CALIFORNIA
ENERGY COMMISSION

Energy Research and Development Division

FINAL PROJECT REPORT

Energy Efficiency and Water Savings in Agriculture by Innovative Plant-Aware Irrigation

Gavin Newsom, Governor
February 2021 | CEC-500-2021-011

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation and bring ideas from the lab to the marketplace. The CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas & Electric Company and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Energy Efficiency and Water Savings in Agriculture by Innovative Plant-Aware Irrigation is the final report for the Energy Efficiency and Water Savings in Agriculture by Innovative Plant-Aware Irrigation System project (Contract Number EPC-15-091, Grant Number PON-15-317) conducted by the Electric Power Research Institute. The information from this project contributes to the Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the CEC at ERDD@energy.ca.gov.

ABSTRACT

California's population growth, frequent drought conditions, and greater awareness of environmental water requirements have increased pressure on agriculture to use water more efficiently. A common irrigation practice for California fruit crops is to apply a fixed quantity of water weekly regardless of crop needs. This method frequently results in overirrigation and is often detrimental to fruit quality or yield.

This study sought to analyze the impact of traditional irrigation practices versus plant-aware irrigation by quantifying water and energy savings and comparing them to the quantity and quality of the grape harvest. The concept behind plant-aware irrigation is to adapt the duration and frequency of irrigation events based on plant water needs using sensors installed on the plant itself. In this approach, the entire plant in effect becomes an instrument that integrates the complex effects of soil moisture, climate, and leaf area variations. As the season unfolds — when the fruit ripens and mass and sugar accumulate — the plant can communicate the level of water it needs.

This project evaluated the technology and its application at three test sites in the wine country of Northern California. For each test site, Plant Aware Irrigation, developed by Fruition Sciences, monitored plant water needs in real time. The researchers set irrigation thresholds to trigger alerts for irrigation according to monitored variations in plant water indices and stages of plant and leaf development. Because water use drives photosynthetic activity, the research team set the irrigation threshold values at a level that would maintain sufficient photosynthetic activity for mature fruit production. The team also applied an analytical platform capable of characterizing climatic demand to convert sap flow data into actionable information for irrigation.

Calculated water and energy savings comparing control and plant-aware irrigation treatment areas on a per-acre basis over one full season achieved, conservatively, 325,354 gallons per acre and 192.7 kilowatts per acre. Across all tested vineyard locations, this amounted to 61 percent average water and energy savings. Vineyard staff indicated that the value of the project was in water, energy, and cost-savings potential through efficient pumping and selective watering. Vineyard staff members were encouraged by the promising vine-health improvements and the ability of the vineyards to provide quality wine.

Keywords: California Energy Commission, agricultural applications, water savings, energy savings, wineries, vineyards, viniculture, sap flow sensors, plant-aware irrigation

Please use the following citation for this report:

Pabi, Sudeshna; Ryan Berg, Marek Samotyj, Thibaut Scholasch, Brandon Burk, Chase Martin, Stephanie Burk, Gino Camozzi, Catherine Gomez, Hope Mendes, Marc Esser, and Bo White. 2021. *Energy Efficiency and Water Savings in Agriculture by Innovative Plant-Aware Irrigation*. California Energy Commission. Publication Number: CEC-500-2021-011.

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EXECUTIVE SUMMARY

Introduction

California's population growth, frequent drought conditions, and greater awareness of overall state water needs have increased pressure on agriculture to use water more efficiently. A common irrigation practice for California fruit crops is to apply water on a weekly schedule with a fixed quantity, regardless of plant water needs. This method frequently results in overirrigation and is often detrimental to fruit quality or yield. The University of California, Davis, estimates water use by viticulture to be 1.5 million acre-feet per year. Agricultural irrigation can consume large amounts of electricity, particularly during drought years.

Project Purpose

The goal of this study was to install and demonstrate a new irrigation technology that can save substantial amounts of water and energy. The technology uses the principle of watering crops only when needed, rather than at set time intervals. Fruition Sciences designed a new technology called "plant-aware irrigation" to address this problem, starting with wine grape crops (viniculture). Because wine grapes are a high cash-value crop, vineyard owners are more likely to experiment with and invest in new technologies.

The unique technology of plant-aware irrigation detects precisely when a vine block needs irrigation and provides the amount of irrigation needed to maintain (or increase) grape quality and yield quantity. This plant-based approach can help improve irrigation practices in California agriculture on a large scale. Much of California's water use is in fruit crops in the Central Valley as well as in large commercial vineyards. Beyond viniculture, any agricultural areas planted with a perennial crop — such as citrus, olives, almonds, and kiwi — could benefit from this plant-based approach.

Project Approach

Plant-aware irrigation technology relies on sap flow sensors installed directly on the stems of vines to collect and send data. The concept adapts the duration and frequency of irrigation events based on plant water needs. The technology allows a plant to in effect become an instrument that communicates the complex effects of soil moisture, climate, and leaf area variations as the seasons unfold and fruit ripens.

This project analyzed the impact of traditional irrigation practices versus plant-aware irrigation. The research team chose three sites to address different climatic zones and grape varietals. The team reported results of plant water stress variations in both methods and recorded the amount of fruit and sugar produced. A very thorough process was implemented to compare results, using aerial maps taken by planes, gauges, and other systematic measurements.

This study had a distinguished technical advisory committee comprised of members from investor-owned utilities, representatives from the California Energy Commission (CEC) and California Department of Food and Agriculture, water research organizations, and vineyard staff. The researchers provided the committee members the details and methods of this project and received advice on specific issues within the members' areas of subject matter expertise.

The research team collected data in the field at the three test sites in the Northern California wine country, one in Livermore and two in Napa Valley. A small control area in each test site used existing irrigation methods without the technology installed during the full measurement and verification period. The team installed the plant-aware technology in the remainder of each test site to inform irrigation schedule revisions. No other changes were made to affect water consumption during the measurement and verification period. Irrigation-relevant conditions such as grape varietal, soil type, and climate were identical in each control and treatment area (referred to as a "block") within the same block pair but varied across different blocks and sites. Although the block selection may not have been representative of all viniculture in California, it should nevertheless allow for cautious extrapolation of the results. Administering these tests in different climates and variety of viniculture field sizes and conditions proved this approach can be further scaled and implemented simultaneously in diverse applications.

Project Results

The researchers metered water consumption for more than a year using utility-grade water meters and calculated water savings for the metered pairs for the measurement period, normalizing for area. Plant density within each control and PAI treatment block pair was uniform. The team estimated pump energy based on volume of water delivered using engineering methods, supplemented by a literature review of relevant agricultural pumping energy.

Calculated water and energy savings comparing control and plant-aware irrigation treatment areas on a per-acre basis over one full season achieved, conservatively, 325,354 gallons per acre and 192.7 kW per acre. Across all tested vineyard locations, this amounted to an average water and energy savings of 61 percent per block and up to 100 percent savings when no irrigation was needed. The results also showed a significant improvement in grape quality. Some vineyards had up to a 100 percent increase in bottle price and up to a 15 percent increase in field yield. This was caused by reducing susceptibility to yield loss due to dehydration, as overwatered fruit are more prone to shriveling. Vines that received PAI treatment were more resistant to drought and yield was not affected even when less water was applied. The reduced watering uses less electricity due to decreased pumping.

A survey was conducted with the demonstration sites to determine their satisfaction with the technology. The demonstration sites were content with the system, installation, maintenance and its performance. Participants indicated that the project was useful and even improved the growth and structure of the viniculture team. The participants see the system providing benefits of water, energy, and cost-savings through efficient pumping and selective watering. Vineyard staff members were encouraged by the promising vine-health improvements and the vineyards' ability to provide good-quality wine. However, future considerations to purchase and employ the technology are cost driven and the technology must have records of proven performance and ease of operation to be considered for future implementation.

Knowledge and Technology Transfer

The plant aware irrigation technology is commercially available and vineyard operators are primarily interested in the data analytics provided by the system to monitor the health, grape quality and water needs. The data informs growers when to water the vines in order to produce optimal grape quality. With recurring droughts in California and elsewhere, this technology has demonstrated the potential to reduce both water and pumping energy. These demonstration efforts raised the visibility of the benefits of this technology to vineyard operators and wineries in improving their grapes and wines while optimizing water use and reducing energy use. More California vineyards have adopted the use of plant aware irrigation technology, such as Les Collines Vineyard, Daou, Ovid and Ridge Vineyards. This technology is also starting to be used in drought prone areas like Australia to optimize irrigation and only water the vines when needed while improving grape quality.

The team used several methods to influence market participants, including live presentations, symposia participation, journal articles, utility provider briefings, meetings and workshops with the Electric Power Research Institute, and word-of-mouth contact. The following are some examples:

- Vintage Report, Napa 2018: The Vintage Report conference was held in Napa on January 22, 2018. The project team presented to a group of wine-grape growers the water- and energy-saving opportunities and background about water-energy nexus. The presentation covered the study's preliminary results of water and energy savings.
- UC Davis Viticulture and Enology Symposium: The project team included this study as part of a presentation at UC Davis' Viticulture and Enology symposium. The presentation addressed the energy-water nexus issue for agriculture by pointing to the need to calibrate atmospheric and airborne measurements with plant-based measurements. The presentation also encompassed a full explanation on how water stress can be defined at a plant level, and then extrapolated from a single plant to the scale of a block by merging climatic and aerial measurements with sap flow.
- Local utilities briefing: This project was presented to local electric utility Southern California Edison via webcast to inform the utility of the innovative technology and electric-energy-savings potential. Other presentations included a Technical Advisory Committee presentation to members of PG&E in Northern California.
- Technical briefings: Briefings were held with the California Winegrape Growers Association and the Livermore Valley Winegrowers Association to discuss the project and conduct energy and water analyses on their vineyards.
- Journal articles: This project was acknowledged as part of a 2019 journal submission titled "Technical and Physiological Considerations to Optimize Vineyard Irrigation," which is a follow up to the review article titled "State of the Art Tools and Methods to Assess Vine Water Status"

Beyond vineyards, other candidate crops that could benefit from the technology are intense water use crops such as almonds. A technical briefing was held at California State University Fresno Center for Irrigation Technology. The Center for Irrigation Technology is researching growth, water, and energy issues for multiple crops through its own on-campus farm. As a result, this may be a good site for a future workshop on this technology and potential to expand to other water intense crops.

Benefits to California

The results from this study show that using plant-aware irrigation technology at all of California’s 880,000 acres of viniculture could save about 297 billion gallons of water per year statewide. These savings would protect California’s precious water resources while also improving fruit composition during the wine industry’s boom and surge of large vineyard plantings. This corresponds to nearly 403-million kilowatt-hours of electricity savings due to reduced pumping energy needed (assuming power need of 440 kilowatt-hours per acre-foot).

Based on the potential electricity savings of 403-million kWh and an average electricity rate of $0.1564 per kWh, the total savings for wine grapes alone can amount to $63 million for California ratepayers. Additional savings could be achieved if the technology was also used with perennial crops.

CHAPTER 1: Introduction

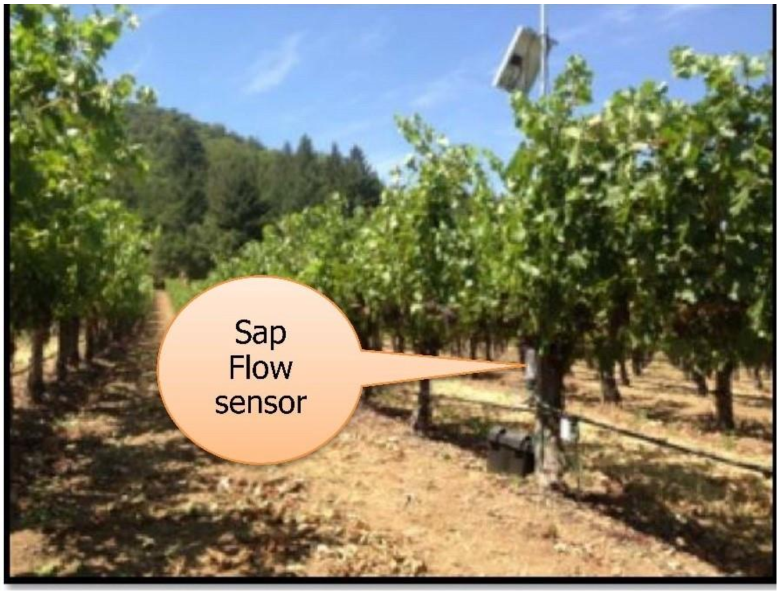
Crop watering technology is quickly causing conventional irrigation tactics, based on fixed quantities, to become outdated. Adopting a technical approach can prevent overirrigation and save considerable amounts of water and energy.

In California, "grapes represent nearly one-million acres of production valued at approximately $6 billion, while fruit and nut orchards represent an additional 2.6-million acres with crops valued in excess of $10 billion annually. To sustainably continue irrigated agriculture production in this region, better tools for managing water use are needed" (Grape Remote Sensing Atmospheric Profile & Evapotranspiration Experiment).

Fruition Sciences developed a new technology called Plant Aware Irrigation (PAI), designed to address this problem. Wine grape crops, or viniculture, was selected as a good beachhead market because the cash value of the grape crop makes it more likely for owners to test new technologies given the higher reward for the potential risk. The researchers chose three sites to address diverse varietals of grapes, variations in operational practices, and differences in climates.

