj. 3. Development of new fruit growth models for Honeycrisp, Fuji, and Golden Delicious

Methods. We collected data from 11 geographic areas representing the topographic and climatic diversity of Central Washington production areas from Brewster Heights to North Pasco. We concentrated on Golden Delicious, Fuji and Honeycrisp, but also collected data on Cosmic Crisp at the WSU Sunrise location. After early drop was completed, we tagged fruit and then measured the same fruit each week until harvest. Each fruit measurement was recorded separately, so that we could assess how the individual fruit size changed over the course of the season. We analyzed the data as the proportion of the final fruit size for each fruit, so that we don't have to worry about the effects of thinning, fruit load, or return bloom size. This method allows us to predict when the fruit reaches a given percentage of the final fruit size. The fruit size data was paired with temperature data, and degree days from 1 January (base temperature 42, upper threshold 77.6).

Results. Our average fruit growth data showed good agreement for most sites and cultivars for 2017-2019. The one variable site was in south Orondo (near Baker Flat) where the orchard was on a south

Fig. 5. Fruit growth throughout the season versus model predictions for each cultivar. Black solid circles indicate areas with anomalous data from South Orondo (Fuji) and Mattawa (Honeycrisp in



facing slope that probably affected the Fuji grow size estimates by being warmer – this showed the same problem in 2017 and 2018 (black dots) (Fig. 5). The Honeycrisp data from 2019 at the Mattawa location in 2019 where the fruit growth appeared delayed (black dots) compared to all the others (Fig. 5). Because these sites were so anomalous, we dropped them from the final predictive model. These models were available on DAS this past year.

Executive Summary

Project Title: Developing and validating models for tree fruit

Keywords: Modeling, pear, apple, pear psylla, rosy apple aphid, apple grain aphid

Abstract. We developed models to predict pear psylla phenology and pesticide effects models to help determine optimal timings for management activities. The models are complete and have been provided to our collaborator (Dr. Louie Nottingham, WSU-TFREC) to help provide the information needed to make the models available to growers; this includes the longevity of different types of pesticides as well as stage specific activity needed. At the same time that we were collecting the data for pear psylla in the early spring, we collected data for models predicting the different bud stages of pear and an extensive collection of bloom timing. Those models will be available on DAS this coming year.

Evaluation of data for mites and aphids allowed us to create two aphid models, one for Rosy apple aphid, and the other for apple grain aphid. These models have been implemented on DAS and were available for our beta users this past year. Both models have also been developed as pesticide-effects models so that users can estimate the efficacy of control programs aimed at those two insects. Models for European red mite, twospotted spider mite, and brown mite were not feasible because of variation in the data, even though we had collected data from multiple locations and years before the current grant period.

Fruit growth models were also completed for the cultivars Cosmic Crisp, Fuji, Golden Delicious, and Honeycrisp, bringing our total number of models for fruit growth to seven different cultivars. These models are currently available on DAS.

CONTINUING PROJECT REPORT **NO-COST EXTENSION**

Project Title: Multi-purpose robotic system for orchards

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Cooperators: Columbia Fruit Packers, Auvil Fruits Inc.

Total Project Request:
Year 1: 248,058 **Year 2:** 250,780 Year 3: 255,692 **Year 4: $0**

Percentage time per crop: Apple: 100% Pear: Cherry: Stone Fruit:

Other funding sources: None

Budget 1
Organization Name: FFRobotics **Contract Administrator: Avi Kahani**
Telephone: +972 545615020 **Email address: avikahani@ffrobotics.com**

Item	2018	2019	2020	2021
Salaries	$59,400	$63,000	$66,150	
Benefits	$5,940	$6,300	$6,615	
Wages	$30,450	$31,500	$33,075	
Benefits	$3,045	$3,150	$3,308	
Equipment	$25,000			
Shipping (**)		$10,000	$10,000	
Supplies	$12,000	$8,000	$6,000	
Travel (*)	$20,000	$21,000	$22,000	
Plot Fees				
Miscellaneous (***)	$10,000	$25,000	$25,000	
Total	$165,835	$167,950	**$172,148**	**0**

Footnotes: Footnotes: (*) Travel budget is requested to cover the travel and accommodation (Travel from Israel)
(**) Shipping product to field experiments (***) Equipment

Budget 2

Organization Name: Washington State University **Contract Administrator:** Katy Roberts
Telephone: (509) 335-4564 **Email address:** katy.roberts@wsu.edu

Item	2018	2019	2020	2021
Salaries	$53,522	$55,662	$57,889	
Benefits	$5,101	$5,304	$5,516	
Wages	$6,000	$6,240	$6,490	
Benefits	$600	$624	$649	
Equipment				
Supplies	$12,000	$10,000	$8,000	
Travel *	$5,000	$5,000	$5,000	
Plot Fees				
Miscellaneous				
Total	$82,223	$82,830	**$83,544**	**$0**

Footnotes: *Travel budget is requested to cover the mileage for field experiments and to visit collaborators/co-PIs

1. OBJECTIVES

The following are the project objectives that remained same as the ones proposed in the original proposal.

1) Optimize camera configuration for multi-arm operation of our robotic harvesting machine
2) Integrate and demonstrate multi-arm harvesting robot to cover entire tree height
3) Evaluate the performance of the harvesting robot while in motion
4) Demonstrate integration of the harvesting robot with fruit conveying and bin filling system
5) Investigate machine vision and robotic end-effectors for blossom and green fruit thinning

1.1 Timeline of the Project Activities

Obj. #	Research Activities	Time						
		Year 1		Year 2		Year 3		Year 4
1	Develop a robotic system with multiple cameras							
	Optimize camera locations and create fruit map for harvesting based on accessibility				(1)			
2	Develop and evaluate a robotic harvesting system with multiple arms for entire tree							
3	Develop a control system for automated forward motion control							
	Evaluate the machine for automated operation during motion							
4	Integrate multi-arm robot with a harvest aid platform							
	Evaluate the performance of the machine for harvesting, conveying and bin filling						(2)	(3)
5	Develop machine vision system for flower and green fruit detection							
	Preliminary evaluation of a robotic system for flower and green fruit thinning							

(1) There is a minor change in the schedule projected at this time. In the table above, **gray** cells represent the original schedule while **green** cell added at the end of second activity for objective 1 shows a minor change this time.

