Project/Proposal Title: Validation of plant-based sensors for making irrigation decisions

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Report Type: Final Project Report

Project Duration: 2-Year

Total Project Request for Year 1 Funding: $ 60,355
Total Project Request for Year 2 Funding: $ 45,050

Other related/associated funding sources: Awarded
Funding Duration: 2021 - 2027
Amount: 20,000,000
Agency Name: NSF/USDA AI Institute
Notes: This sensor project allowed us to leverage this as a key contributor to the water ag thrust and getting a running start on data analysis and collaborations for this project.

Budget 1
Primary PI: Lee Kalcsits
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Contract Administrator: Darla Ewald
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Item	2021	2022
Salaries	18,000[1]	18,720[1]
Benefits	8,437[2]	8,774[2]
Wages	7,800[3]	8,112[3]
Benefits	1,749[4]	1,819[4]
Equipment		
Supplies	20,344[5]	3,600[5]
Travel	4,025	4,025
Miscellaneous		
Plot Fees		
Total	60,355	45,050

Footnotes:
[1] Support of a research assistant at 50% for the duration of the project to collect and curate data, maintain experiments and prepare results for reporting and publication
[2] Benefits are at a rate of 46.87%
[3] Wages are to support a summer staff person to aid in collecting data, writing extension material, and for maintaining experiments
[4] Benefits for the summer staff position is 22.4%
[5] Supplies include the purchase of stem and fruit dendrometers, field consumables, and cellular data loggers. Both the sap flow system and microtensiometers were already purchased.

Objectives

1. Deploy and evaluate the accuracy and precision of dendrometers, sap flow sensors, and stem microtensiometers in measuring plant water status
2. Identify critical factors affecting the adoption of these technologies in Washington state tree fruit production
3. Develop Extension materials and train growers in using these technologies.

All sensors were installed in both 2021 and 2022 in the smart orchard and were also used for experiments conducted in pear at the WSU Sunrise Research Orchard. We have completed all three objectives and the report below will highlight our key findings and recommendations for the use of these different sensors in orchard decision making.

Significant Findings

- Florapulse microtensiometers were highly accurate and precise in measuring stem water potential in real-time. These can be a viable replacement to making pressure chamber measurements manually.
- Florapulse sensors had a ~90% installation success. Minimum trunk diameter for installation is ~40 mm. Smaller trunks make installation difficult.
- Fruit growth sensors are difficult to maintain. They were knocked off the fruit easily and need to be checked daily. Furthermore, the orientation of the sensor on the fruit affects measurements and the spring tension affects fruit growth. These factors suggest that irrigation decisions cannot be made with fruit sensors alone. Fruit growth rates are heavily influenced by many factors that are difficult to account including crop load.
- Stem dendrometers and sap flow sensors have been more commonly used as research tools. Stem dendrometers are useful integrators of plant stress. However, their sensitivity decreases when stem water potential decreases under water limitations. These sensors are more useful when trying to optimize irrigation for maximizing fruit diameter.
- In order of ease of interpretation of data: Florapulse = Pressure Chamber > Stem Dendrometer > Sap flow > Fruit diameter
- In order of ease of installation: Fruit diameter> Stem dendrometer > Florapulse > Sap flow
- Costs for these sensors can vary and depend on variability and the number of irrigation zones in the orchard.

Methods

Smart Orchard

We deployed commercially available dendrometers (fruit, trunk, and stem), sap flow sensors, and stem microtensiometers into the WTFRC-funded sensor orchards (in collaboration with Bernardita Sallato, Lav Khot, Dave Brown, and Steve Mantle) (Figure 1). Two trees were selected from a high and low vigor site within the spatially variable block. These same sites were aligned with the deployment for other sensors and monitoring equipment from other collaborators.

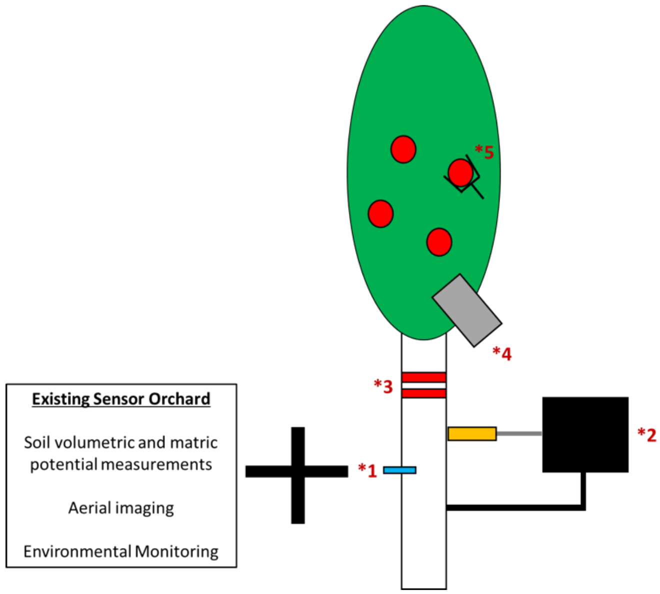

Figure 1. Plant-based monitoring approaches that are proposed to be added to the sensor orchard in Grandview, WA that will include: 1. Microtensiometers, 2. Stem dendrometers, 3. Sap flow sensors, 4. Traditional stem water potential checks, and 5. Fruit dendrometer sensors.