PAI detects when a vine in a defined vineyard surface area, referred to as a block, must be irrigated or not, while maintaining grape quality and yield. In fact, water stress may have positive effects on grapes by increasing quality and yield. PAI technology relies on sap flow sensors installed directly on the stems of vines (Figure 1) that collect and send data every 15 minutes. Proprietary algorithms developed by Fruition Sciences use sap flow data and climate data to derive a daily Water Deficit Index (WDI). The WDI is used to trigger or not trigger an irrigation event. Only two selected vines blocks were instrumented with sap flow sensors. Aerial imagery helped extrapolate the sap flow measurements and WDI calculations from only two vines to the whole block, which generally contains a few thousand vines. The results were confirmed by several monitored small high-end Napa Valley vineyards: (1) an average of 60 percent water and energy input savings and up to 100 percent savings within the times there was no irrigation was needed and (2) a significant improvement in grape quality. Some vineyards had up to a 100 percent increase in bottle price and up to a 15 percent increase in field yield. This was caused by reducing susceptibility to yield loss due to dehydration, as overwatered fruit are more prone to shriveling. The reduced watering also uses less electricity due to decreased pumping.

Figure 1: Location of Plant Aware Irrigation Sap Flow Sensor



Grape vine equipped with a sap flow sensor.

Source: Fruition Sciences

Any agricultural areas planted with perennial crops such as citrus, olives, almonds, and kiwi could benefit from the plant-based irrigation approach (Ortuño et al., 2006). The researchers favor perennial crops because the sap flow sensor needs to be attached to a rigid stem section. However, successful experiments have been reported in scientific literature with strong stem-section crops such as corn. (Liwen et al., 2016).

Table 1 shows the electrical consumption associated with irrigation in California and indicates that agricultural irrigation consumes large amounts of electricity, even more so during drought years. Given the rapid expansion of permanent crops in California, it is likely the numbers have increased since the report was published.

Table 1: California Irrigation Annual Electrical Energy Consumption

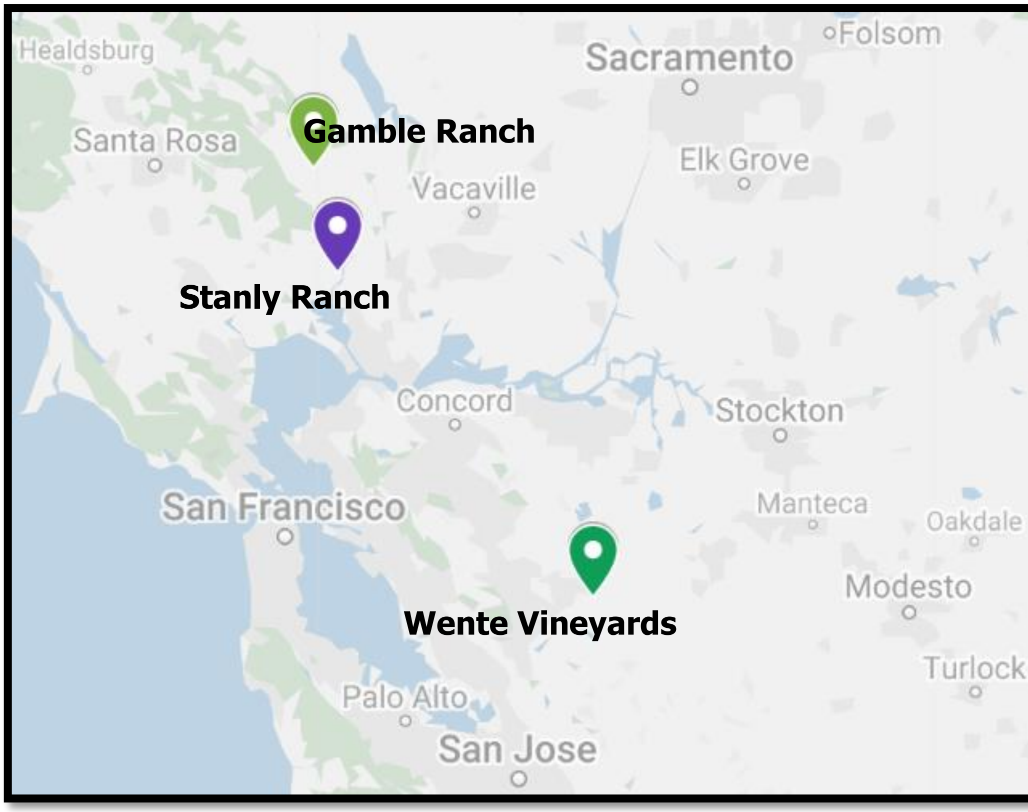
Surface Water Reduction	Consecutive Year of Drought	District Surface Water Pumping (MWH/ Year)	District Groundwater Pumping (MWH/ Year)	On-Farm Groundwater Pumping (MWH/ Year)	On-Farm Booster Pumping (MWH/ Year)	Conveyance to Districts (MWH/ Year)	Energy for Water Banking and Transfers to MWD (MWH/ Year)	Total Energy Use for CA Ag Water (MWH/ Year)	Energy Requirement for Ag Water (MWH/AF)
Baseline	0	821,800	246,000	4,499,000	2,873,500	1,719,600	Variable	10,159,900	0.28
20%	1	657,400	300,300	5,693,700	2,873,500	1,400,400	+66,567	10,991,867	0.30
20%	5	657,400	382,900	6,912,100	2,873,500	1,400,400	+66,567	12,292,867	0.34
40%	1	493,100	369,000	7,159,900	2,873,500	1,081,200	+159,820	12,136,520	0.33
40%	5	493,100	625,300	11,592,300	2,873,500	1,081,200	+159,820	16,825,220	0.46
60%	1	328,700	436,400	8,646,300	2,873,500	762,000	+375,947	13,422,847	0.37
60%	5	328,700	901,400	17,616,100	2,873,500	762,000	+375,947	22,857,647	0.63

Source: Burt and Howes, *2005 Estimated Energy Requirements Under Drought Conditions. A Special Report to the California Energy Commission*

CHAPTER 2: Project Approach

The goal of this project was to quantify water and energy savings resulting from the use of an advanced plant aware sensor technology in viniculture crops in California. The research team collected data in the field at three test sites in Northern California's wine country: Wente Vineyards in Livermore (blocks Smith, Reuss, Karl, and Mel) and Treasury Wine Estates in Napa Valley (blocks Gamble Ranch and Stanly Ranch). All vineyard locations are shown on the map in Figure 2:

Figure 2: Geographical Locations of Test Vineyards



Source: Google Maps

Several pairs of baseline (control) and experimental (PAI treatment) vine blocks were selected in close cooperation with Fruition Sciences and the test site operators.

Quantifying Water and Energy Savings

The research team measured water consumption using one or more water meters, irrigation gauges, or logs with appropriate output for each baseline and PAI treatment block pair. Researchers calculated water-use savings for each site for a yearlong measurement period. The blocks were carefully chosen to ensure uniformity of plant density within each control and PAI treatment block pair.

For each of the sites (*i*), water use (*V*) savings per area (A) was as follows:

$$Water\ Savings\ per\ Area_{i,saved} = \frac{\sum_{t=0}^{t=N} V_{i,baseline}}{A_{i,baseline}} - \frac{\sum_{t=0}^{t=N} V_{i,retrofit}}{A_{i,retrofit}}$$

The team estimated pump energy using engineering methods that consider pump efficiency, water flow rates, irrigation schedules, head pressure, and other factors as needed.

The team estimated pump-energy usage determined by the water-use data and assuming identical and fixed pressure head and pump efficiency across all blocks. Per the American Society of Heating, Refrigerating, and Air-Conditioning (ASHRAE) Handbook for Heating, Ventilation, and Air Conditioning (HVAC) Systems and Equipment, the pump energy equation for water is:

$$bhp = (Q \cdot \Delta h)/(3960 \cdot \eta)$$

Where:

$bhp = brake\ horse\ power$

$Q = fluid\ flow\ rate, gpm$

$3960 = units\ conversion, ft \cdot gpm\ per\ hp$

$\Delta h = total\ head, ft\ of\ fluid$

$\eta = pump\ efficiency$

The anticipated water savings were 60 percent based on past results collected from small-scale testing performed at small high-end Napa Valley vineyards. The energy use was directly proportional to water use because the pump run times and irrigations were concurrent and, therefore, expected to report the identical savings percentage of 60 percent.

Plant Aware Irrigation Method

Effective irrigation management requires distinguishing water use from water stress. Water use can be estimated via various methods. However, water stress relates actual plant transpiration to its potential transpiration. Actual transpiration typically represents a fraction of potential transpiration as soil moisture depletion reduces the amount of water use. Potential transpiration represents the maximum amount of water a plant can use when soil moisture is nonlimiting for a given climatic demand. Such distinction is important since it is water stress and not water use that influences fruit quality and yield.

This project measured water stress at the plant level and extrapolated the measurements at the vineyard level using atmospheric measurements from an onsite weather station in conjunction with maps describing field spatial structure. In this context, irrigation recommendations can be calibrated according to plant water needs while considering water-stressing conditions, which were specific to each site.

For a discussion on the details of plant measurement versus atmospheric measurement to measure water stress in plants, refer to Appendix A.

Leveraging Synergies Between Measurement Techniques

Since every method has limitations, the best approach to optimize irrigation for this study was to combine methods and leverage synergies to assess plant water stress.

Atmospheric measurements required calibration to compute a plant-based stress index. Authors have reported that, "transpiration/evapotranspiration estimates obtained by merging atmospheric measurements with remote sensing imagery require independent measurements, such as vine transpiration using sap flow gauges to determine stress levels, which directly impacts yield and fruit composition" (Kustas et al., 2018).

Sap flow measurements needed to be assessed in the context of plant vigor variations, which can be described with aerial imagery.

New analytical methods combining data-fusion processing and machine-learning algorithms with direct and indirect measurements of vineyard evapotranspiration (ET) have yielded successful results (Alfieri et al., 2018; Andújar et al., 2019; Helman et al., 2018; Prueger et al., 2018; Romero et al., 2018; Semmens et al., 2016) and could be promising tools for plant water status assessment and irrigation monitoring in the future. Fruition Sciences analytical framework 360viti, an online viniculture platform used in this project, was developed to address this need commercially and leverage synergies between heterogeneous data sources.

Considerations for Plant Aware Irrigation Strategy

The irrigation strategy for the PAI treatment aimed at optimizing the timing of the first irrigation and the frequency of irrigation.

Timing the First Irrigation

Strategically timing the first irrigation involved withholding irrigation as long as possible, provided that canopy development was sufficient to reach production objectives. This reflected hydraulic and winemaking considerations. Reports indicated that early-season water deficit toughens the vine hydraulic system. Munitz et al. (2018) has shown that high water availability in the early season (such as during the xylem formation period) leads to wider vessels and increased hydraulic conductivity. In turn, high water availability early in the season increased vine water use and made the vineyard more prone to embolism during drought periods, leading to greater risk of yield losses via berry dehydration. From a winemaker's standpoint, known benefits from an early, moderate water deficit included an earlier start for sugar loading and color accumulation, (Castellarin et al., 2007 (a); Castellarin et al., 2007 (b); Deluc et al., 2009; Deluc et al., 2011), and faster color extraction into wine and higher polymeric pigment in wine (Cooley et al., 2017; Bindon et al., 2007; Brillante et al., 2018; Koundouras et al., 2009).

Monitored Irrigation Frequency

Strategizing irrigation frequency consisted of favoring larger, less frequent irrigations to induce a slower Transpiration (T)/Evapotranspiration (ET_{ref}) decline (slower progression of water stress), which resulted in less cumulated stress over the season. Authors have shown that more irrigation can induce a faster T/ET_{ref} decline, including a faster soil moisture depletion rate, which resulted in a similar seasonal stress compared to PAI treatment with less water applied during warmer temperatures (Bonada et al., 2018).

Two-Step Approach

The first step consisted of a preliminary analysis of field spatial structure to understand its effect on plant performances. The results from the spatial study are used to the design of a field sampling strategy to optimize water-use monitoring.

The second step consisted of installing a suite of sensors at predefined sampling locations to monitor temporal changes observed in plant, fruit, and climatic parameters. A web application collected, gathered, and analyzed temporal variations observed for each parameter. Simultaneously, temporal variations were interpreted in the context of spatial variations observed at the whole field scale via another web application. Results from the combined analysis of spatial and temporal information were synthesized into a dashboard. During the season, the dashboard summarized "calls to actions," such as irrigation alerts and other field information affecting crop conditions, such as high sugar accumulation.

Step 1: Optimizing Sampling Design and Field Monitoring Strategy

The team acquired and generated maps showing spatial variations in plant performance indices such as: Physiocap (the amount of wood produced), yield (the amount of fruit produced), multiplex (the amount of color produced), and aerial images (the amount of leaf area produced).

This spatial study enabled the team to conclusively:

1. Validate the best candidates for the experiment.
2. Verify the sampling scheme to compare irrigation PAI treatments, while considering field spatial variability.

Soil composition is never uniform in a field, therefore it was important to ensure that deployment in relatively uniform soil. Without this approach, the effect of irrigation could be confused with the effect of soil composition on plant performance. To best control for this, the impacts of soil composition on plants developments were analyzed to validate the position of each measurement site prior to installation. Later this was also used to validate the results compared to the control sites.

This analysis ensured that the technology would be deployed uniformly. This avoided the concern of confusing the benefit of the PAI technology used with the fact that the soil may be better where PAI took place.

The researchers characterized each block for plant performance such as amount of color, wood, and leaf area produced. Based on this characterization, each block received PAI treatment to reflect a similar level of heterogeneity. When there was a section of high color production (or low color) within the vineyard, half of it was devoted to the control, and the other half devoted of it to PAI treatment.

Appendix C discusses and analyzes the spatial structure of vineyard blocks selected to deploy the PAI treatments. Red dots indicate where to position the smart point (sap flow sensors for vine water-use monitoring and fruit sampling for sugar per berry) for each PAI treatment based on maps analysis.

Appendix D studies the relationship between field spatial structure and yield variations in absence of PAI treatment application. The results discuss reasons the initial Sonoma region site was unfit for trial due to inconsistencies among field yield variations and ancillary data obtained via different mapping technologies (Physiocap, aerial images, and multiplex). Preliminary analysis concluded that the selected vineyard was under a high disease pressure that was likely to affect PAI treatment outcomes.