(2) COVID-19 effect - Evaluate the performance of the machine for harvesting, conveying and bin filling,

(3) See below

Progress report:

1. Since our last trials in WA. Orchards, we have made significant progress in our development process, and, naturally, planned to be able to have final tests and demos in WA. during the coming (2020) apple harvesting season.
2. Regrettably, the COVID-19 crisis affected us as well:
    a. Thinning:
    Instead of using the FFRobot as planned, we have decided with WSU to use the Bandits (Automated Ag Thinner) and robotic manipulator. The same Linear approach.

Predicted bloom density is estimated to be 82 percent similar to ground true density in terms of luminance, contrast, and structure.

b. Certain hardware parts, including electric engines, controllers and other sub-systems have been and some still are late in delivery to our premises, causing us further delays in assembling them into a fully working harvesting system to be demonstrated on time.
It is now estimated that - barring additional presently unforeseen obstacles - we will arrive towards late November to demonstrate the new model and the integrated solution (see the attached).

c. System improvements:

Mechanical Design
Reduced width
Support Transportation Height limitations
Telescopic Z axis
New frame
Fruit transportation conveyance system
Platform (Automated Ag)
Stem clipping (basic design)
Detection & Classification System
Wires detection
Fruit Orientation
Obstacles detection
Color Classification
Framos Camera
Thinning Blossom density estimation

The task we will not be able to complete during the program 3rd year:

Evaluate the performance of the machine for harvesting, conveying and bin filling,

In order to preform the task during the harvesting season of 2021 we kindly ask the Commission to transfer $25K from year 3 to year 4 to support our activities during 2021 season.

3. As part of the lesson learned, we will work to define the right pruning and design of the orchard to reach the best performance using our solution.

We will continue to update the Commission on our progress and changes during the Covid-19 challenging times.

FINAL PROJECT REPORT

Project Title: WTFRC Test Orchard (evolving to Smart Orchards Year 2 + Connectivity)

PI: Steve Mantle
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Cooperators: Columbia Reach/Chiawana Orchards – Shawn Tweedy (area), Martin Ramirez (site), Amy Mattingly (data); WSU – Lav Khot (imaging, data interpretation), Dave Brown (micro climate), Bernardita Sallato (root nutrient uptake); Microsoft – Puneet Singh (Farmbeats data platform), . Sensor providers – Davis Instruments (weather), Tuctronics/AgriNET (weather, soil moisture, water pressure, PAR), AquaSpy (soil moisture, air temp/RH), MeterGroup (weather station API access), Teralytic (soil nutrients), Green Atlas (canopy mapping post-harvest), SmartGuided Systems, Phytech (dendrometer, Predictive Nutrient Solutions (soil lab testing). OSU unable to participate (sap flow) due to COVID.

Percentage time per crop: Apple: 100% Pear: Cherry: Stone Fruit:

Total Project Funding: $15,000 + $10,000 expenses

Budget History:

Item	**Year 1:**
Salaries	
Benefits	
Wages	
Benefits	
Equipment	
Supplies	
Travel	
Plot Fees	
Miscellaneous – "Ag Data as a Service" **"WSU imaging analysis services"**	$15,000 $7,846
Total	$22,846

Notes: $15,000 "ag data as a service" fully invoiced; $7,846 for "WSU imaging analysis services" to be fully invoiced by innov8.ag thru 5/30/21, to align with 1-year timeline from initial out-of-band grant funding by WTFRC.

Original Objectives:
The problem we are looking to address: set up an automated system that collects, and synthesizes data from an orchard to track performance over time, with the ultimate goal of providing decisions and insights for more consistent management decisions to enable optimization of fruit quality.

1.Sensorize an orchard block with an array of sensors, with goal to:

- Bring together disparate data silos from multiple vendors
- Shift grower decision making process to enable management decisions based on unified data, and 'smart management' where possible
- Compare pack-out (quality & quantity) vs a neighboring 'control block' (same soil, topography, variety, root stock)

The orchard blocks are owned by Columbia Reach's Chiawana Orchards location at 1741 Auburn Road, Pasco WA 99301. Block 662 (19.2 acres, test) will be compared against neighboring block 661 (20 acres, control).

2.Collaborate with WSU and sensor providers to

- Create opportunities for larger collaboration in the future.
- Learn capabilities of modern orchard decision making with basic AI and Data Analytics.
- Provide a learning orchard for scientists and industry to visit.

Significant Findings:

1. **Grower, equipment/sensor provider, & researcher engagement around a smart orchard showcase is extremely positive.**
    a. Growers were surveyed by WSU in the Spring, and overwhelmingly expressed positive or extremely positive interest in learning from and applying smart orchard learnings to their operation – with a particular interest in irrigation optimization. Due to COVID restrictions, we were unable to offer formal "field days" for growers, but instead had informal tours every 2-4 weeks through the growing season, all of which were attended by growers & ecosystem participants (eg GS Long).
    b. Participating sensor providers & researchers were highly engaged & supportive throughout the season – with donations of sensors, loaning of equipment, & investment of personnel onsite and remotely for training, research, & troubleshooting. Additionally, WSU researchers requested collaboration on two proposals to USDA & NSF and three proposals to WTFRC building upon smart orchard learnings from 2020. Finally, WSU requested a "digital transformation in ag" presentation at the 2020 Digital Ag Summit (attended by hundreds of researchers around the world), where smart orchard learnings informed a call to action for academia, industry, government, & all supporting stakeholders.
    c. Consolidated access to data enabled new collaboration & innovation opportunities, including hackathons (two with Microsoft, one with WSU) that highlighted new data-enabled approaches & insights.
2. **Data ingestion, normalization, & rationalization from many different sensor, equipment, & management data sources requires significant investment of time & resources for ag data solution providers.**
    a. Innov8 Ag partnered with several different providers to ingest data from APIs, CSV downloads, and Excel spreadsheets. While we generally selected providers that have

invested in streamlining data sharing, it's clear that there are categories of "data sharing lifecycle maturity"

i. Highly mature – published their own APIs for years, can also flow their data into API-centric datahubs (such as Microsoft Farmbeats), and have substantial documentation for both scenarios. Example – Davis Instruments
ii. Mature – published their own APIs for years, and have some published documentation. Example - AquaSpy
iii. Emerging – CSVs can be downloaded from website. Example - Phytech
iv. Early – can email CSVs or require manual download from originating sensors or databases. Example – Teralytic, SmartGuided Systems

b. Inconsistent formatting of times, dates, and units of measurement requires substantial investment in time for "data transformation" and normalization.

i. For sensors & equipment data, this was anticipated.
ii. For management data – specifically labor & chemical, this is more challenging as getting to the source of the data can be challenging (eg timesheet data may be summarized weekly and available/extracted from Famous vs. the timesheet source) and the summary lacks the frequency or consistency in units of measure to be of use for relation to sensor & equipment data.

c. Management data relatability requires substantial investigation to understand accuracy & context (underscoring criticality of machine-based data such as from a smart sprayer or smartphone-sourced labor tracking)

i. Data may not actually be what it appears. Example – irrigation labor data is mapped to an orchard block, but when irrigator interviewed it's clear much of the time the time allocation is erroneous. Or sprayer application data is mapped to a block, but when sprayer lead interviewed - realistically it's averaged out across several blocks.