Table 1. Sensor deployment in Smart Orchard in 2021 and 2022

Plant Sensors	Environmental Sensors	Soil Sensors
Stem dendrometer (Edaphic Scientific) Fruit dendrometer (Edaphic Scientific) Microtensiometer stem water potential (Florpulse) Scholander chamber stem water potential Sap flow (Dynamax and Tree2Scope)	Air temperature Relative Humidity Wind speed Radiation	Soil volumetric water content

Pear study site and irrigation treatments

The experiment was conducted in 2021 and 2022 at the experimental orchard of the Washington State University located in Rock Island (Washington State, USA, 47° 19′ N, 120° 04′ W) on a 2 acre pear block (*Pyrus communis* L.), planted in 2007 on a shallow sandy loam soil. ‘D'Anjou’' pear trees were grafted on OHxF.87 rootstock and trained on a central leader system at a tree density of 344 trees per acre. Horticultural practices (e.g. fertilization, pruning and weed control) were the same for all trees in the block and followed commercial regular practices. Full bloom was in April, and harvest was in late August. Trees were drip irrigated by a system consisted of a single drip line per tree row and five emitters per tree of 0.5 gallon h-1 discharge rate.

Two irrigation treatments were imposed, a control treatment (CTL) irrigated at 100% of crop evapotranspiration (ET_c) to ensure non limiting soil water conditions and a regulated deficit irrigation treatment (DI), irrigated at 100% of ET_c from April 1st to June 27th, and 50 % of ET_c from June 28th to October 15th. Crop water requirements (ET_c) were calculated using: $ETc = ET_o \times K_c \times K_r$, where ET_o is the reference evapotranspiration, K_c is the crop-specific coefficient reported for adult pear trees, and K_r is a factor of localization. Treatments were distributed according to a completely randomized block design with three replicates per treatment. Within each replicate, two trees were selected to assess their tree water status during the season. All measurements were conducted in the same 12 trees selected for their uniformity (average ground cover of 41 % and mean trunk diameter of 10.5 ± 0.23 cm).

Environmental data and soil water content

Air temperature, relative humidity, wind speed, precipitation, solar radiation and reference evapotranspiration were continuous recorded by an AgweatherNet weather station located at the experimental orchard (http://www.weather.wsu.edu; "Sunrise sta-tion"). Moreover, two temperature and relative humidity sensors (ATMOS-14, METER Group Inc., Pullman, WA, USA) were installed in the pear block. Every 15 minutes, mean air vapour pressure deficit (VPD) was calculated using air temperature and relative humidity data (Allen 1998). Soil volumetric water content (SWC) was obtained with two capacitance/frequency domain sensors (TEROS 11, Meter Group, Pullman, WA, USA) per replicate at 10 and 20 inch depths located under the canopy projection at 10 inches from the drip emitter per replicate.

Stem water potential

Ψ_{stem} was measured by two different methods with the Scholander pressure chamber (PC) and with the microtensiometers (MT). Ψ_{stem} measured with the PC (Model 615D, PMS Instrument Company, Albany, OR, USA). Mature and healthy leaves close to the trunk were wrapped with black polyethylene bags and aluminum foil two hours prior to the measurement. Measures were performed on one leaf per tree, two trees per replicate. In the same six trees, six MT (FloraPulse, Davis, CA, USA) were embedded into the tree trunk away from the sunlight at 1.0 m height.

Trunk diameter fluctuations

Trunk diameter was monitored in 8 trees every 10 minutes using linear voltage differential pressure transducer dendrometers (LVDT, model DE-1T, Implexx Sense, Melbourne, Australia) installed on the northern side of the trunks, 30 cm above the point where the microtensiometers were installed. Sensors had a 0.001 mm resolution. Maximum daily shrinkage (MDS) was calculated as the daily difference in diameter between the maximum and the minimum values.

Results and Discussion

Smart orchard data examples and data analysis plan (Apple)

Connectivity was improved in 2022 compared to 2021 with signal boosters installed in the Florapulse sensors and stem water potential, sap flow, and dendrometer data. We have collected microtensiometer, dendrometer, sap flow, fruit growth, soil moisture, and environmental conditions from the orchard location. We did not have dendrometers in both high and low vigor locations, but we have all other data sets for high and low vigor locations within the orchard. Data was organized and provided to the AgAID project for model development to predict plant water status from these various parallel datasets. This will help provide feedback for users with soil-based or weather-based sensors for making irrigation decisions as well as to fine tune baseline values for making stem-water potential-based irrigation decisions.

Trees at the low vigor site consistently had lower stem water potential than the high vigor site which has implications for not just overall tree vigor but also fruit growth and size potential. Stem water potential acquired with a pressure chamber corresponded well to those measured with microtensiometers (Figure 2). Fruit growth rates were the highest when evapotranspiration demand was the lowest. However, inconsistency in fruit monitoring, movement of sensors, and low replication across an orchard block limit the application of this type of monitoring to make progress for irrigation management (Figure 4).