Step 2: Real Time Analysis of Plant Water Needs Over Heterogeneous Areas

The researchers combined two approaches to assess plant water needs in a spatially variable system:

1. Simultaneous monitoring of climate, plant, and fruit parameters considering field spatial heterogeneity.
2. Irrigation threshold leveraging plant physiological adaptation to drought.

Parameter Monitoring

The research team implemented Fruition's 360viti, a suite of web applications that consist of measuring vineyard data and performing analytics in real time. The technologies characterized variations in plant and fruit indexes. Various technologies were combined into the analytics to identify synergies and vineyard data was combined into a single platform for analysis called Fruition analytics.

Using the analysis of vineyard spatial structure, specific vines were chosen for sap flow sensor installation. After installation, sap flow sensors were monitored remotely with Fruition's software. Plants across a same field were expected to need watering at different times due to soil effects on plant leaf area variations. Therefore, to optimize irrigation it was necessary to combine information and perform a joint analysis relative to spatial and temporal changes. The researchers used two web applications called "mapping" and "graphs" in tandem. A third web application called "dashboard" was used to combine results from mapping and graphs application. Thus, the suite of web applications (see appendix A) was designed to analyze water-use variations measured in individual plants (via time signature application); to extrapolate results over large and heterogeneous areas (via mapping application); and to display results in a concise manner to summarize the "call to action" (via the dashboard application).

Threshold for Irrigation According to Plant Stress

To avoid unnecessary irrigation, the team designed an alert threshold to tolerate a moderate reduction in plant water use. To implement PAI treatment, results were leveraged from two distinct sources:

1. Mapping application: historical maps and updated aerial views incorporated the field spatial variability on plant water use variations during the season. (Larger plants accommodate for larger variations in absolute amount of water use.)
2. Time-signature application: plant-based water stress threshold triggered a call for irrigation only when a plant functioned below its optimal level for photosynthetic activity. It was not necessary to fully satisfy plant water needs to maintain 100 percent

of photosynthetic activity. Technically, thresholds have been defined to improve plant water use efficiency, which increased under moderate water deficit.

Figure 3 displays the inside of the sap flow sensor. An orange sleeve applied heat around the stem of the plant. Thermocouples were embedded within the cork material for heat displacement measurement. A schematic view of the sap flow sensor and steps taken during sap flow sensor installation are in Appendix A.

Figure 3: Inside the Sap Flow Sensor

Picture shows the inside of the sap flow sensor. Orange sleeve applies heat around the stem. Thermocouples are embedded with the cork material for heat displacement measurement.

Source: Fruition Sciences

CHAPTER 3: Project Results

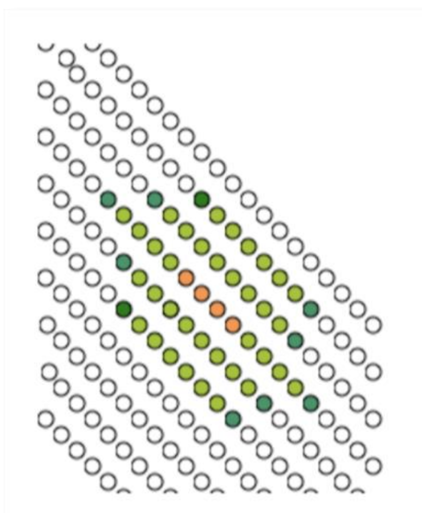
Case Study Analysis

A stratified sampling technique for plant and fruit parameters was used by developing smart points at strategic locations within the field. The PAI model was anchored on a few representative plants for extrapolation at the whole block or ranch level. The following are time-profile case studies performed at sampling block Smith in Wente Vineyards during the 2017 and 2018 seasons. The objective of the following case study sampling was to exemplify the data collection work at each location essential to calculate the effect that PAI treatment versus traditional irrigation has on a plant water status variation in real-time, and the water-savings effect on berry mass and sugar accumulation. Each site was collectively and simultaneously monitored, and the data was analyzed according to a uniform protocol at all locations.

Smart Point Configuration

A typical smart point format is comprised of a center row of 14 vines, 10 vines on each row adjacent to the center row, followed by an additional eight vines on each row next to those rows. Figure 4 illustrates the 50-vine smart point by Fruition Sciences. The researchers identified plants in rows that fit in a circle around a central point that are representative of the rest of the trees.

Figure 4: 50 Vines Smart Point Configuration



A typical smart-point format.

Source: Fruition Sciences

The outermost vines in the sample are represented by dark green circles, light green circles depict the inner vines, and orange circles classified the ideal vine locations for the sap flow sensors; only two out of the four center vines were used for sap flow measurements. The researchers flagged the smart point vines in the vineyard to ensure that the berry sample collections came from the same 50 vines on each collection date. A single cluster from each vine in the smart point was sampled for four berries at every collection period.

Vine Transpiration

Vine transpiration varied every day according to the daily variations of climatic demand. The team reported a typical profile of water use from one smart point. As demonstrated in Figures 5 and 6, transpiration in the early season (beginning of May to the end of June) increased as a function of seasonal increase in climatic demand and leaf-area size. From the end of June to the end of August, plant water use fell roughly between 1.5 mm and 2.5 millimeters (mm) per day, and from September on 1 mm to 2 mm per day. These variations were due to several factors:

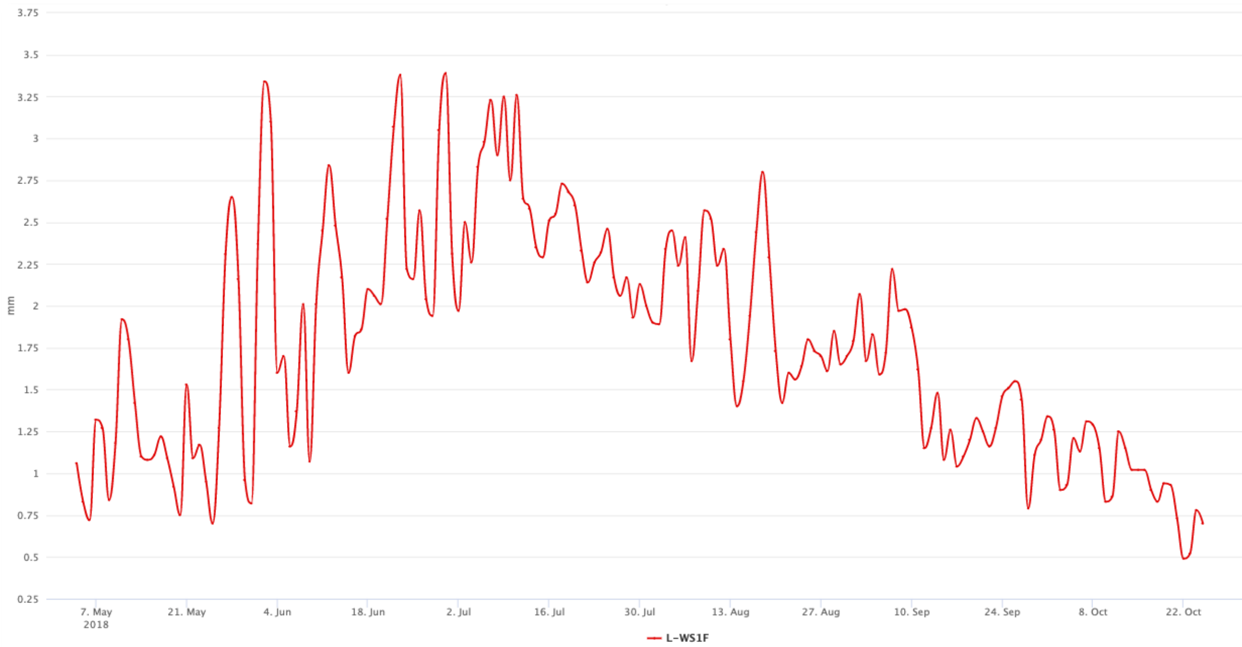
- Sun position and row orientation modulated the amount of light intercepted by the plant.
- Seasonal canopy size variations.
- Plant aging affecting leaf water use.
- Field operations (hedging, leaf pulling, and cluster thinning).
- Physiological changes, such as fruit transitioning from being a source (fruit was green and behaved like a leaf) to a sink (fruit was red and accumulated sugar).
- Crop load (the amount of fruit per plant).
- Extreme climatic events, such as heat waves.

Figure 5: Vine Transpiration at Wente Block Smith in 2017

Vine transpiration in 2017 at Wente block Smith (units are millimeter on Y axis; civil calendar on X axis).

Source: Fruition Sciences

Figure 6: Vine Transpiration at Wente Block Smith in 2018



Vine transpiration in 2018 at Wente block Smith (units are millimeter on Y axis; civil calendar on X axis).

Source: Fruition Sciences

Evaporative Demand

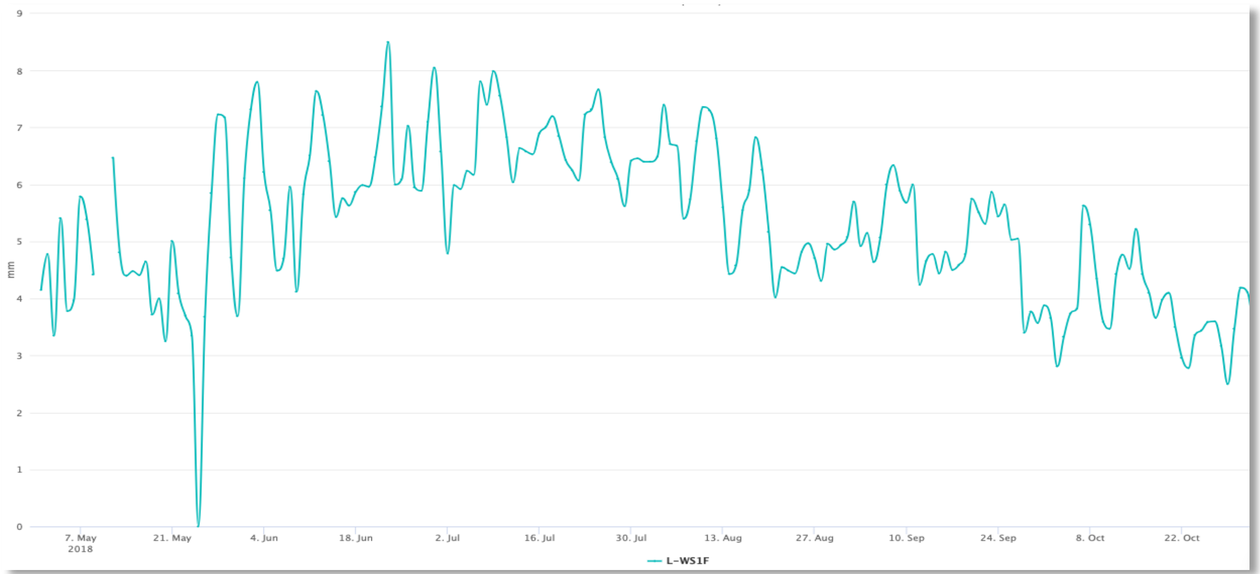
The team collected a typical profile of climatic demand computed as reference ET_{ref} expressed in millimeters per day. Figure 7 and Figure 8 show such typical profiles characterizing climatic demand.

Figure 7: ET_{ref} at Wente Block Smith in 2017

Calculated ET_{ref} in 2017 at Wente block Smith (units are millimeter on Y axis; civil calendar on X axis).

Source: Fruition Sciences

Figure 8: ET_{ref} at Wente Block Smith in 2018



Calculated ET_{ref} in 2018 at Wente block Smith (units are millimeter on Y axis; civil calendar on X axis).

Source: Fruition Sciences

Fluctuations in the reported ET_{ref} reflected site-specific changes in climatic conditions. For example, ET_{ref} spiked around September 1 during the 2017 Labor Day heat wave in Northern California. Low dips, such as on April 16, 2017, were a result of cool and cloudy weather. During 2017, ET_{ref} varied from a low value of 0.35 mm per day to a high of 8.71 mm per day.

In the 2018 study, when the vines had fully transpired leaves (roughly between March 15 to October 31), site specific ET_{ref} varied between a low of 1.00 mm per day, to the same maximum of 8.71 mm per day reported in 2017.

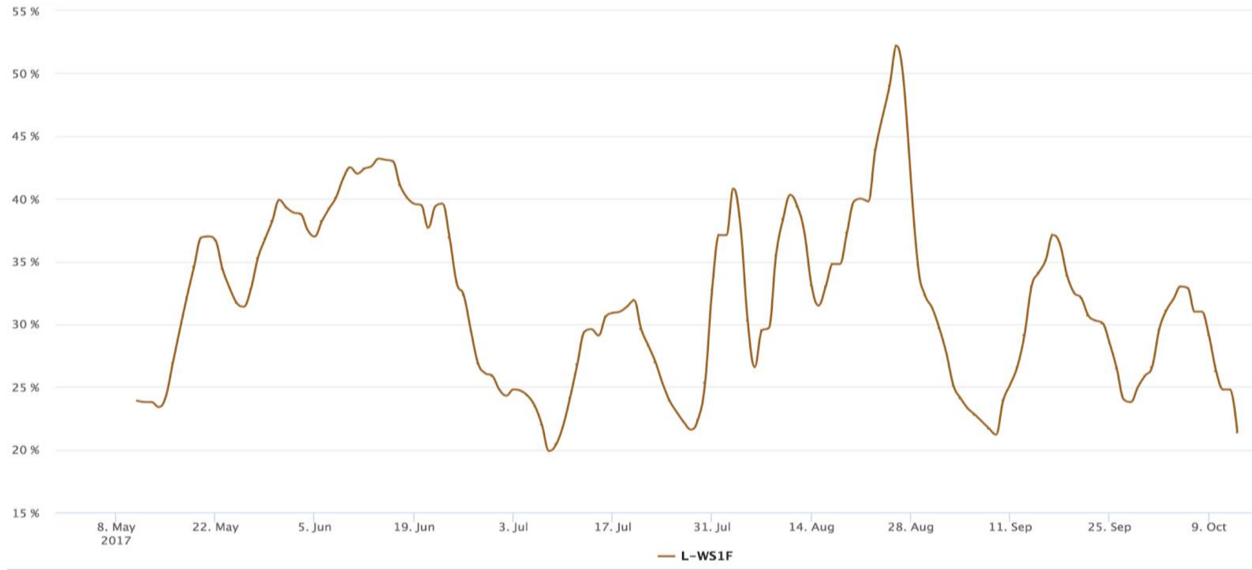
Transpiration Ratio

The transpiration ratio expressed the amount of water use per plant over the climatic demand. The ratio between vine transpiration and evaporative demand is shown below:

$$Transpiration\ Ratio = \frac{T}{ET_{ref}}$$

Since T and ET_{ref} are both expressed in mm, the volume of daily water use can be expressed as a fraction of daily ET_{ref}. Figure 9 and Figure 10 show such typical profiles characterizing the transpiration ratio.