3. **Sensor, equipment, & imagery provider openness to data sharing of "raw data" is viable for most; unacceptable to some.**

a. We've found that most providers were highly collaborative on sharing their raw data, particularly given the enablement to collectively learn as to how to provide more value to growers.
b. There is a minority of providers that are resistant (or refuse) to share raw data out of concern that new data products will be produced resulting in emergence of competitive capabilities by other sensor/equipment/datahub providers.
c. Point b unfortunately perpetuates the data silo challenge facing growers (including "who owns the data", particularly if the grower discontinues the service and/or the provider ceases operations), but at the same time – may bring value to the grower by providing a "one stop shop" for data insights. Industry examples reluctant to share raw data are Phytech & Semios; example of a provider that ceased operation in 2020 is Terravion, relegating access to "grower-owned" imagery to navigating bankruptcy court.

4. **Tracking of grower management data is dramatically more viable when a grower-employed data analyst is assigned; tracking – and influencing - grower management decisioning is more challenging.**

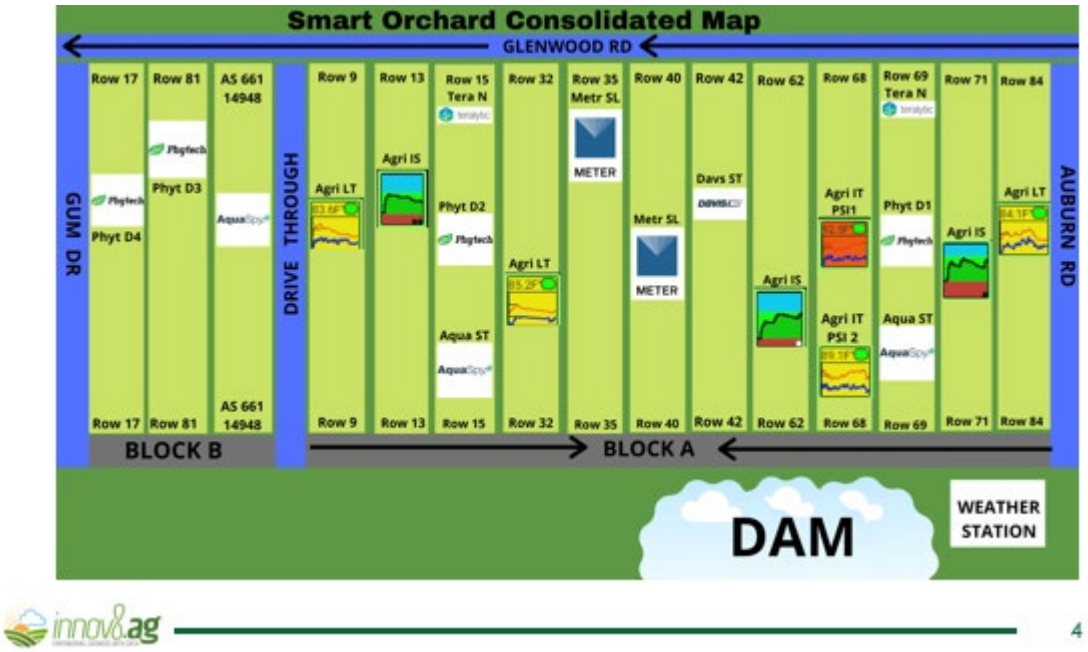
a. At the outset of this project, the grower employed and assigned a data analyst to work with the project team. The analyst provided substantial value to the team, as they consolidated, rationalized, and interpreted data tied to management. This included labor & chemical records, water & electricity meter data, as well as context on "data holes" or system changes that impacted data quality.

b. Tracking cause and effect requires prioritization of which decisions to track, then a systematic approach to consistently capturing those decisions, and mapping to anticipated outcome.

5. **Expecting tracking of pack-out and comparing against other blocks is unrealistic if expecting to show value from data-driven decisioning.**
    a. Pack-out data isn't always tracked at the block level. When it is, the data typically won't be available until 3-6 months post-harvest, as the relevant apples are counted when shifting from storage to packing production.
    b. Tracking/predicting yield at and within the block level is an approach that complements the latent packout data. Upon realizing this, innov8.ag invested in tree imaging/apple counting research with Microsoft & WSU, then subsequently obtained ATV-based imaging capability for crop density & tree height/area to pull into the 2021 smart orchards project proposal. This capability wasn't originally expected or scoped for 2020, but it's clear that this dataset will be fundamental to enabling data-driven insights *throughout the season* in future projects.

Results & Discussion:

Sensors were deployed across the 20-acre block #662 as indicated in the physical layout view depicted in Figure 1:



The sensor specifics deployed were as follows (table 1):

Category	Purpose/ location	Instrument	Manufacturer	Specifications*
Weather	Open-field & In-orchard	ATMOS 41	Meter Group	12 weather parameters
	Above canopy, in-canopy at 3' and 6' AGL	Vantage Pro2 6820	Davis instruments	5 weather parameters, A: 2%