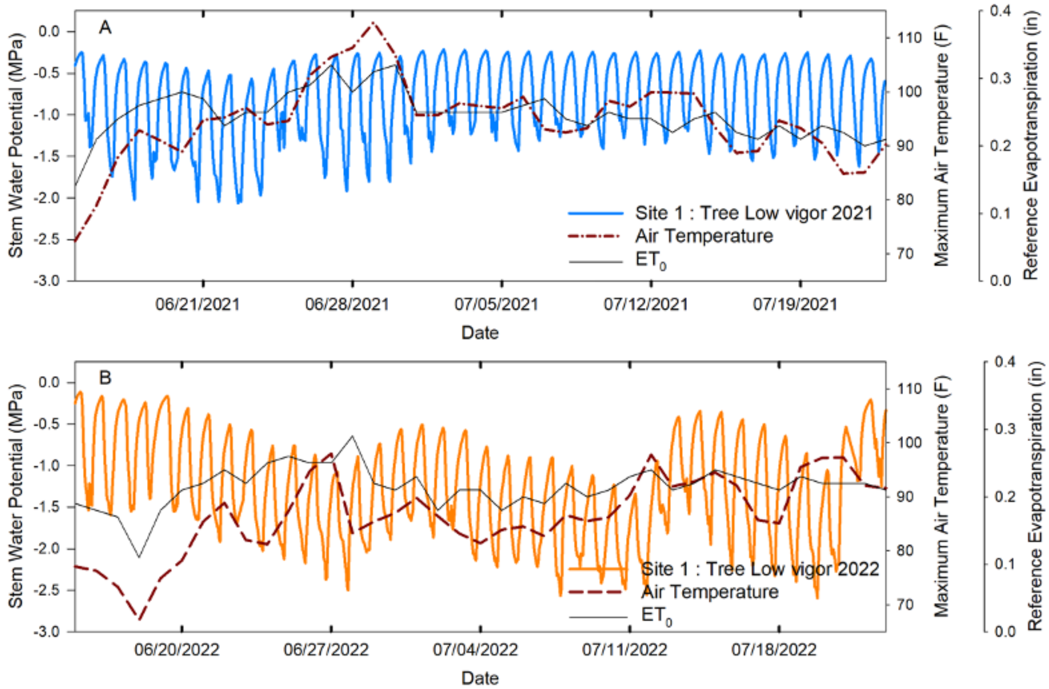

Figure 2. Evolution of the daily maximum air temperature, reference evapotranspiration and stem water potential recorded by the microtensiometers in the same tree (site 1 -low vigor) for the same period in 2021 (A) and 2022 (B)

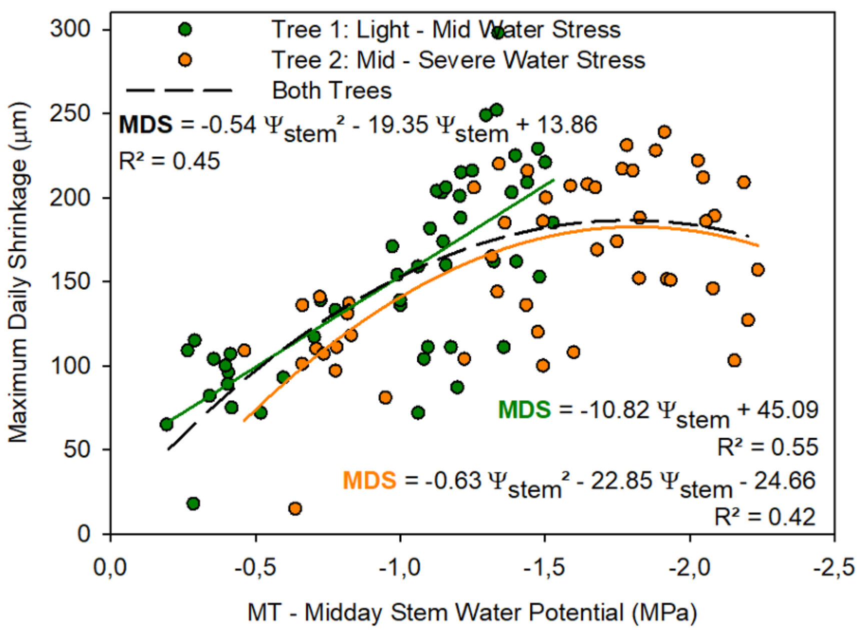

Figure 3. Relationship between the midday stem water potential and the maximum daily trunk shrinkage (MDS) of two trees in site 1 - low vigor (green – light mid water stress and orange – mid severe water stress). Data recorded from June to July, 2022.

MDS values never exceeded 300 µm in either location in the apple orchard and when stem water potential was exceptionally low (below -1.5 MPa), MDS did not continue to increase showing when these relationships break down (Figure 3). This demonstrates the limitation of using dendrometers. They are good for maximizing stem water potential and maintaining fruit growth but are not suitable for deficit irrigation practices in cultivars like Honeycrisp.