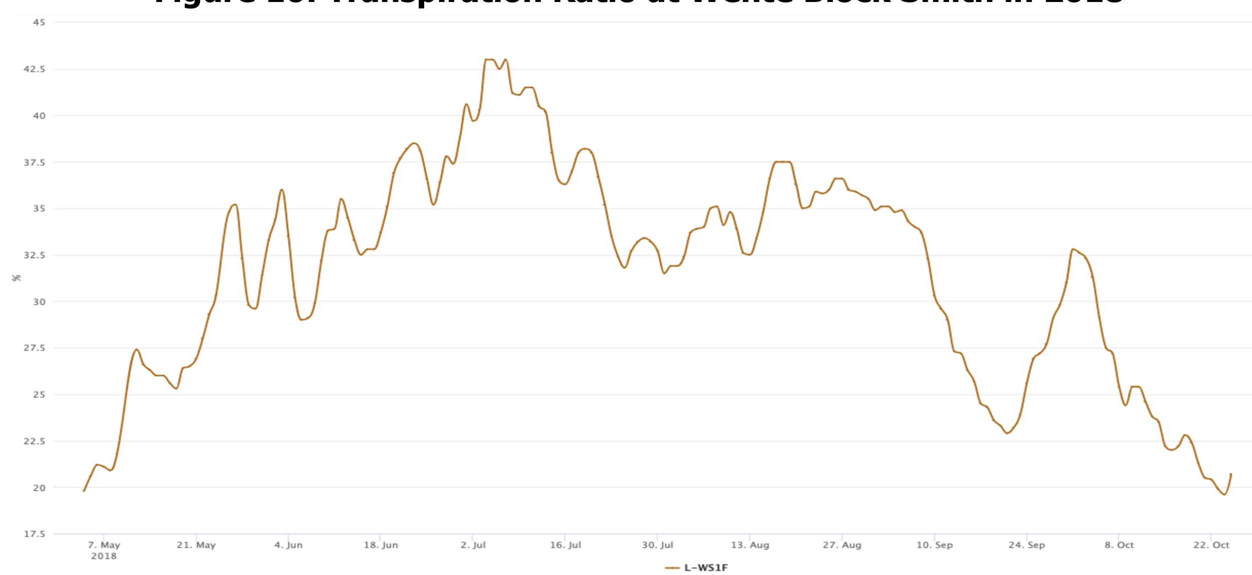
Figure 9: Transpiration Ratio at Wente Block Smith in 2017



Calculated transpiration ratio in 2017 at Wente block Smith (units are percentage on Y axis; civil calendar on X axis).

Source: Fruition Sciences

Figure 10: Transpiration Ratio at Wente Block Smith in 2018



Calculated transpiration ratio in 2018 at Wente block Smith (units are percentage on Y axis; civil calendar on X axis).

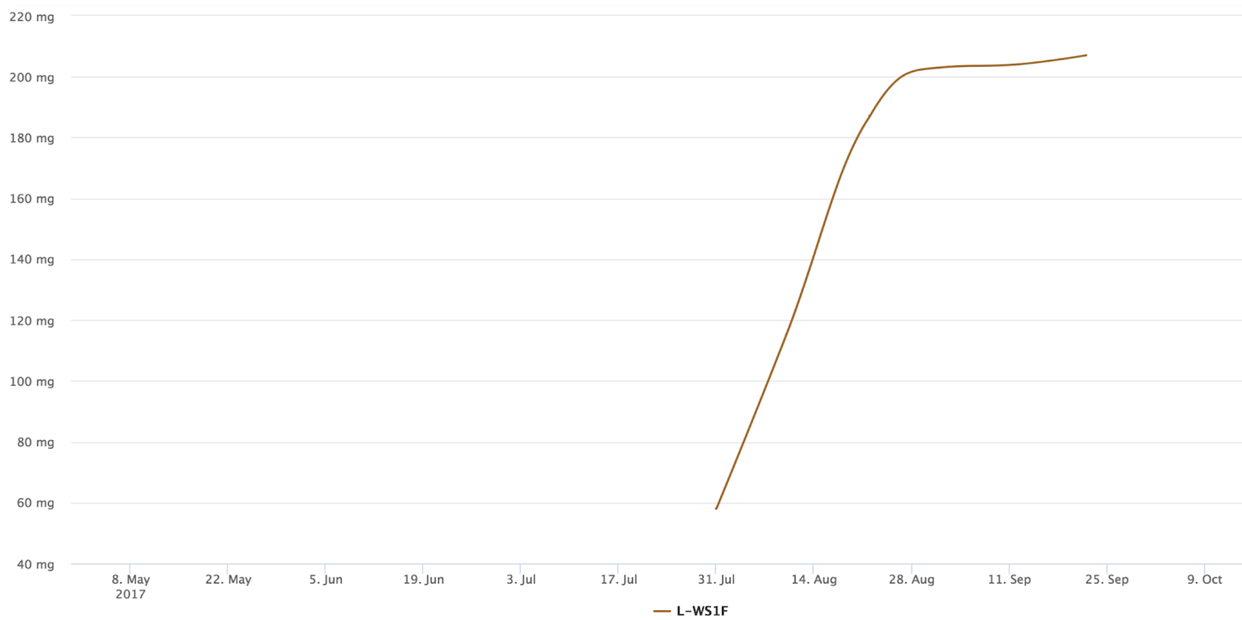
Source: Fruition Sciences

Irrigation was applied to PAI treatment blocks when the threshold was reached at one of the monitored sap flow locations. For instance, irrigation was applied on July 8, 2018 when a low-boundary threshold of 20 percent transpiration ratio was met. As a consequence of water application, the transpiration ratio increased. Following the irrigation, plant water intake increased because root access to soil water was no longer limited. Typically, lower plant water use was obtained through the plant's tighter control over its stomata. As a result of irrigation, more water evaporated freely into the air.

Sugar Accumulation

Sugars accumulated in each berry throughout the process of maturation until harvest. The team analyzed the time profile of sugar accumulation on a per-berry basis. Results were obtained and recorded in milligrams (mg) per berry at several dates within each season using a manual 200-berry sampling protocol on 50 vines located around the sap flow sensor, as per the smart point design. Figure 11 and Figure 12 show such typical profiles characterizing sugar loading into the berries.

Figure 11: Sugar Loading Profile at Wente Block Smith in 2017

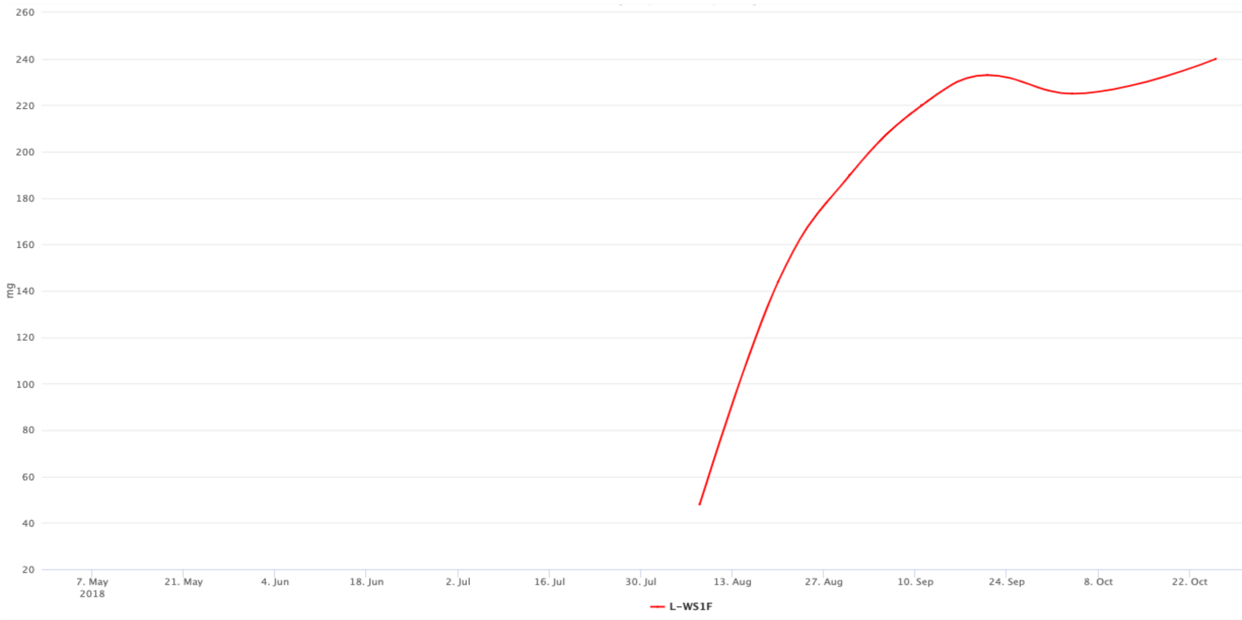


Sugar per berry test results in 2017 at Wente block Smith (units are milligrams per berry on Y axis; civil calendar on X axis).

Source: Fruition Sciences

Results showed a steady sugar accumulation throughout July, until a plateau around the end of August in 2017 and 2018. This profile was typical of vines with normal function. Plants were able to perform photosynthesis and to accumulate sugars normally even if some water deficit was imposed. As a result, fruit accumulated more mass and the inflow of sugar was smooth until an upper threshold was reached, typically before harvest time. The maximum amount of sugar per berry was calculated at 207 mg/berry for this case study.

Figure 12: Sugar Loading Profile at Wente Block Smith in 2018



Sugar per berry test results in 2018 at Wente block Smith (units are milligrams per berry on Y axis; civil calendar on X axis).

Source: Fruition Sciences

Collective Operational Data Analysis

Climatic Demand

The team analyzed global trends observed across all sites and PAI treatments by focusing on climatic demand variations, and level of vine water use expressed as a fraction of climatic demand. Tables 2 and 3 present the observed values for evapotranspiration and rainfall.

Table 2: ET_{ref} (mm/day) Minimum and Maximum by Vineyard (March 1–October 15)

Site	2016 $ET_{Ref, min}$	2016 $ET_{Ref, max}$	2017 $ET_{Ref, min}$	2017 $ET_{Ref, max}$	2018 $ET_{Ref, min}$	2018 $ET_{Ref, max}$
Wente	0.66	7.96	0.86	8.80	0.45	8.50
Gamble	0.41	7.28	0.71	6.35	0.56	7.85
Stanly	0.46	5.72	0.38	5.95	0.46	6.09

Source: Fruition Sciences

Table 3: Cumulative Rain (mm) by Vineyard (November 1–October 31)

Site	2015–2016	2016–2017	2017–2018
Wente	415	512	243
Gamble	342	494	455
Stanly	471	767	366

Source: Fruition Sciences

Over the three sites, the intensity of climatic demand was the highest at Wente (Livermore), followed by Gamble Ranch (Yountville), and lastly Stanly Ranch (Napa), which was the coolest.

Cumulated annual rain values were calculated over the seasonal cycle. The season started after leaf fall (November 1 of the previous year), to account for the effect of winter rain on the root reservoir refilling before beginning new vegetative development at the budbreak stage, which typically occurs in March. The end of the seasonal cycle concluded after harvest (October 31). Over the last three seasonal periods (2016—2018), cumulative rain between each site varied.

Maximum Transpiration Ratio Analysis

The researchers selected locations for low and high vegetative areas based on the preliminary analysis of field spatial variations and adjusted based on aerial images showing the spatial distribution of leaf area vegetative index. The maximum transpiration ratio ($K_{cb, max}$) was recorded for each control and PAI treatment block for the 2017 and 2018 seasons, as shown in Tables 4 and 5. $K_{cb, max}$ values fluctuated each year and were dependent upon such factors as planting architecture (row spacing, row height, row width, and row orientation), leaf area size, and leaf area composition (such as nitrogen content).

Table 4: Treatment Blocks Maximum K_{cb}

Site-Block	Treatment Average $K_{cb, max}$	
	2017	**2018**
Wente-Karl	0.257	0.381
Wente-Mel	0.222	0.293
Wente-Reuss	0.460	0.359
Wente-Smith	0.419	0.357
Gamble-11	0.307	0.215
Gamble-8	0.423	0.354
Gamble-9	0.400	0.363
Stanly-1C	0.416	0.442
Stanly-5J	0.419	0.503

Source: Fruition Sciences

In 2017 and 2018, the level of maximum vine water use, $K_{cb, max}$, (expressed as a percent of ET_{ref}) was similar in low and high vegetative development areas for each vineyard, regardless if it was designated as a PAI treatment or control. This was expected, since planting density and leaf area development were the main drivers for $K_{cb, max}$ and should not have interfered with treatment. Areas of higher vegetative development tended to reach higher $K_{cb, max}$ (Kustas et al., 2018).