	In-canopy at 3' AGL	ANTHA	Tuctronics	Temperature, humidity and leaf wetness
Soil, Water	Soil moisture at 2' depth	Drill & Drop	Sentek	Measurements every 4"
	Soil moisture, nutrients and temperature at 4'	AquaSpy probe	AquaSpy	Measurements every 4"
	Soil water potential	Teros 21	Meter Group	R: 0.1 kPa, A: 90%
	Soil quality at 6", 18", and 36" depths	Soil probe	Teralytic	NPK, moisture, salinity, aeration, respiration, temp., light & RH
	Irrigation monitoring	PS-1 irrigation pressure switch	Meter Group	Set point: 5 psi (± 1)
	Tree trunk and fruit size	Dendrometer	Phytech	Shrink-swell in µm
	Leaf wetness	LWS	Campbell Scientific	Measurement time: 10 ms, Output: 250–1500 mV
	Canopy health (NDVI, PRI)	Spectral Reflectance Sensor	Meter Group	A: > 90%; Green-1: 532 nm, Green-2: 570 nm, Red: 650 nm; NIR: 810 nm
	Canopy health (NDRE)	Custom development	WSU	Bands: NIR and RE
	Canopy vigor	2D LiDAR	Smart Guided Systems LLC	AR: 0.25º, Scan frequency: 25 Hz
	RGB imaging	RGB imager w/ DJI Phantom 4 (in WSU inventory)		PR: 12.4 Mega Pixels, SR: 5 cm @ 100 m altitude
	Multispectral imaging for canopy vigor/health	10-band dual camera imaging system	Micasense Inc.	SR: 7 cm @ 100 m altitude Bands: Coastal blue (444 nm), blue (475 nm), green-1 (531 nm), green-2 (560 nm), red-1 (650 nm), red (668), red edge-1 (705), red edge-2 (717 nm), red edge-3 (740 nm) & NIR (842 nm)

Thermal imaging for canopy temperature and health	FLIR Duo Pro R w/ AgBOT quadcopter (in WSU inventory)	A: 95%, lens size: 13 mm, Spectrum: 7500–13500 nm, SR: 13 cm @ 100 m altitude

The ingested sensor data is available via

- web browser (figure 2), iOS and Android app for grower personas
- ODBC consolidated raw data access (figures 3a & b) for data analyst & researcher personas
- and PowerBI via web browser, iOS and Android app (figure 4) for management personas [focused around a irrigation planning use case, aligned to results from WSU survey seeking grower interest in the smart orchard pilot]

Fig 2 – web browser view of sensor data:

For the ODBC view (raw access to consolidated data, there are 11 tables for this dataset under the schema `ColumbiaReach` (left in Figure 3a) organized by provider and sensor type (right in Figure 2). All the sensor metadata, for example installed location (`latitude, longitude, elevation`), provider (`provider_id`), type (weather or soil), whether installed inside canopy or outside (`inside_canopy`), and in which table telemetry is stored (`table_name`) are included in table `ColumbiaReach.sensors`. These sensors are referenced in all telemetry tables by their unique `sensor_id`.

For example, the Tuctronics telemetry and sensor meta info will look like Figure 3b. Tuctronics provided five ANTHA sensors installed to monitor weather and three Sentek Drill & Drop probes to monitor soil. Figure 3 shows one weather sensor with id 104 and one soil sensor with id 125. Note that for the 5 ANTHA weather sensors, they all have measurements for air temperature and humidity, but

only three of them have measurements for leaf wetness and two of them have measurements on irrigation PSI/temperature. For variables that do not have measurements from a given sensor, the corresponding columns will be filled with NULL. These sparse columns exist in almost all the weather tables in our database.

Figures 3 – ODBC consolidated raw access view, as supplied to smart orchard stakeholders & participants, Microsoft hackathon participants, and WSU hackathon participants:

Fig 3a. Tables included in the consolidated database (left) and their structure relationship (right)

Dimensions	ColumbiaReach.providers
	ColumbiaReach.sensors
Tuctronics (AgriNet)	ColumbiaReach.tuctronics_weather
	ColumbiaReach.tuctronics_soil
Davis Instruments	ColumbiaReach.davis_weather
Meter Group	ColumbiaReach.meter_weather
	ColumbiaReach.meter_soil
AquaSpy	ColumbiaReach.aqua_weather
	ColumbiaReach.aqua_soil_history
Teralytic	ColumbiaReach.teralytic_weather
	ColumbiaReach.teralytic_soil

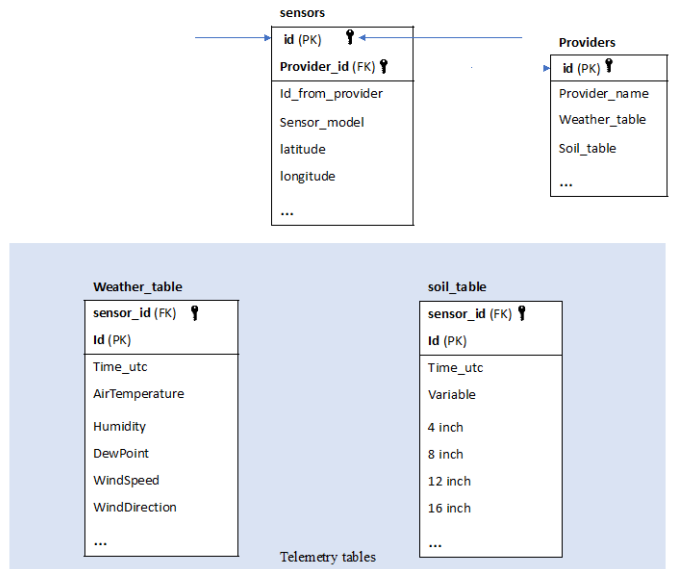
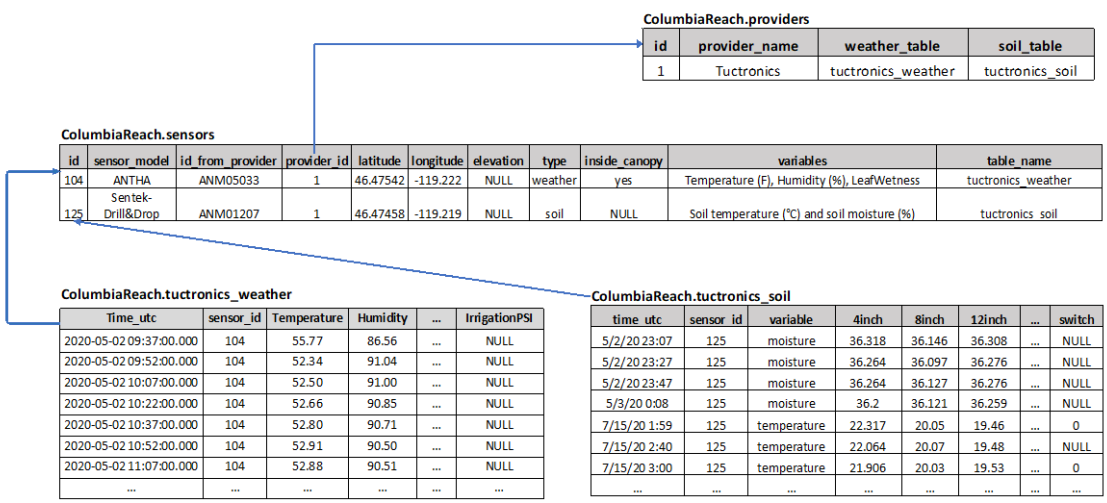