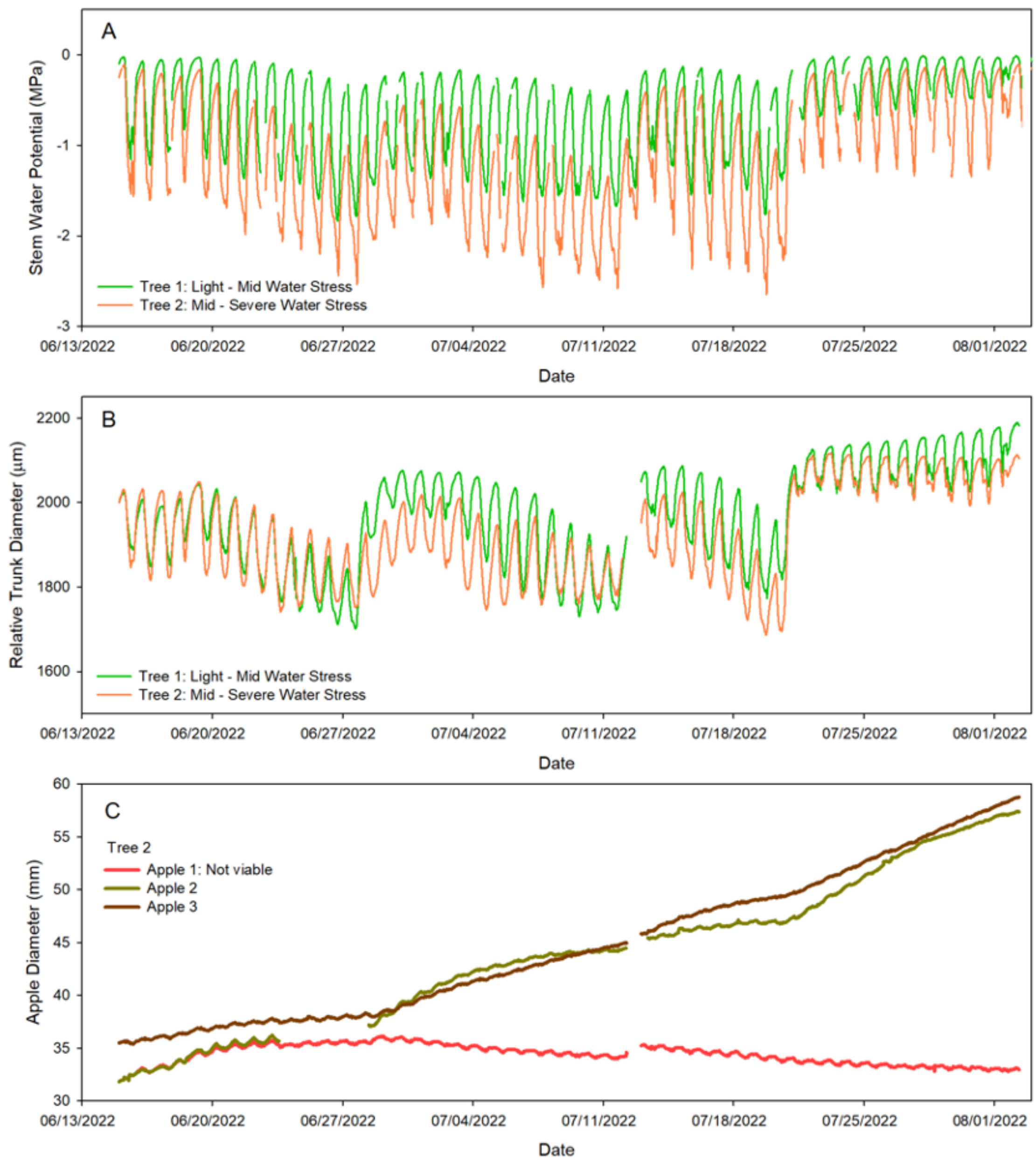

Figure 4. Evolution of the stem water potential recorded by the microtensiometers (A) and the variations of trunk (B) and fruit (C) recorded by the dendrometers in two trees in site 1 -low vigor (green – light mid water stress and orange – mid severe water stress) from June to July, 2022.

Stem dendrometers and microtensiometers were both sensitive to changes in water availability and corresponding changes in stem water potential measured with a pressure chamber. However, stem dendrometers and variable changes in trunk diameter decrease during the season, even under non-limiting conditions that affect how we interpret the sensors and associated irrigation decisions. Microtensiometers were effective but reliability and reuse of the sensors still need to be addressed. When installation is successful, microtensiometers are very accurate in determining irrigation needs by the tree and sensors are responsive to sudden changes in water supply or demand (e.g. evaporative cooling or precipitation event). Fruit dendrometers are useful but monitoring a small number of fruit has a high risk of not monitoring the average fruit in the block. Furthermore, small changes in positioning, fruit drop, or the tension affecting fruit growth are three things that need to be considered when using these sensors to make irrigation decisions.

Inducing differences in plant water status to detect sensitivity of real-time stem water potential sensing (Pear)

Through the application of deficit treatments in pears, we were able to test these different plant sensors across a range of soil moisture and environmental conditions (Figure 5). Direct measurements of plant stress have the potential for application of precision irrigation strategies. Other than Ψ_{stem} and MDS, other direct measures of plant water relations with potential for irrigation automation include canopy temperature, leaf turgor pressure, and trunk water content. However, since canopy temperature can be related to stomata closure, this thermal index might not be able to detect water stress as early as those water status indicators which directly measure Ψ_{stem}. Sap flow can be useful to assess the water status but can have high variability and is not as sensitive to the changes in soil and the atmosphere water status in the early season as plant water potential. There are also trunk water content sensors that are able to monitor changes in the tree water status. These sensors are related to trunk diameter but, unlike microtensiometers, are delayed by three hours compared to diurnal variations in trunk diameter. Ψ_{stem} recorded by microtensiometers responded quicker than variations in trunk diameter and do not require individual calibration like some sap flow and trunk water content sensors. Microtensiometers directly measure Ψ_{stem} and do not need to be transformed into a different index like thermal indices or leaf turgor. However, across an entire season, microtensiometers consistently underestimated Ψ_{stem} during the afternoon (Figure 6) and did not detect water deficit earlier than the pressure chamber in either season.