Table 5: Control Blocks Maximum K_{cb}

Site-Block	Control Average $K_{cb, max}$	
	2017	**2018**
Wente-Karl	0.272	0.446
Wente-Mel	0.269	0.211
Wente-Reuss	0.365	0.328
Wente-Smith	0.270	0.510
Gamble-11	0.241	0.175
Gamble-8	0.343	0.352
Gamble-9	0.428	0.341
Stanly-1C	0.374	0.365
Stanly-5J	0.437	0.447

Source: Fruition Sciences

Irrigation Threshold and Lowest Water Deficit Index Analysis

The lowest value of transpiration ratio reflected the most severe level of water deficit the plant experienced during a given season. To compare sites with contrasting $K_{cb, max}$ values, site-specific lowest transpiration ratios by site specific $K_{cb, max}$ were normalized. The research team calculated the average value of the lowest WDI after analyzing time variations of the ratio using the following formula:

$$WDI = \left(\frac{Transpiration\ Ratio}{K_{cb,max}}\right) \times 100$$

By experimental design, the irrigation strategy in the PAI treatment consisted of monitoring WDI time variations to trigger irrigation according to WDI variations. As a season unfolded, vine WDI dropped gradually, as a function of plant developmental stage, climatic demand, root architecture, available moisture (fraction of transpirable soil water), soil texture, crop level, and so forth. In the PAI treatment, following the preliminary spatial study, contrasting vineyard plots were selected to monitor vine water use at key locations. A wide range of vine water-use variations was captured, based on plants having a high or low leaf area development. Typically, vines showing a higher level of leaf area were expected to have a higher level of water use. The production goal for the PAI treatment was to maintain WDI above 50 percent. During the first period of the season, irrigation was triggered each time a vineyard spot reached a WDI of 50 percent. During the second period of the season (after veraison stage, the onset of ripening of the grapes), the threshold was higher, and irrigation was triggered each time the WDI reached 55 percent. Standard practice irrigation is applied on a weekly schedule regardless of plant water needs. The vineyard decides this schedule, which is fixed and does not depend on any variables.

The study determined that the most severe water stress levels were not always from the plants with the lowest leaf area. The rate of T/ET_{ref} decline (proportional to WDI decline) can be faster in larger plants with greater leaf area, and water stress can appear faster in larger plants even if they operate under higher water use level.

A minimum WDI value per PAI treatment was reported for treatment and control blocks to confirm that seasonal plant water stress level was maintained within a moderate range and in agreement with irrigation threshold, as shown in Tables 6 and 7.

Table 6: Treatment Blocks Minimum Water Deficit Index

Site-Block	Treatment Average of Lowest WDI	
	2017	2018
Wente-Karl	48%	42%
Wente-Mel	39%	42%
Wente-Reuss	38%	40%
Wente-Smith	30%	47%
Gamble-11	55%	58%
Gamble-8	84%	76%
Gamble-9	71%	77%
Stanly-1C	70%	73%
Stanly-5J	67%	55%

Treatment average of lowest WDI listed for each site in 2017 and 2018.

Source: Fruition Sciences

Table 7: Control Blocks Minimum Water Deficit Index

Site-Block	Control Average of Lowest WDI	
	2017	2018
Wente-Karl	51%	33%
Wente-Mel	44%	38%
Wente-Reuss	34%	52%
Wente-Smith	43%	55%
Gamble-11	62%	72%
Gamble-8	87%	84%
Gamble-9	76%	50%
Stanly-1C	63%	52%
Stanly-5J	61%	75%

Control average of lowest WDI listed for each site in 2017 and 2018.

Source: Fruition Sciences

The research team constantly maintained the seasonal WDI minimum value at the Gamble and Stanly Ranches above 50 percent in the PAI treatment. In Gamble block 11, one irrigation happened slightly too early during the second stage. Consequently, the minimum WDI value only reached 58 percent instead of 55 percent.

There were occasional delays at Wente Vineyards (in a warmer and more arid climate) between the irrigation request and the actual irrigation. Thus, the minimum WDI recorded during the season within the PAI treatment was lower than the WDI threshold in some cases. However, the 50 percent threshold was set at a high value to accommodate for the vineyard showing a rapid WDI decline. As such, in the most severely stressed areas, WDI never reached a level of stress more severe than 40 percent during the 2018 season, which was acceptable during the first stage of the season.

In the control, a higher level of irrigation may have induced more notable WDI variations in between two irrigations, particularly at Wente and Gamble Ranch, where the maximum level of water stress could be more severe. This trend reflected a faster decline of the ratio T/ET_{ref} in response to more irrigation and was expected. Applying less water during PAI treatment did not lead to more severe water stress. In fact, a reduction of vine susceptibility to drought was expected in response to less water applied early season, as confirmed by the data (Munitz et al., 2018; Bonada et al., 2018). This chapter details an in-depth water use analysis on control and PAI treatment blocks.

Sugar Loading Analysis

Traditionally, industry standards rely on berry sugar concentration, expressed in Brix, to assess fruit ripeness before harvest. Sugar concentration estimates are performed two to four times before harvest. When weather conditions are not likely to cause fruit dehydration (no heat spell before harvest), fruit sugar concentration is expected to increase regularly with time. For chardonnay and pinot noir, a minimum of 22 Brix of sugar concentration is reached before harvest and a minimum of 23 Brix for cabernet sauvignon. However, due to more frequent heat waves, an increase in sugar concentration has been observed due to fruit dehydration, instead of plant photosynthetic activity. Therefore, indexes to monitor fruit ripening are now becoming the new industry standard.

Under severe high vapor pressure deficit conditions (heat waves) as a result of global warming, some confusion may occur about active sugar accumulation resulting from regular plant photosynthesis during ripening (berry volume increase) with passive sugar accumulation resulting from berry water loss (berry volume decrease). To distinguish between these two phenomena, sugar concentration and berry volume were monitored at each smart point.

The researchers created the photosynthetic fruit index, or sugar per berry, by dividing the sugar concentration by berry volume and used the index to monitor fruit ripening under contrasted irrigation regimes and climates. The sugar-per-berry time-profile analysis helped differentiate two situations:

1. Excess plant water deficit reduced photosynthesis, meaning that not enough irrigation water was applied. Plant photosynthesis stopped and sugar stopped accumulating (sugar per berry stalled at a low value).
2. Excess heat (high vapor pressure deficit [VPD] in the air) reduced berry volume without necessarily stopping sugar from accumulating (sugar per berry kept increasing until its maximum value, because plant water status and photosynthesis were below well-maintained conditions).

The team documented the maximum amount of sugar per berry (S_{max}) for each smart point and categorized the lowest and highest S_{max} values observed for each PAI treatment as shown in Table 8 and Table 9. A range of sugar per berry concentrations typically observed around harvest for the California wine industry and results tables of the sugar loading analysis are shown:

- Chardonnay (22 Brix and above)
  - 260–400 mg/berry
- Pinot noir (22 Brix and above)
  - 240–320 mg/berry
- Cabernet sauvignon (23 Brix and above)
  - In very-low vigor areas (small berry sizes): 130–140 mg/berry
  - In low/moderate vigor areas (small to moderate berry sizes): 140–260 mg/berry
  - In high-vigor areas (large berry sizes): >260 mg/berry

Table 8: Plant Aware Irrigation Treatment Blocks Maximum Sugar per Berry (mg/berry)

Site-Block	Treatment Lowest S_{max} SP		Treatment Highest S_{max} SP	
	2017	2018	2017	2018
Wente-Karl	169	200	216	212
Wente-Mel	183	186	190	213
Wente-Reuss	160	138	186	178
Wente-Smith	188	225	207	240
Gamble-11	226	242	228	264
Gamble-8	263	347	333	391
Gamble-9	265	278	280	304
Stanly-1C	248	299	311	323
Stanly-5J	348	323	379	370

Treatment blocks maximum sugar per berry for each site in 2017 and 2018.

Source: Fruition Sciences

Table 9: Control Blocks Maximum Sugar per Berry (mg/berry)

Site-Block	Control Lowest S_{max} SP		Control Highest S_{max} SP	
	2017	2018	2017	2018
Wente-Karl	180	190	226	229
Wente-Mel	184	171*	201	171
Wente-Reuss	138	164	192	180
Wente-Smith	230	283	230	308
Gamble-11	222	251	228	253
Gamble-8	356	340	379	404
Gamble-9	253	262	281	280
Stanly-1C	275	291	312	331
Stanly-5J	322	328	340	363

Control blocks maximum sugar per berry for each site in 2017 and 2018.

***Yield not harvested separately.**

Source: Fruition Sciences

The range of maximum amount of sugar per berry was between 138 mg and 370 mg in the weak vigor spots, and between 171mg and 404 mg in the high vigor spots. Those values were within the industry standards and reflected the main trend expected from varietal effect on maximum amount of sugar per berry. Thus, researchers observed a higher sugar amount per berry in chardonnay sites Gamble block 8 and Stanly block 5J, followed by pinot noir site Stanly block 1C, and then the other sites planted with cabernet sauvignon. This trend confirms that the level of water stress imposed in the PAI treatment blocks did not affect fruit-ripening conditions and fruit quality. In fact, for red varietals, a qualitative improvement was often reported as a higher color extraction rate was anecdotally observed (data not shown) resulting from moderate water stress imposed early in the season.

Results from this study determined that sugar accumulation profiles were within industry standards and were typical of vines whose photosynthetic activity was not negatively affected by excess soil moisture deficit.

Yield Collection Analysis

The research team obtained yields at harvest using a combination of methods. For most sites, total tonnage of harvested fruit was recorded for each zone. Tonnage values were then expressed on a per-ground-area basis using the acreage calculated for each PAI treatment zone. Table 10 presents the results of the yield collection analysis, and a visual representation of the yield per vineyard block is provided in Figure 13 and Figure 14. Notably, yields from zones unable to be harvested separately were extrapolated from cluster counts and weights collected manually from 50 vines in each block. The 50 vines were comprised of 10 vines selected at five separate locations. Three locations overlapped with sap flow locations and two additional sites were chosen in low- and high-vigor areas, according to Normalized Difference Vegetative Index (NDVI) aerial map interpretations. Unfortunately, no yield data was collected during harvest in 2017 at sites Gamble block 8, Stanly blocks 1C and 5J (Figure 13).

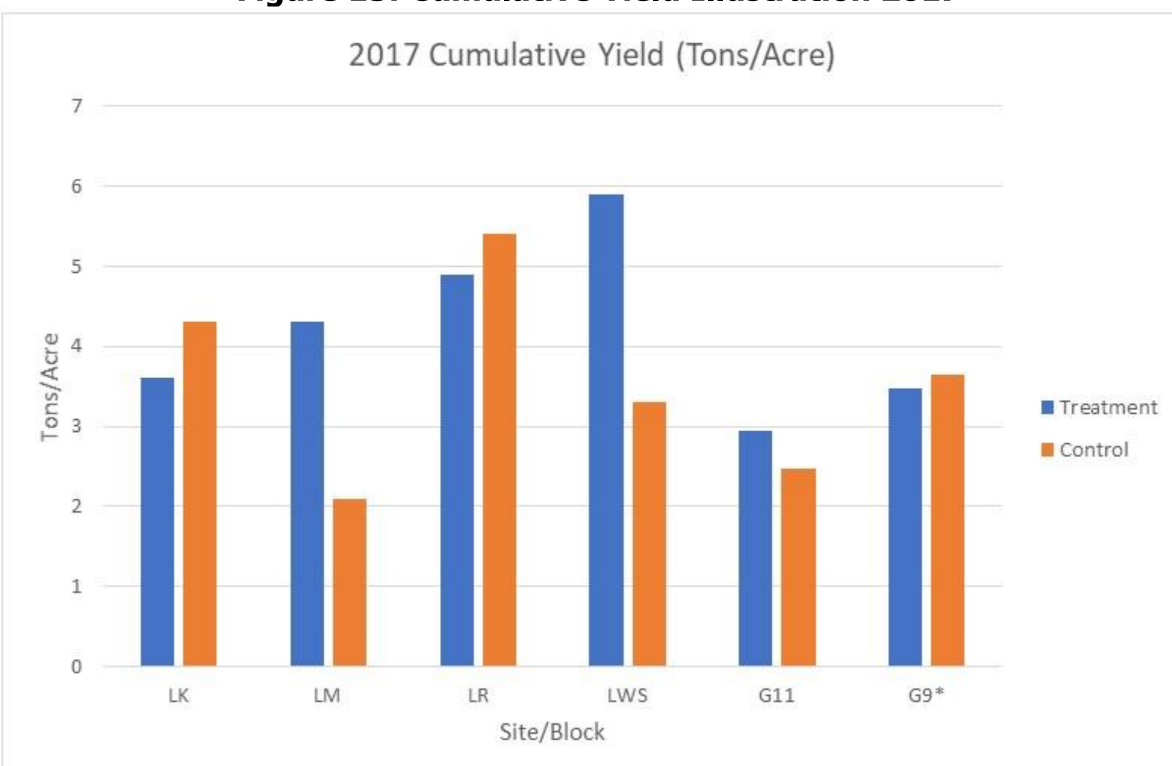
Table 10: Cumulative Yield (tons/acre)

Site-Block	2017		2018	
	PAI Treatment	PAI Treatment	PAI Treatment	PAI Treatment
Wente-Karl (LK)	3.6	4.3	4.15	3.93
Wente-Mel (LM)	4.3	2.1	3.72	5.76
Wente-Reuss (LR)	4.9	5.4	4.71	2.22
Wente-Smith (LWS)	5.9	3.3	9.48	9.06
Gamble-11 (G11)	2.94	2.47	3.58	3.07
Gamble-8 (G8)	—	—	4.32*	5.05*
Gamble-9 (G9)	3.48*	3.64*	5.11*	4.40*
Stanly-1C (S1C)	—	—	4.03	3.31
Stanly-5J (S5J)	—	—	9.48	7.84

Cumulative yield of PAI treatment and control at each site for 2017 and 2018. *Yield not harvested separately.