Fig 3b. Tuctronics tables



ColumbiaReach.providers

id	provider_name	weather_table	soil_table
1	Tuctronics	tuctronics_weather	tuctronics_soil

ColumbiaReach.sensors

id	sensor_model	id_from_provider	provider_id	latitude	longitude	elevation	type	inside_canopy	variables	table_name
104	ANTHA	ANM05033	1	46.47542	-119.222	NULL	weather	yes	Temperature (F), Humidity (%), LeafWetness	tuctronics_weather
125	Sentek-Drill&Drop	ANM01207	1	46.47458	-119.219	NULL	soil	NULL	Soil temperature (°C) and soil moisture (%)	tuctronics_soil

ColumbiaReach.tuctronics_weather

Time_utc	sensor_id	Temperature	Humidity	...	IrrigationPSI
2020-05-02 09:37:00.000	104	55.77	86.56	...	NULL
2020-05-02 09:52:00.000	104	52.34	91.04	...	NULL
2020-05-02 10:07:00.000	104	52.50	91.00	...	NULL
2020-05-02 10:22:00.000	104	52.66	90.85	...	NULL
2020-05-02 10:37:00.000	104	52.80	90.71	...	NULL
2020-05-02 10:52:00.000	104	52.91	90.50	...	NULL
2020-05-02 11:07:00.000	104	52.88	90.51	...	NULL
...	...	...	...	...	...

ColumbiaReach.tuctronics_soil

time_utc	sensor_id	variable	4inch	8inch	12inch	...	switch
5/2/20 23:07	125	moisture	36.318	36.146	36.308	...	NULL
5/2/20 23:27	125	moisture	36.264	36.097	36.276	...	NULL
5/2/20 23:47	125	moisture	36.264	36.127	36.276	...	NULL
5/3/20 0:08	125	moisture	36.2	36.121	36.259	...	NULL
7/15/20 1:59	125	temperature	22.317	20.05	19.46	...	0
7/15/20 2:40	125	temperature	22.064	20.07	19.48	...	NULL
7/15/20 3:00	125	temperature	21.906	20.03	19.53	...	0
...	...	...	...	...	...	...	...

1. Notes on Measurement Interpretation

- Soil moisture measurement

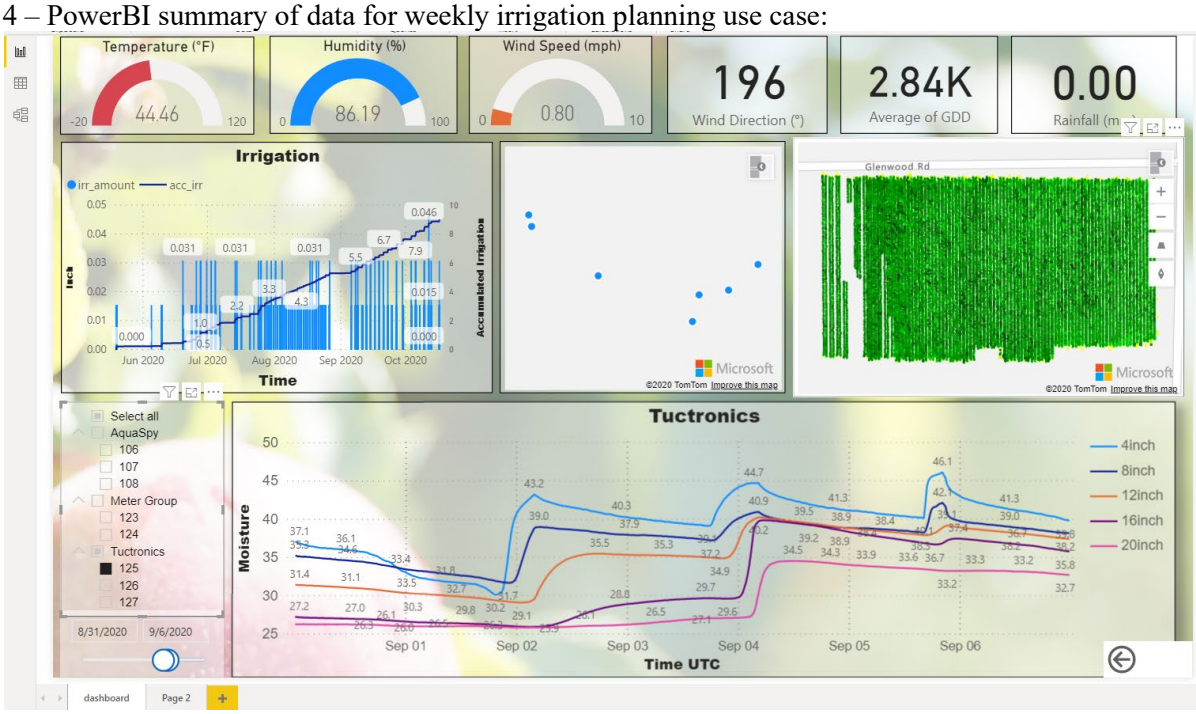
For soil measurement, the main properties observed are soil temperature and soil moisture. Soil temperature are measured in either Fahrenheit or Celsius and the absolute values across different providers are comparable after unit transformation (Figure 5). Unlike temperature, soil moisture is measured by either the ratio of volumetric water content over field capacity (%, such as AquaSpy and Tuctronics) or by soil matric potential (kPa) (such as Meter Group's TEROS-21 soil sensor). Even

when AquaSpy and Tuctronics both use % to indicate soil moisture, they are calibrated differently. Hence we might observe similar temporal variability but will also observe a systematic difference in the absolute values (Figure 4).