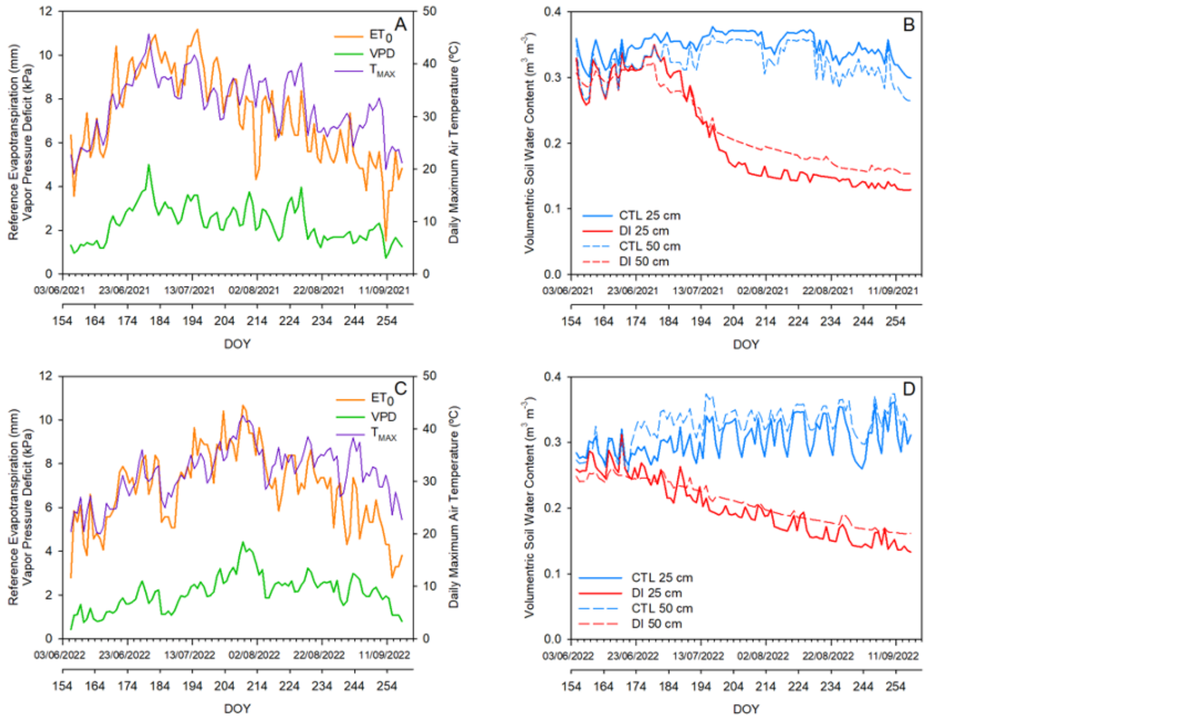

Figure 5. Evapotranspiration (ET_0), vapor pressure deficit (VPD), and maximum daily temperatures (T_{max}) (A and C) and volumetric soil water content (m^3 m^{-3}) at 25 and 50 cm depth (B and D) for 2021 and 2022.

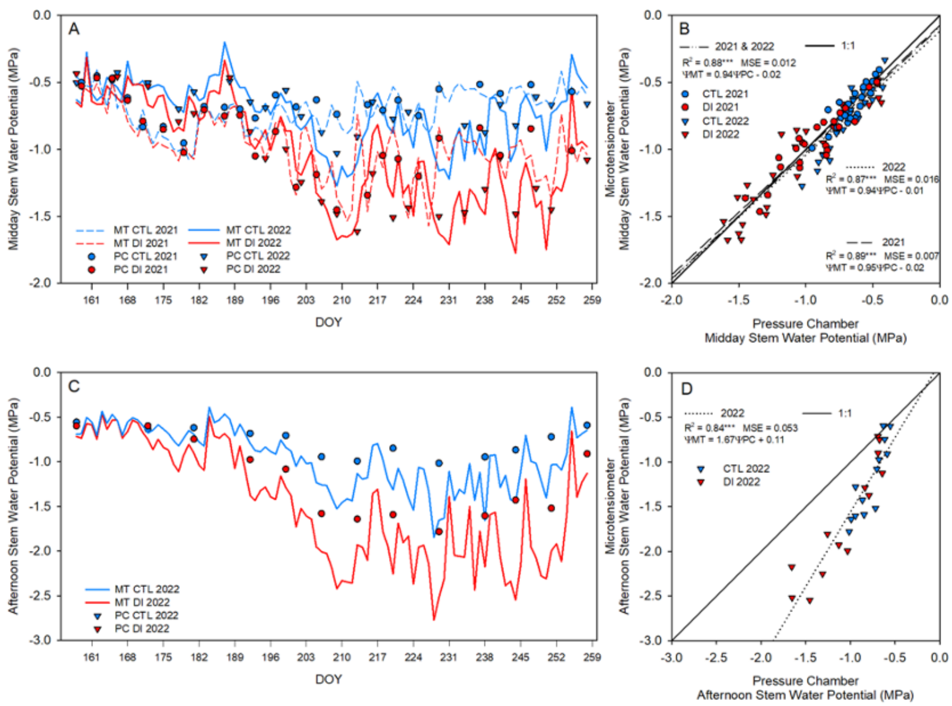

Figure 6. Top: Daily midday stem water potential measured with the microtensiometers (MT) and the pressure chamber (PC) for both years 2021 and 2022 (A) and the linear relationship between them for each season and both seasons together (B). Bottom: Daily stem water potential measured in the afternoon (15:30 - 16:30 h) with the MT and the PC during the 2022 season (C) and the linear relationship between them (D).

Stem water potential measured at noon were the same either using the microtensiometer or through using a pressure chamber. These patterns were repeated across years and under different water availability. However, microtensiometers were lower later in the afternoon than the pressure chamber (Figure 6). Further work is needed to resolve these differences and understand whether it is a problem with the microtensiometer or with the approaches used to indirectly measure stem water potential using a leaf with a pressure chamber. Regardless, these clear relationships and responsiveness of microtensiometers demonstrate their usefulness for monitoring plant water status during the season. Even when soil moisture levels are high, stressful conditions contribute to lower stem water potential for the control on days when temperatures and vapor pressure deficit are high.