Source: Fruition Sciences

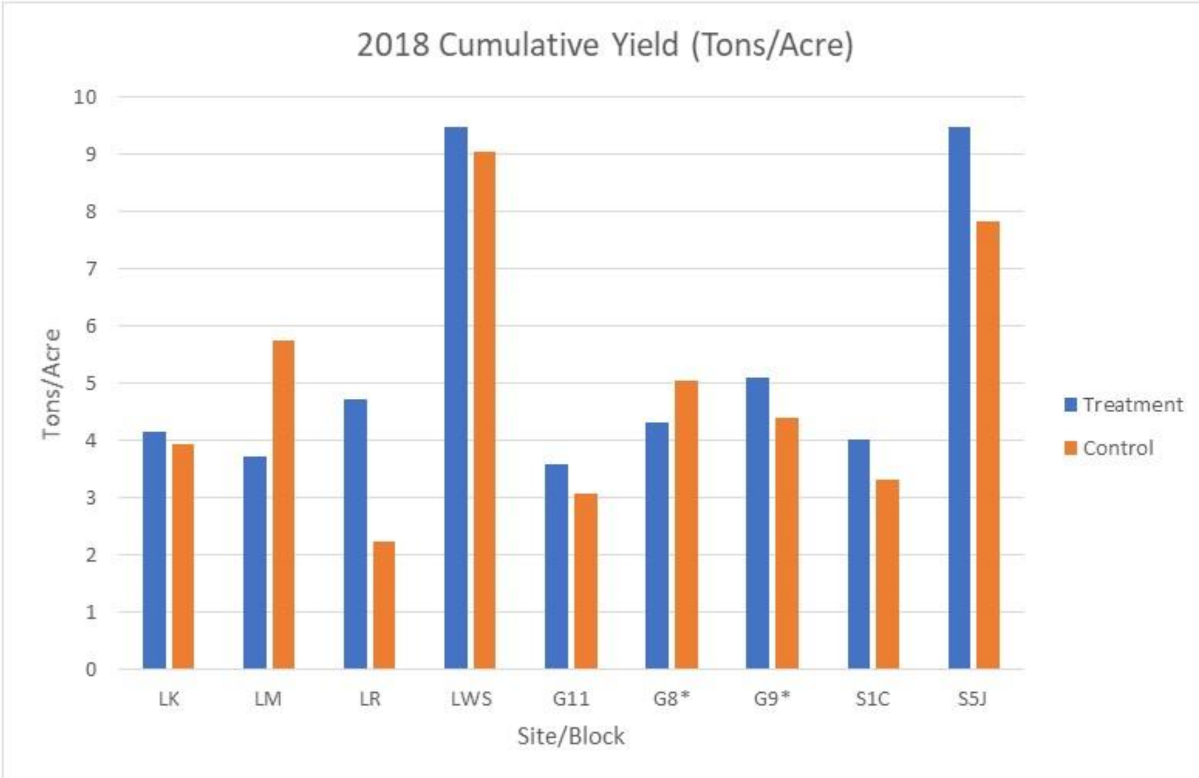
Figure 13: Cumulative Yield Illustration 2017



Cumulative yield PAI treatment and control at each site for 2017 (units are tons per acre on Y axis; vineyard location on X axis).

Source: Electric Power Research Institute

Figure 14: Cumulative Yield Illustration 2018



Cumulative yield treatment and control at each site for 2018 (units are tons per acre on Y axis; vineyard location on X axis).

Source: Electric Power Research Institute

The researchers recorded yield values in PAI treatment blocks similar to the control. Using less irrigation could have lowered susceptibility to drought toward the end of the season. This may have contributed to keeping a higher berry moisture content, thus a higher berry volume until later in the season, particularly as late season Indian summer heat waves occurred. The PAI treatment did not reduce the yield.

Using less irrigation lowers vine susceptibility to drought particularly toward the end of the season when the fruit reaches its maximum size and contributes to keeping a higher berry moisture content. This results in a higher berry volume later in the season, even if late season heat waves are known to cause berry dehydration and yield losses.

Vines that received PAI treatment were more resistant to drought and yield. With the control blocks vines were less resistant to drought and their yield may be more reduced because heat waves have a more severe impact at reducing berry size due to dehydration. In conclusion, the PAI treatment did not reduce the yield, even when less water was applied.

Water-Use Savings Analysis

The research team assigned each subblock as control or PAI treatment. Each block consisted of either a water meter, vendor-provided flow-rate monitoring equipment at one dripper, or both. The water-meter-measurement period lasted from April 27, 2018 to March 1, 2019, and the dripper monitors from July 13, 2018 to October or November 2018. Water meter data was collected until August 1, 2019; however, the analysis was limited to March 1, 2019 to encompass one full growing season. Water-meter data from the Wente Mel subblock was omitted from the analysis due to the logger failing to record data, and one water meter data series pair for Treasury's Gamble block 9B was also omitted because vineyard staff mistakenly watered the PAI treatment area despite the vendor not calling for the event. For each included sub-block and measurement equipment type, the researchers calculated water consumption per unit area. Table 11 presents the recorded total gallons per acre according to each subblock.

Table 11: Total Gallons per Acre per Block

ID	Site-Block	Control or PAI Treatment (C/T)	Acres	Water Meters Start Date	Water Meters End Date	Water Meters Gal/ Acre	Dripper Monitoring by Vendor Start Date	Dripper Monitoring by Vendor End Date	Dripper Monitoring by Vendor Gal/Acre
72815655	Wente-Reuss	C	5.63	4/27/18	3/1/19	267,052	7/13/18	11/2/18	210,378
72814186	Wente-Reuss	C	4.71	4/27/18	3/1/19	219,873	—	—	—
9991	Wente-Reuss	C	5.97	—	—	—	7/13/18	11/2/18	254,368
72814406	Wente-Reuss	T	5.43	4/27/18	3/1/19	179,595	7/13/18	11/2/18	142,989
72710127	Wente-Reuss	T	5.23	4/27/18	3/1/19	50,956	—	—	—
72814416	Wente-Reuss	T	5.00	4/27/18	3/1/19	88,760	—	—	—
72708406	Wente-Reuss	T	5.30	4/27/18	3/1/19	103,094	—	—	—
9992	Wente-Karl	C	7.41	—	—	—	7/13/18	10/17/18	176,187
72815670	Wente-Karl	T	4.62	4/27/18	3/1/19	157,703	—	—	—
72814410	Wente-Karl	T	6.00	4/27/18	3/1/19	152,788	—	—	—
72814385	Wente-Karl	T	6.76	4/27/18	3/1/19	175,089	—	—	—

ID	Site-Block	Control or PAI Treatment (C/T)	Acres	Water Meters Start Date	Water Meters End Date	Water Meters Gal/ Acre	Dripper Monitoring by Vendor Start Date	Dripper Monitoring by Vendor End Date	Dripper Monitoring by Vendor Gal/Acre
72342391	Wente-Karl	T	6.25	4/27/18	3/1/19	152,030	7/13/18	10/17/18	85,042
9994	Wente-Mel	C	4.73	—	—	—	7/13/18	10/17/18	133,757
72814391	Wente-Mel	T	4.81	—	—	—	7/13/18	10/17/18	109,600
72815648	Wente-Mel	T	4.62	4/27/18	3/1/19	196,840	—	—	—
9995	Wente-Smith	C	6.85	—	—	—	7/13/18	10/26/18	183,994
9996	Wente-Smith	T	8.40	—	—	—	7/13/18	10/26/18	69,147
72814664	Gamble-8	C	12.53	4/27/18	3/1/19	3,142	—	—	—
72814418	Gamble-8	T	32.77	4/27/18	3/1/19	6	—	—	—
72815714	Gamble-S1C	C	4.85	4/27/18	3/1/19	2,041	—	—	—
72814657	Gamble-S1C	T	4.85	4/27/18	3/1/19	—	—	—	—

Total gallons of water per acre consumed by each sub-block.

Source: NegaWatt Consulting

Three of the line items have measurements from both a water meter and a dripper monitor. This is how they stack up against identical measurement windows:

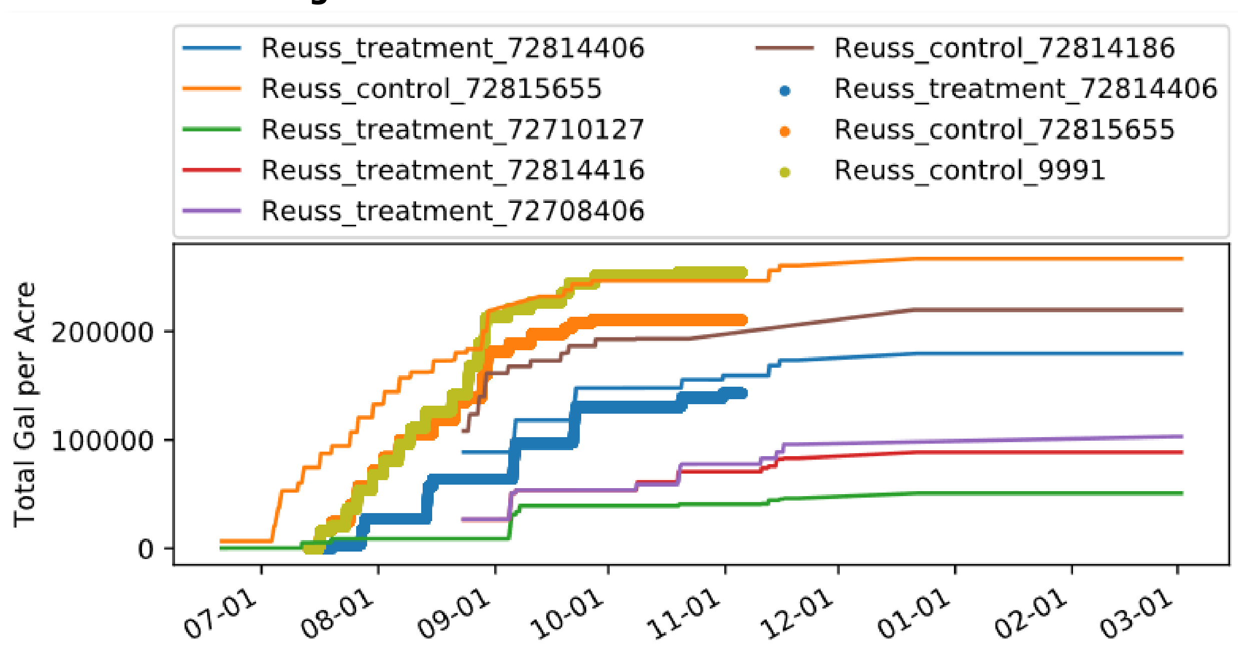
1. ID 72815655: 171,883 versus 210,378 gallons/acre, a 22 percent difference.
2. ID 72814406: 159,280 versus 142,989 gallons/acre, a -10 percent difference.
3. ID 72342391: 107,294 versus 85,042 gallons/acre, a -21 percent difference.

In each line item above, the ID number is followed by the water meter value and the dripper monitor value. Note that only the dripper monitor values line up with Table 11 above. The water meter values do not line up because the measurement windows here are shorter.

The researchers assumed discrepancies were a measurement error of the dripper monitors. Each monitor measured flow rate through one dripper in an irrigation line. The team calculated flow for the full subblock by multiplying the measurement by the total number of drippers in the sub-block, with the assumption that all emitters have an identical flow rate.

Figures 15-20 show plots of cumulative water usage per unit area for each block. Water meter data series are shown as thin lines. Dripper data series are shown as dots in the legend, thick lines in the plot, and have matching colors, when appropriate.

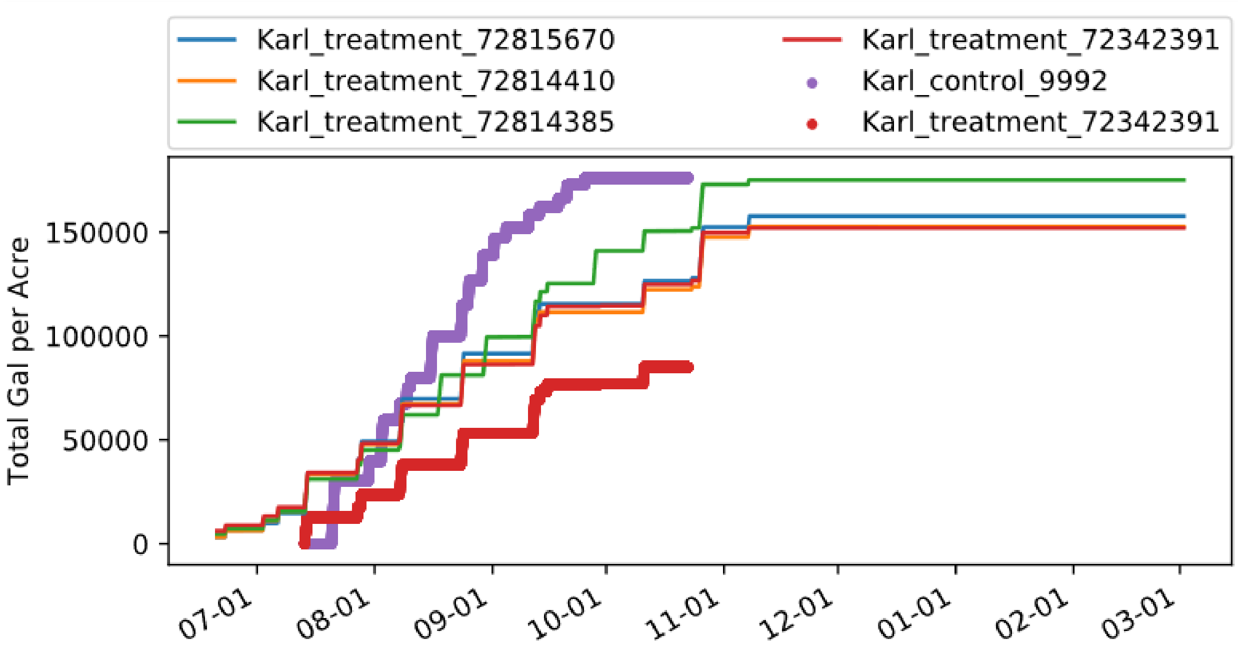
Figure 15: Water Use at Wente Block Reuss



Cumulative water usage at Wente block Reuss between July 1, 2018 to March 1, 2019 (units are gallons per acre on Y axis; civil calendar on X axis).