- Leaf Wetness measurement

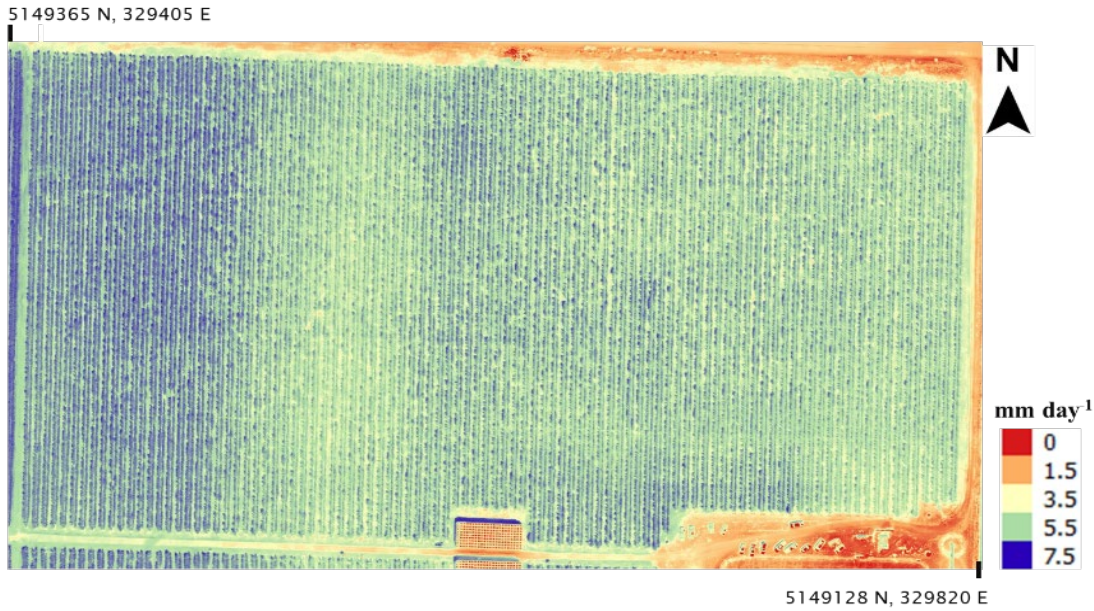
Unlike other variables that are either directly measured or prescribed based on directly measured variables, leaf wetness can be indirectly measured by change in electrical resistance or change in dielectric or change in some hygroscopic properties of the sensors. Hence the absolute values of leaf wetness provided by different manufacturers can have very different units.

Fig 4 – PowerBI summary of data for weekly irrigation planning use case:



A number of resultant data insights, presentations, and takeaways were built by various stakeholders (full summary presented in associated PPT & recording), with cross-data insights highlighted as follows:

Fig. 5. High resolution evapotranspiration map of smart orchard test-block, enabling reconsideration of irrigation application requirements throughout a block – Lav Khot team.



Fig

Fig 6. Air temp & RH variations from in-canopy vs above-orchard vs out-of-orchard, enabling reconsideration of spray timing/efficacy based on new in-canopy data (vs nearest AgWeatherNet station), as well as tuning application of disease & pest models

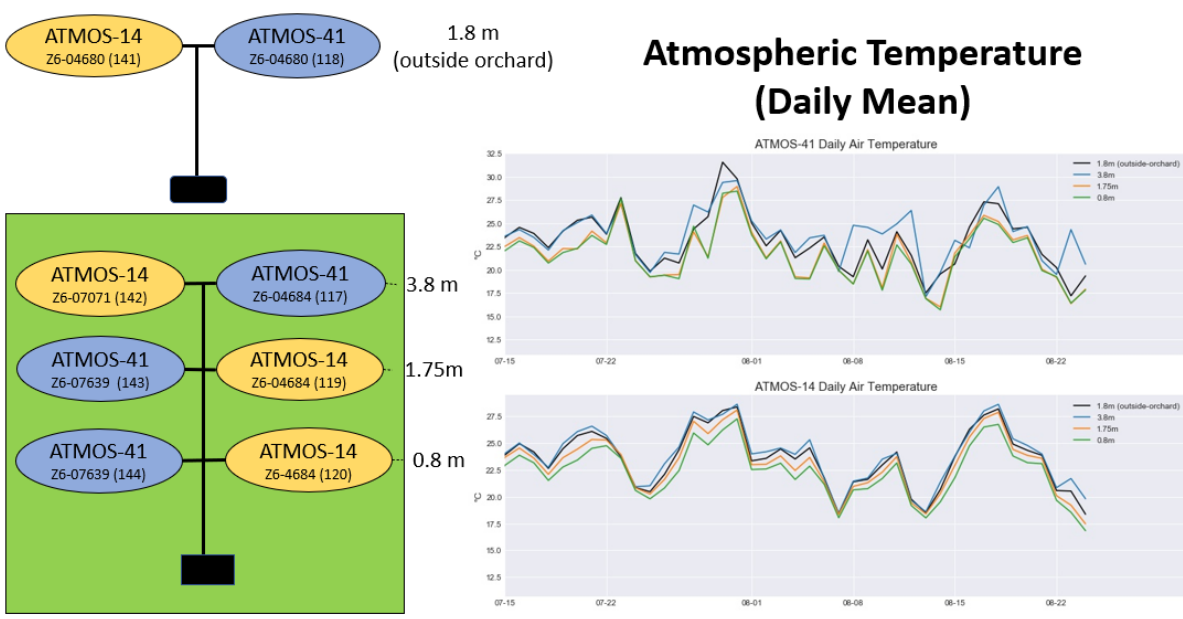


Fig 7 – Apple Counting using AI summary using video captured by smartphone analyzed at Microsoft hackathon, providing ability to look at yield predictions and tying to labor and/or chemical planning:

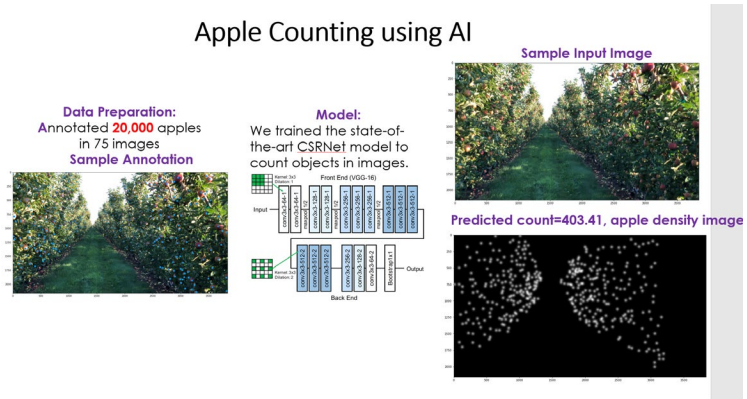


Fig 8 – Canopy area variability using Green Atlas at end of season, providing understanding of tree maturity/vigor for nutrient planning:

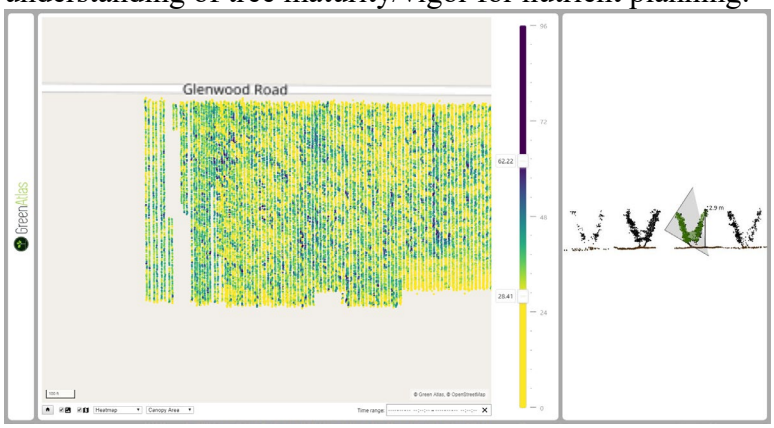


Fig 9 – Predicting fruit quality based on soil nutrient analysis from sensors & lab data, as detailed further by Bernardita Sallato in a separate report

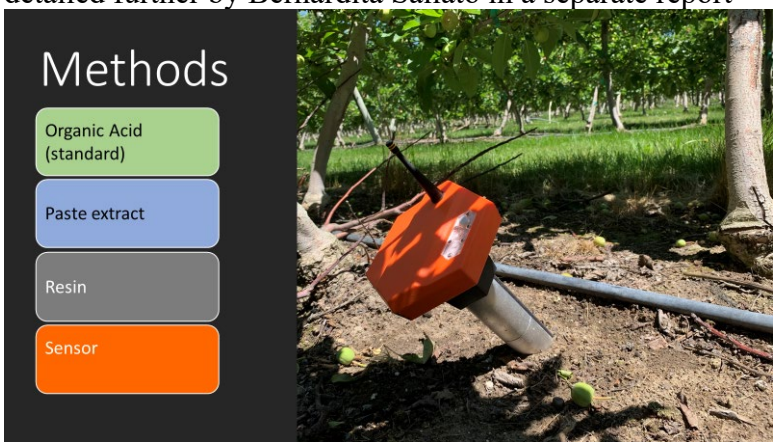
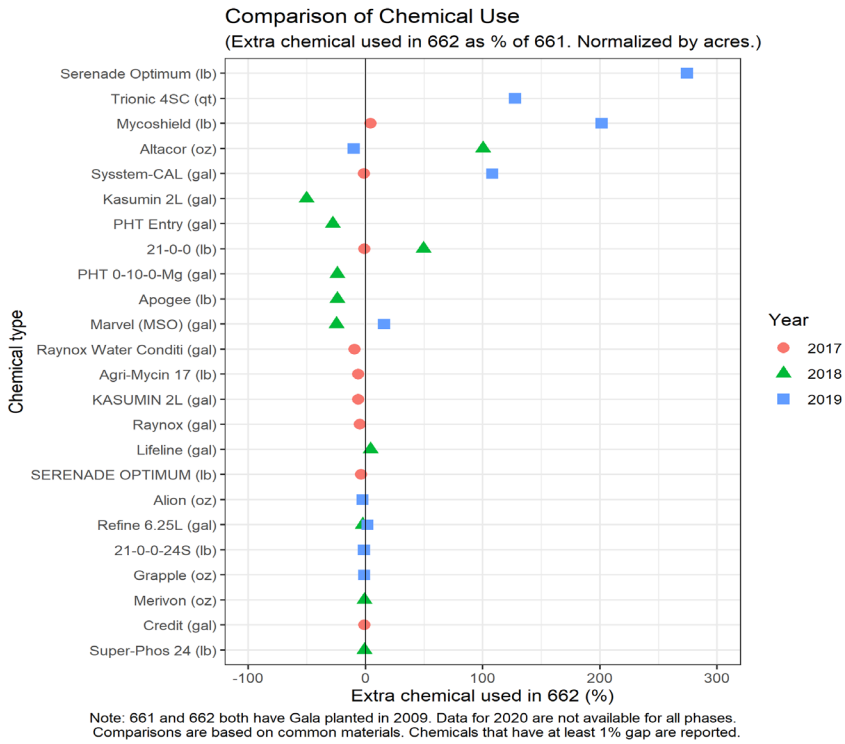


Fig 10 – Analysis of chem applications across two blocks, complemented by reason for application:



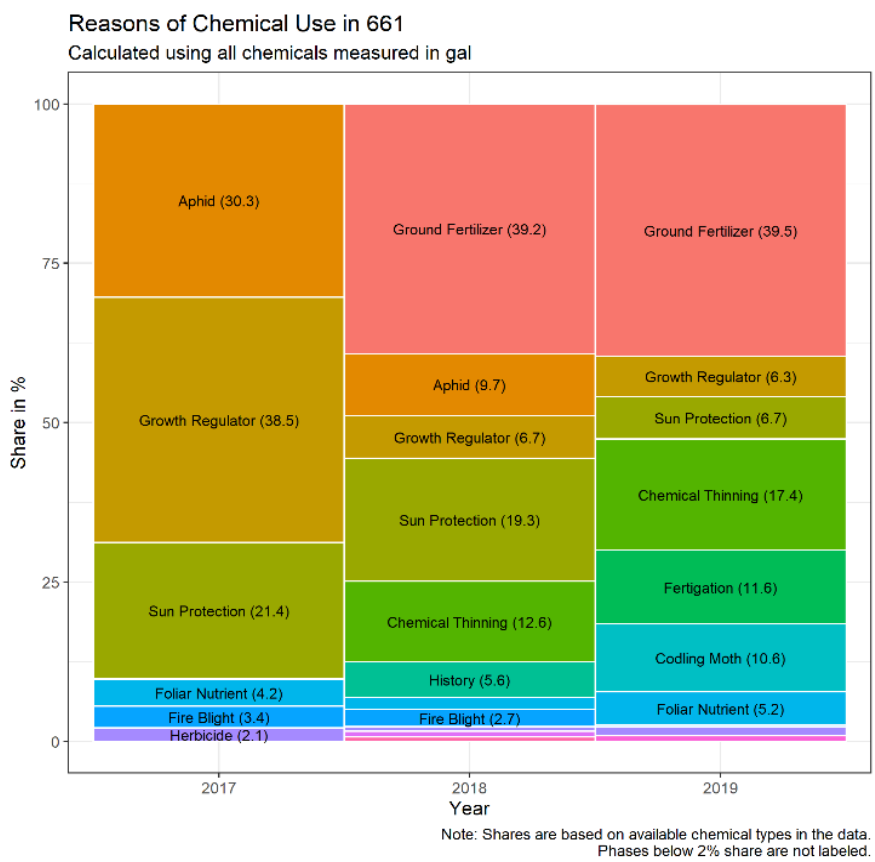


Fig 11 – Analysis of labor usage across two blocks, categorized by reason/type:

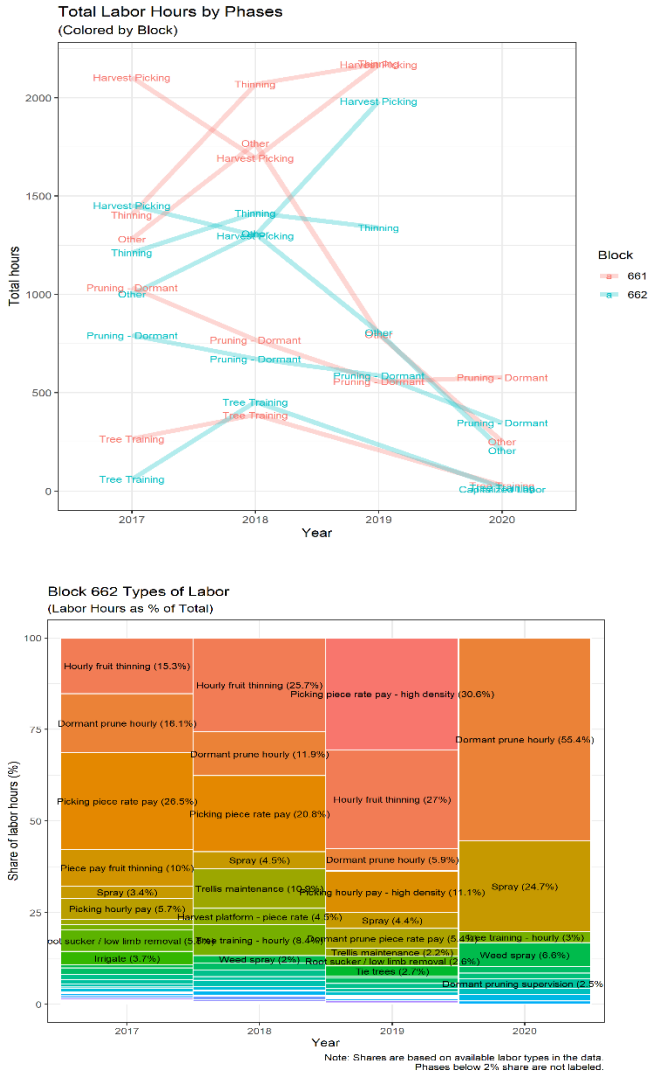
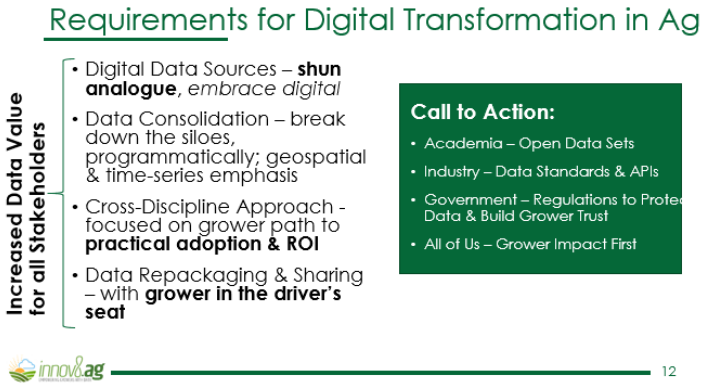


Fig 12 – Requirements for Digital Transformation in Ag takeaways shared with audience at WSU Digital Ag Summit, based on Smart Orchard learnings:



A playlist of videos that summarizes the project, including 3 smart orchard data research projects as part of the 1st WSU Digital AgAthon and 2 related hackathon projects at Microsoft, is available at www.innov8.ag/smartorchard

EXECUTIVE SUMMARY

Project title: WTFRC Test Orchard (evolving to Smart Orchards Year 2 + Connectivity)

Key words: smart orchard, artificial intelligence, data, internet of things, sensors

Abstract: The Smart Orchard project started out-of-cycle in 2020, as the WTFRC technology committee identified that growers struggle with too many data siloes, impeding ability for growers to make informed decisions that may be better informed based on a unified view. Year 1 was about laying the groundwork for a smart orchard test block to collect data for many different sources. Our takeaways after 5 months of sensor implementation, data collection, and stakeholder collaboration:

1. Grower, equipment/sensor provider, & researcher engagement around a smart orchard showcase is extremely positive.
2. Data ingestion, normalization, & rationalization from many different sensor, equipment, & management data sources requires significant investment of time & resources for ag data solution providers.
3. Sensor, equipment, & imagery provider openness to data sharing of "raw data" is viable for most; unacceptable to some.
4. Tracking of grower management data is dramatically more viable when a grower-employed data analyst is assigned; tracking – and influencing - grower management decisioning is more challenging.
5. Expecting tracking of pack-out and comparing against other blocks is unrealistic if expecting to show value from data-driven decisioning.

A playlist of videos that summarizes the project, including 3 smart orchard data research projects as part of the 1st WSU Digital AgAthon and 2 related hackathon projects at Microsoft, is available at www.innov8.ag/smartorchard