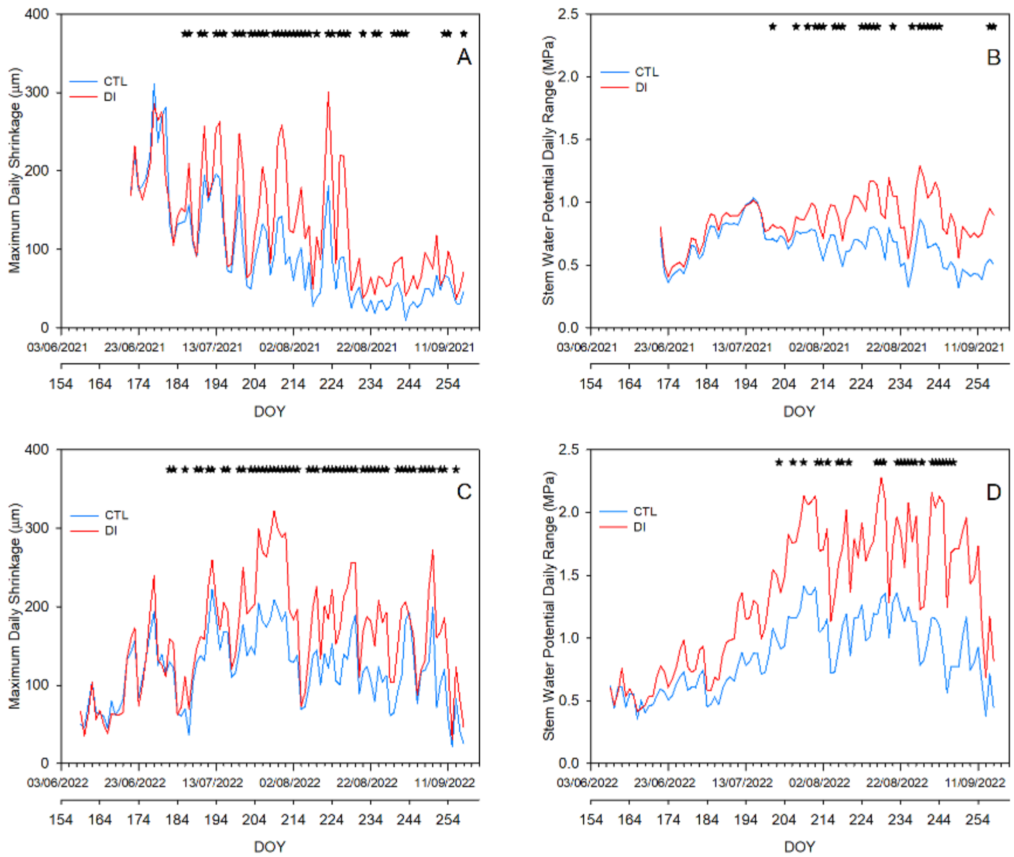

Figure 7. Mean maximum daily shrinkage of CTL and DI trees (N = 4) in 2021 (A) and 2022 (C) and daily stem water potential range (N = 6) for the same period in 2021 (B) and 2022 (D). Black asterisks denote significant differences between CTL and DI trees according to ANOVA ($P < 0.05$).

Maximum daily shrinkage was less variable when temperatures were lower. For example, in the second half of August in 2021, mean daily maximum temperatures were below 80 F and maximum daily shrinkage (MDS) rapidly decreased as a result. However, in 2022, when temperatures were warmer during the same time period (daily maximum temperatures of 95-100 F), MDS values were higher (Figure 7). When comparing the patterns of MDS with the daily range of stem water potential (Max-Min), there was little agreement, especially in 2021. Differences appeared between the deficit irrigated and control treatments earlier for MDS than the daily range in stem water potential. Moreover, when the relationship between the stem water potential and the trunk diameter changes was studied, we observed that fluctuations in trunk diameter followed changes in water potential (Figure 8).