Source: NegaWatt Consulting

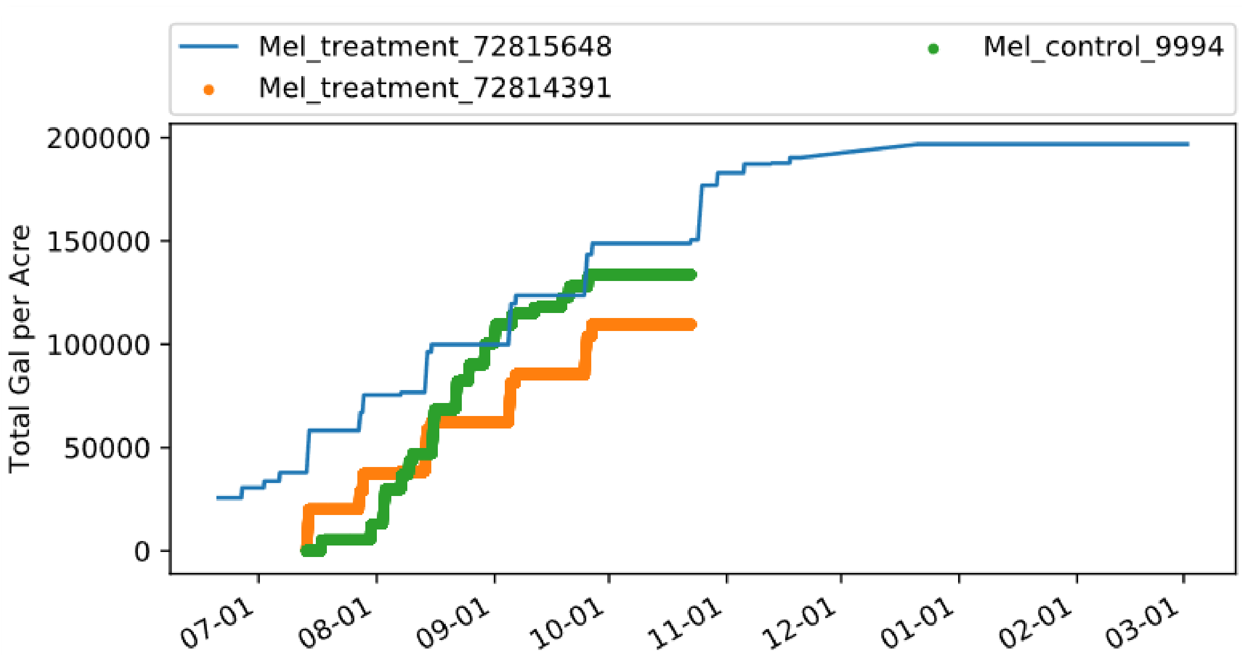
Figure 16: Water Use at Wente Block Karl



Cumulative water usage at Wente block Karl between July 1, 2018 to March 1, 2019 (units are gallons per acre on Y axis; civil calendar on X axis).

Source: NegaWatt Consulting

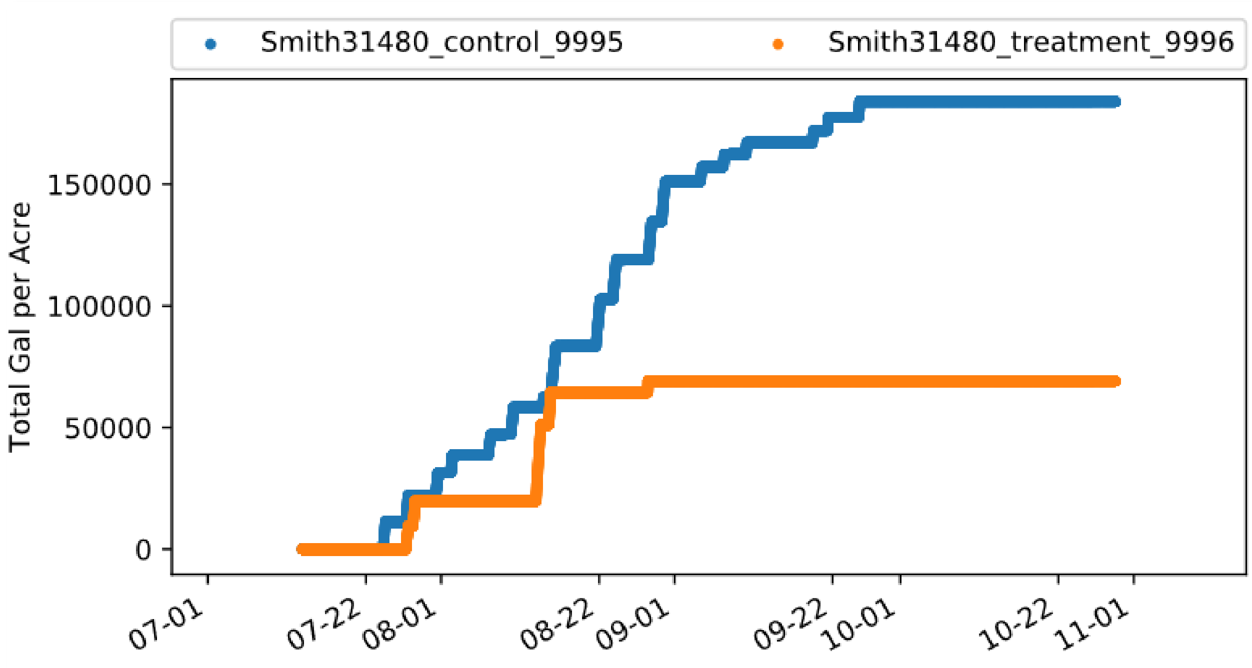
Figure 17: Water Use at Wente Block Mel



Cumulative water usage at Wente block Mel between July 1, 2018 to March 1, 2019 (units are gallons per acre on Y axis; civil calendar on X axis).

Source: NegaWatt Consulting

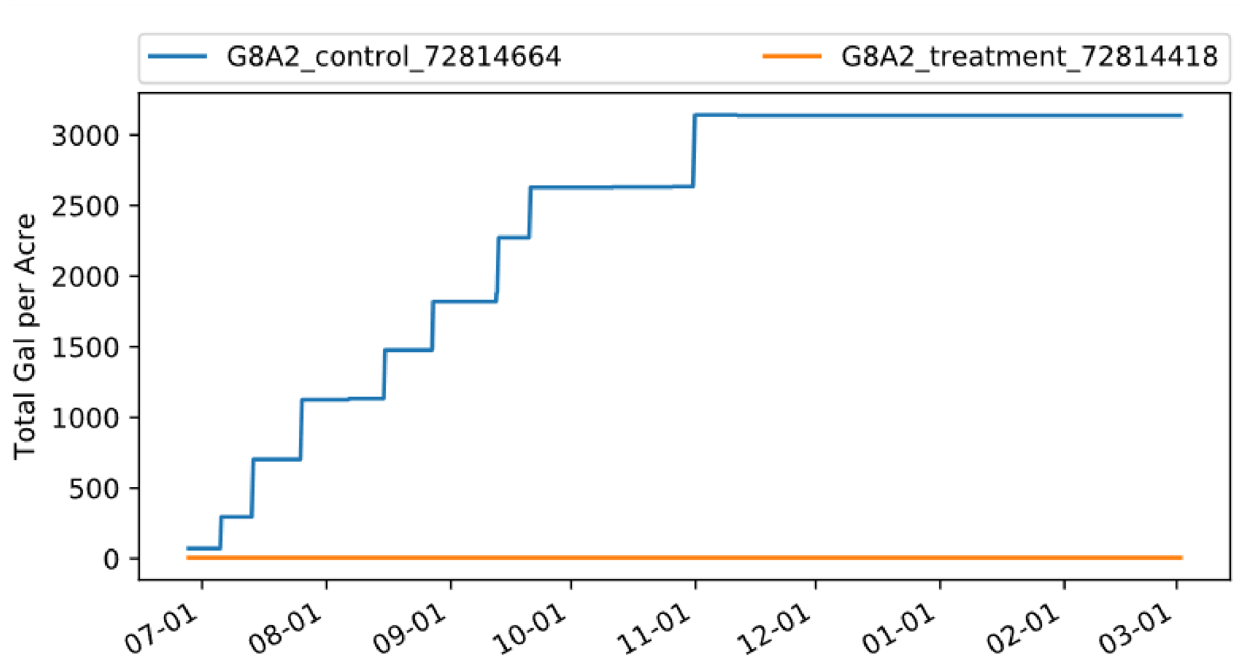
Figure 18: Water Use at Wente Block Smith



Cumulative water usage at Wente block Smith between July 1, 2018 to November 1, 2018 (units are gallons per acre on Y axis; civil calendar on X axis).

Source: NegaWatt Consulting

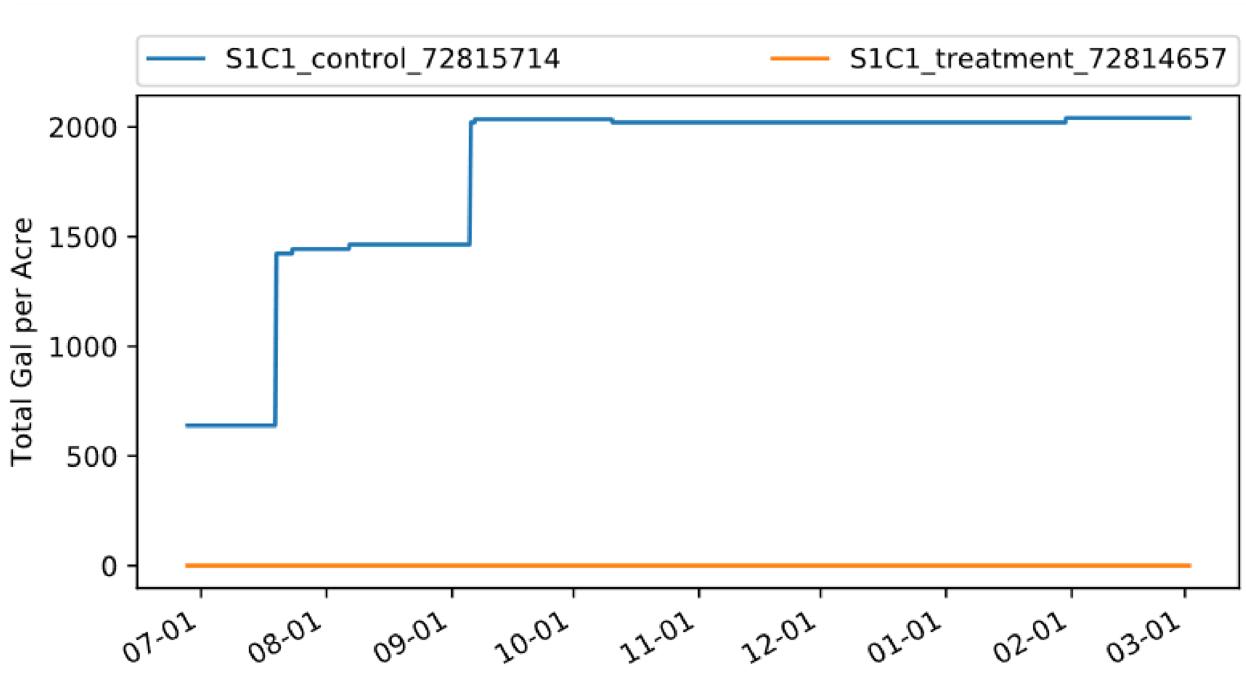
Figure 19: Water Use at Gamble Block 8A



Cumulative water usage at Gamble block 8A between July 1, 2018 to March 1, 2019 (units are gallons per acre on Y axis; civil calendar on X axis).

Source: NegaWatt Consulting

Figure 20: Water Use at Stanly Block 1C1



Cumulative water usage at Stanly block 1C1 between July 1, 2018 to March 1, 2019 (units are gallons per acre on Y axis; civil calendar on X axis).

Source: NegaWatt Consulting

For each block and for each measurement equipment type, the researchers compared control subblocks to PAI treatment subblocks and did not perform a savings calculation unless at least one control and one PAI treatment subblock for a given type of measurement equipment existed. If multiple controls or the treatment subblocks existed for a given equipment type, the team summed water volumes and divided by the total area. Table 12 shows these results.

Calculated water savings ranged from 18 percent to 62 percent at Wente Vineyards and 99.8 percent to 100 percent at Gamble and Stanly Ranches. Wente's Reuss block savings vary between the water meter and dripper monitor due to differences in included control and PAI treatment areas, measurement periods, and measurement error. The 100 percent and near-100 percent savings percentages recorded at Gamble block 8 and Stanly block 1C were due to the vineyard site staff watering the control areas while no watering event was requested and, therefore, did not occur in the corresponding PAI treatment block. Note that the researchers disregarded Gamble block 9 due to the staff inadvertently watering a PAI treatment area despite the vendor not administering the watering event.

The average savings at Wente Vineyards using the dripper-monitored data were 43 percent and the average savings at Gamble and Stanly Ranches using the water-meter data were 100 percent. The combined savings across each vineyard fell within the predicted range of 60 percent that was witnessed during the small-scale testing performed at the smaller high-end Napa Valley vineyards and the vineyard testimonies.