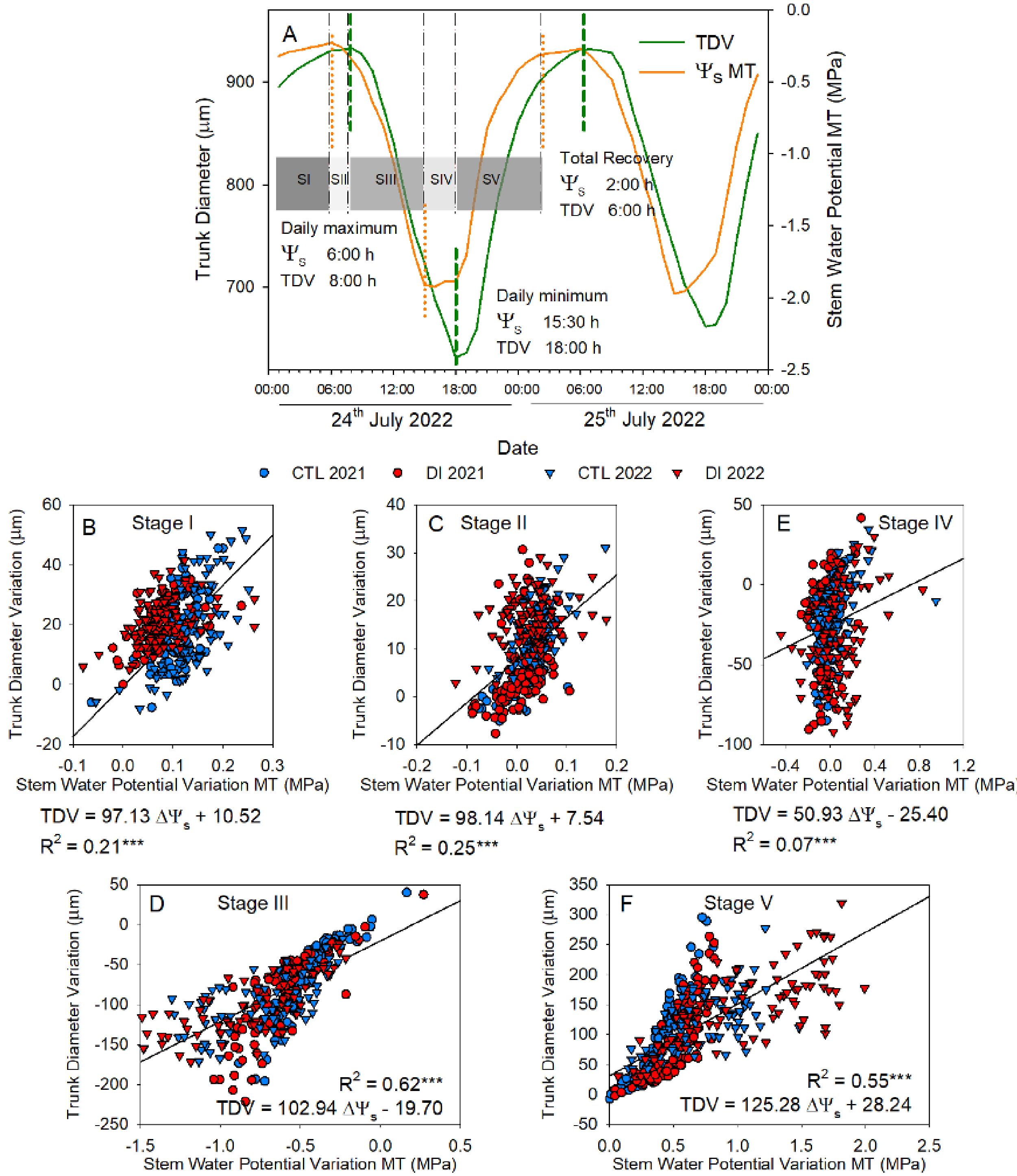

Figure 8. Daily evolution of trunk diameter and Ψ_{stem} on July 24 and 25, 2022 (A). Daily maximum, minimum, and recovery of trunk diameter and stem water potential are indicated. Linear relationships between the variation of both indicators are indicated by five stages: Stage I (SI; B), Stage II (SII; C), Stage III (SIII; D), Stage IV (SIV; E) and Stage V (SV; F) for both treatments (CTL and DI) and both seasons (2021 and 2022).

Extension programming

Smart Orchard Field Day. We organized and participated in field days in 2021 and 2022 to provide firsthand information of the plant sensors installed in the smart orchard and we were part of the Next Generation Growers Network. The target audience were growers, and farm-making decision individuals in the tree fruit industry. Ninety-four participants attended the event in 2021 and almost the same amount in 2022. Overall, from the participants that completed the evaluation of the field day, 95% valued the information presented as excellent (60%) or good (35%).

With the purpose to evaluate the effectiveness of the field day to transfer the information about sensors, we assessed the level of knowledge before and after this event (Figure 9). The participants gained knowledge about the use of plant sensors in the orchards, as most of them reported to have little knowledge prior to the event but higher after the field day.

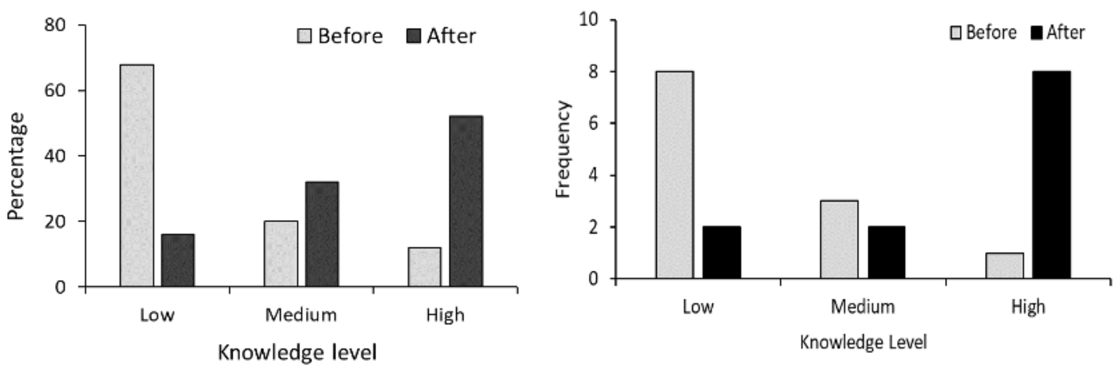

Figure 9. Percentage of participants and knowledge level before (gray bars) and after (solid bars) attending Field days. **Left:** Smart Orchard- Plant based sensors section. (n = 30). **Right:** Field Day at the Roza in Spanish. (n= 15).

***Field day in Spanish*.** During a field day in Spanish organized in the experimental orchard the Roza-WSU – IAREC, we presented basic information related to the use of dendrometers in the apple industry, and we also prepared and shared an infographic about this topic. The event was attended by 15 farmworkers from the south area of the state. Similar to the Smart Orchard event, the evaluation of the field day shows that the participants understood the information provided, and gained knowledge related to the dendrometers. (Figure 9).

Multi-year sensor installation. None of the microtensiometers that remained in either pear or apple during the winter worked correctly for the entire second year. Some sensors started the season working correctly but stopped working mid-season. There is potential to remove and reinstall the sensors each year following a specific protocol to protect the pressure transducer chip but that still needs to be tested.

Table 2. Summary table. Evaluation of sensors response.

Plant Sensors	Ready for Industry Use	Pros	Cons
Scholander chamber stem water potential	Yes	Gold standard of measuring plant water status Easy to interpret data	Not continuous Labor intensive
Fruit dendrometer (Edaphic Scientific)	No	Direct measurement of fruit growth and how it is affected by irrigation. Precise and accurate technology	High variability among fruit even in the same tree. High maintenance, need to check that the dendrometer is attached to the fruit.
Microtensiometer stem water potential (Florpulse)	Yes	Continuous measurements of stem water potential Highly accurate and precise	Cost of sensors Reusability of sensors is questionable
Stem dendrometer (Edaphic Scientific)	Yes	Real-time, continuous and direct measurements of the tree water status. Early water stress detection. Rapid response to changes in the tree water status.	Need to calculate the MDS and TGR. It is difficult to interpret absolute values, need to compare the trees with a reference tree in the orchard. Highly dependent on other factors, not only water stress.
Sap flow (Dynamax and Tree2Scope)	No	Continuous	Inconsistent data that may not be associated with plant water status

Project outputs

(Publication) Blanco V, Kalcsits L. 2022. Long-term validation of continuous measurements indicate different diurnal patterns of stem water potential and trunk diameter under water limitations in pear. In review.

(Publication) Blanco V, Kalcsits L. 2021. Microtensiometers Accurately Measure Stem Water Potential in Woody Perennials. *Plants*, *10*(12), 2780.

(Extension Publication) Blanco, V, Bolivar-Medina J, Casagrande-Biasuz E, Willsea N, Kalcsits L. 2022. Trunk and Fruit dendrometers: Detecting early signs of water stress in fruit trees before visual cues. Fruit Matters June 2022. http://treefruit.wsu.edu/trunk-and-fruit-dendrometers-detecting-early-signs-of-water-stress-in-fruit-trees-before-visual-cues/

(Extension Publication) Blanco, V, Bolivar-Medina J, Casagrande-Biasuz E, Willsea N, Kalcsits L. 2022. Microtensiometers: a new tool to monitor your apple trees for deciding when and how much to irrigate. Fruit Matters May 2022. http://treefruit.wsu.edu/microtensiometers-a-new-tool-to-monitor-your-apple-trees-for-deciding-when-and-how-much-to-irrigate/

(Field Day) July 30 (English) and August 2 (Spanish), 2021. Smart Orchard Field Day.

(Field Day) July 26 (English) and 27 (Spanish), 2022. Smart Orchard Field Day.

(Field Day) October 11, 2022. Next Generation Growers Network: Irrigation strategies and technology. Sunrise Research Orchard

(Presentation) Kalcsits L. 2021. Water management in pears. Southern Oregon Research Station. May 27, 2021.

(Presentation) Kalcsits L, Khot L, Sallato B, Mantle S, Blanco V. 2022. Smart Orchard 2.0. HortGro Annual Tree Fruit Meeting. Sumerset West, South Africa. June 4, 2022.

(Presentation) Blanco V, Willsea N. Plant-based sensors for irrigation. Columbia Club Growers Meeting. June 30, 2022.

(Presentation) Kalcsits L, Blanco V, Horning P. 2022. Plant-based sensors for managing irrigation. International Tree Fruit Association Summer Tour. July 18, 2022.

(Presentation) Blanco V, Kalcsits L. 2022. Irrigation Strategies and Technology. Next Generation Fruit Growers Meeting. Cashmere, WA. October 12, 2022.

(Presentation) Kalcsits L, Blanco V. 2022. Panelist: Why is regulated water stress not widely used in commercial horticulture? International Horticulture Congress. Angers, France. August 18, 2022.

(Presentation) Blanco V, Kalcsits L. 2022. Soil temperature and water stress affect the physiological response, nutrient uptake and distribution of young pear trees. International Horticulture Congress. Angers, France. August 16, 2022.

EXECUTIVE SUMMARY

Project title: Validation of plant-based sensors for making irrigation decisions

Key words: Stem water potential, dendrometers, fruit diameter, sap flow, microtensiometers, water relations

Abstract: Early detection of undesirable water deficit is important for avoiding any penalization in fruit size, yield and tree growth. Early visual cues indicating water stress in apple trees are not so perceptible once they appear, it is often too late to avoid negative effects of severe water stress causes on fruit quality, yield, and tree growth. Precision sensors such as dendrometers can be crucial and make that task much easier. Dendrometers are well-studied, plant-based sensors that continuously measure small fluctuations (shrinkage and swelling) in trunk or fruit diameter resulting from variation in sap flow. Trunk and fruit dendrometers can be used to detect and quantify water stress to improve irrigation scheduling in fruit trees. Microtensiometers are plant-based water status sensors than can continuously measure stem water potential, the reference indicator for assessing water status in trees. Midday stem water potential measured with microtensiometers and with a pressure chamber and maximum daily shrinkage, (MDS) were compared in both pear and apple. Stem water potential measured by the microtensiometers and the pressure chamber as well as the MDS were directly influenced by the water supply to the trees from the soil and atmospheric demand from environmental conditions. MDS was able to detect water stress in DI trees the earliest. However, it showed the highest variability and was not sensitive enough to detect significant differences between irrigation treatments late in the season. On the other hand, midday stem water potential measured by both methods had low variation and was able to distinguish both irrigation strategies during both seasons. Midday stem water potential measured by both methods had a strong linear relationship with no differences between the two methods. However, when stem water potential was measured in the middle of the afternoon, stem water potential measured by microtensiometers were much lower than stem water potential measured using a pressure chamber. This behaviour was observed on hot and cold days and these differences were more visible when trees were water limited. The daily relationship between the trunk diameter variations and midday stem water potential measured with the microtensiometers followed five different stages. Changes in trunk diameter were delayed relative to changes in xylem potential. The seasonal relationship between the MDS and stem water potential was strongly related at the start of water limitations in apple and pear, but when the complete season was considered, this relationship declined. MDS appeared to have a maximum season value of 300 µm despite water limitations that should have pushed those trunk contractions higher. Stem dendrometers are also useful but loss accuracy when water limitations are applied indicating a best fit for use in low stress situations when trying to maximize fruit weight. Fruit dendrometers suffer from reliability and stability of measurements. Sap flow sensors are not good integrators of factors that contribute to fruit growth and are difficult to interpret right now. Microtensiometers are highly accurate and ready for use as a continuous sensor in automatic irrigation systems as a reliable method to monitor tree water status and provide a continuous alternative to a pressure chamber.