Table 12: Water Savings per Block

Site-Block	Control (C) or PAI Treatment (T)	Water Meters Gal/Acre	Water Meters Savings Gal/Acre	Water Meters %	Dripper Monitoring by Vendor Gal/Acre	Dripper Monitoring by Vendor Savings Gal/Acre	Dripper Monitoring by Vendor %
Wente-Reuss	C	245,561	139,077	56.6%	233,017	90,028	38.6%
Wente-Reuss	T	106,484			142,989		
Wente-Karl	C	—	—	—	176,187	91,145	51.7%
Wente-Karl	T	159,928			85,042		
Wente-Mel	C	—	—	—	133,757	24,157	18.1%
Wente-Mel	T	196,840			109,600		
Wente-Smith	C	—	—	—	183,994	114,847	62.4%
Wente-Smith	T	0			69,147		
Gamble-8	C	3,142	3,136	99.8%	—	—	—
Gamble-8	T	6			—		
Stanly-1C	C	2,041	2,041	100.0%	—	—	—
Stanly-1C	T	0			—		

Water savings per control and PAI treatment sub-blocks.

Source: NegaWatt Consulting

Energy Savings Analysis

Per the ASHRAE Handbook for HVAC Systems and Equipment, the pump energy equation for water is:

$$bhp = (Q \cdot \Delta h)/(3960 \cdot \eta)$$

Where

$bhp = brake\ horse\ power$

$Q = fluid\ flow\ rate, gpm$

$3960 = units\ conversion, ft \cdot gpm\ per\ hp$

$\Delta h = total\ head, ft\ of\ fluid$

$\eta = pump\ efficiency$

Total head depended on the pipe length, diameter, material, and fittings from the pump to the irrigation drippers, as well as any pressure at the pump inlet. Total head differed from block to block and was not affected by the implemented technology. Pump efficiency also varied for each block, but also was not affected by the technology. Therefore, both total head and pump-efficiency values were assumed to be constant. For simplicity, 100 feet was used for the total head, and the state average for agricultural pump efficiency of 53 percent as mentioned in Pacific Gas and Electric's (PG&E's) "Reducing Energy Use and Costs for Pumping Water" presentation, was used for pump efficiency.

The fluid flow rate (Q), was nearly constant for each block with or without the technology, but the technology reduced pump runtime. Pump energy was pump power multiplied by runtime and 1 hp equals 0.7457 kW or:

$$E = (V \cdot \Delta h \cdot 0.7457)/(60 \cdot 3960 \cdot \eta)$$

Where

$E = pump\ energy, kWh$

$V = Q \cdot runtime\ or\ fluid\ volume, gpm \cdot minutes\ or\ gallons$

$0.7457 = units\ conversion\ from\ bhp\ to\ kW$

$60 = units\ conversion\ from\ minutes\ to\ hours$

Dividing by the irrigated area A gave the pump energy per unit area:

$$E/A = [(V/A) \cdot \Delta h \cdot 0.7457]/(60 \cdot 3960 \cdot \eta)$$

Where

$E/A = pump\ energy\ per\ unit\ area, kWh/acre$

$V/A = water\ volume\ per\ unit\ area, gal/acre$

Since total head and pump efficiency were assumed to be fixed values, pump energy was directly proportional to water use, and the savings percentages are identical. Table 13 shows the pump energy per unit area results.

Table 13: Pump Energy Savings per Block

Site-Block	Control (C) or PAI Treatment (T)	Pump Energy via Water Meters (kWh/Acre)	Pump Energy via Water Meters Savings (kWh/Acre)	Pump Energy via Water Meters (%)	Pump Energy via Dripper Monitoring by Vendor (kWh/Acre)	Pump Energy via Dripper Monitoring by Vendor Savings (kWh/Acre)	Pump Energy via Dripper Monitoring by Vendor (%)
Wente-Reuss	C	145.4	82.4	**56.6%**	138.0	53.3	**38.6%**
Wente-Reuss	T	63.1			84.7		
Wente-Karl	C	—	—	—	104.3	54.0	**51.7%**
Wente-Karl	T	94.7			50.4		
Wente-Mel	C	—	—	—	79.2	14.3	**18.1%**
Wente-Mel	T	116.6			64.9		
Wente-Smith	C	—	—	—	109.0	68.0	**62.4%**
Wente-Smith	T	—			40.9		
Gamble-8	C	1.9	1.9	**99.8%**	—	—	—
Gamble-8	T	0.0			—		
Stanly-1C	C	1.2	1.2	**100.0%**	—	—	—
Stanly-1C	T	0.0			—		

Pump energy per unit savings by subblock.

Source: NegaWatt Consulting

Survey Results and Holistic Assessment

A survey of involved staff members at the participating vineyards uncovered motivations and gathered meaningful opinions, comments, and feedback. The survey questions were written to adhere to the research goals and to provide a roadmap for prospective adopters. Below are the aggregated responses:

- Question: What was your general impression of the project?
  - The survey showed common contentment of the system and its performance. Participants indicated that the project was useful and they stated that it even improved the growth and structure of the viniculture team.
- Question: What was your general impression of the conducted operations?
  - Respondents claimed general satisfaction with installation, maintenance, and other services provided. They said it was easier to operate at a smaller scale; however, nothing hampered the day-to-day processes.
- Question: What potential benefits do you see deriving from the technology used in the project?
  - The benefits conveyed by vineyard staff members shadowed the objectives of the project: water, energy, and cost-savings potential through efficient pumping and selective watering. Vineyard staff members were encouraged by the promising vine-health improvements and the vineyards' ability to provide good-quality wine.
- Question: What factors would cause consideration to adopt the technology?
  - Primarily, the survey discovered that future considerations to purchase and employ the technology are cost driven. Secondarily, the survey found that technology must have records of proven performance and ease of operation to be considered for future implementation.
- Question: Where do you see room for improvement for future projects?
  - Participants said that room for improvement existed in the communications for watering. Currently, the watering needs are communicated strictly when plants need water. Respondents suggested that weekly communication is preferred to assist advanced planning. In addition, the survey results indicated that implementing an automated irrigation system may resolve any troubles with communication.

CHAPTER 4: Technology/Knowledge/Market Transfer Activities

Accomplished Activities

Technology, knowledge, and market transfer activities were focused on the project's overall objectives, framing how they were accomplished through data gathering and analysis. The following is a summary of the team's efforts:

1. Presentations
    a. Vintage Report, Napa 2018
    b. UC Davis Viticulture and Enology Symposium
    c. Briefing to Local Utilities
2. Journal Articles
3. Electric Power Research Institute (EPRI) Meetings and Activities
    a. EPRI Advisory Meetings
    b. EPRI Power-in Pollinators Workshop
4. Word-of-Mouth Contacts

Presentations

Presentations explaining the benefits of the PAI system were delivered at Napa's Vintage Report conference, the University of California (UC) Davis Viticulture and Enology Symposium, and via webcasts. This increased stakeholders' understanding and encouraged them to recognize the system's benefits. Several presentations were given to key participants.

- Vintage Report, Napa 2018: The Vintage Report conference was held in Napa on January 22, 2018. The project team presented to a group of wine-grape growers the water- and energy-saving opportunities and background about water-energy nexus. The presentation covered the study's preliminary results of water and energy savings. The conference presented information about cutting-edge innovation and was well attended by viniculture's most prominent thought leaders. (https://www.vintagereport.com/en/napa-2018)
- UC Davis Viticulture and Enology Symposium: The project team included this study as part of a presentation at UC Davis' Viticulture and Enology symposium on April 18, 2019. The presentation addressed the energy-water nexus issue for agriculture by pointing to the need to calibrate atmospheric and airborne measurements with plant-based measurements. The presentation also encompassed a full explanation on how water stress can be defined at a plant level, and then extrapolated from a single plant to the scale of a block by merging climatic and aerial measurements with sap flow. Presenters explained why leaf-water potential (a destructive plant water stress technique) is not appropriate in California due to the effects of heat waves making the

leaf-level measurements hydraulically disconnected from the rest of the plant-water status. (https://wineserver.ucdavis.edu/extension/ve-extension/campus/past-events/2019/honoring-larry-williams-program-focused-vineyard-water-management)

- Local Utilities Briefing: This project was presented to local electric utility Southern California Edison (SCE) via webcast in May 2017 to inform the utility of the innovative technology and electric-energy-savings potential. Other presentations included a Technical Advisory Committee presentation to members of PG&E in Northern California.
- CEC Symposium: The CEC's Electric Program Investment Charge (EPIC) Symposiums were designed to disseminate information on EPIC technologies, engage attendees in panel discussions and breakout sessions, and to prepare posters with relative material for poster sessions. The CEC hosted an EPIC symposium on February 7, 2018 at the Sacramento Convention Center. The PAI project was showcased during the "Energy Technology Solutions for Food Production" breakout session. (https://ww2.energy.ca.gov/research/notices/2018-02-07_symposium/2018-02-07_EPIC_program_online.pdf)

Journal Articles

This project has been acknowledged as part of a 2019 journal submission titled "Technical and Physiological Considerations to Optimize Vineyard Irrigation," which is a follow up to the review article titled "State of the Art Tools and Methods to Assess Vine Water Status".

EPRI Meetings and Activities

EPRI holds regular conferences and workshops with key market participants and utility advisors who contributed information developed during the course of this project.

- EPRI Advisory Meetings: The EPRI Advisory Council conducts a comprehensive review of ongoing research and identifies and prioritizes future research and development opportunities by encouraging collaboration with industry peers around the world. The meetings showcase and shape EPRI research, develop demonstration and marketing opportunities for technologies, provide a conduit for the advisors to impart information to colleagues, and formulate local programs to boost acceptance. Advisory meetings are held twice a year during the spring and fall seasons. The PAI project was presented as part of EPRI's Energy-Water nexus initiative and continues to be presented at both of EPRI's semi-annual advisory committees.
- EPRI Power-in-Pollinators Workshop: EPRI's Pollinator Workshop was held March 27 through 29, 2019 in Sacramento, California to advance the understanding, technical research, and efforts among industry leaders to more effectively consider the intersection of human wellbeing, pollinators, and power companies. The team explored the critical issues, benefits, and opportunities of the food-water-energy nexus with chief thought partners from various fields of agriculture, including the almond and viniculture industries. The research from the PAI project served as an educational platform during the poster session to all attendees. (http://rightofway.erc.uic.edu/event/epri-2019-pollinator-workshop-intersection-of-human-wellbeing-pollinators-and-power-companies/)

Word of Mouth Contacts

The team created a word-of-mouth movement by involving opinion leaders, while convincing them of the PAI system's benefits. Project staff also mentioned the undertaking at key meetings to promote awareness of this system's benefits in reducing energy and water use.

Promising Opportunities Ahead

The Plant Aware Irrigation technology is commercially available through the website https://fruitionsciences.com/en/home

Future technology, knowledge, and market transfer activities focused toward communities of distinguished wine-grape growers and water-intense agriculture sectors, include:

- Local communities of wine-grape growers recognized as the California Winegrape Growers Association (CWGA) and Livermore Valley Winegrowers Association have been identified as primary candidates to present the PAI findings and benefits to industry influencers. A series of technical briefings were conducted in late 2019 to the CWGA and Livermore Valley Winegrowers Association. The presentations concentrated on the project's overall objectives, as well as on practical aspects allowing participants to understand the requirements needed to conduct water and energy analyses in their own operations.
- The secondary candidate for use of the PAI technology would be water intensive crops such as almonds. A technical briefing was held at California State University (CSU) Fresno Center for Irrigation Technology (CIT) as an optimal workshop location. The CIT is researching growth, water, and energy issues for multiple crops through their own on-campus farm. Reaching out to alternative agriculture sectors is an opportunity to:
    - Assess how similar water-savings efforts could be implemented for other crops.
    - Gain a better understanding of boundary conditions required for direct vs. indirect transfer of techniques and instrumentation used in this project.
    - Increase productivity of California farms through improved irrigation techniques and better-related energy-cost management.
    - Assess how irrigation of different crops can affect overall cost structure and its elements.

CHAPTER 5: Conclusions and Recommendations

This study showed that implementing an analytical framework merging atmospheric measurement with remote-sensing imagery and plant-based measurement was an effective method to convert water-use measurements into actionable indexes to trigger and optimize irrigation practices. Atmospheric measurement alone may not be sufficient to convert the water-use estimate in a water stress index that is useful to trigger irrigations; however, leveraging synergies between plant scale, atmospheric measurement, and remote sensing measurements compensated for the limitations inherent to each method. Using plant-based measurements was necessary to convert atmospheric water-use measurement into water stress for assessing irrigation needs. The analytical framework was designed to accomplish this task and was an effective tool to optimize irrigation and to promote a more sustainable use of environmental resources, including water and energy.

The water deficit imposed by optimized irrigations based on plant-specific needs did not affect fruit quality. The water deficit would need to be more severe than what was recorded to restrict photosynthetic activity and to reduce the flow of sugar to the berries. Nor was fruit quantity reduced by the PAI treatment. The data reflected that the yield was either maintained or was even higher when less water was applied. Under a higher-irrigation regime, such as the traditional methods used to irrigate the control blocks, vines can be more sensitive to drought, particularly toward the end of the season (Munitz et al., 2018; Scholasch and Rienth, submitted). The conventional process favored loss of berry moisture content before harvest and may have contributed to lower yield in control blocks where more water was applied.

Overall, the study’s results showed it is possible to achieve an average savings of 61 percent of water and energy input compared to traditional irrigation strategies. Moreover, financial benefits of improved production value and vineyard performance have been associated with the study’s more conservative irrigation strategy. Administering these tests under various climates and at vineyards of various sizes showed that this approach is scalable and can be implemented simultaneously in contrasting situations.

CHAPTER 6: Benefits to Ratepayers

The PAI system showed higher than expected annual water and energy savings in almost all the sites. UC Davis estimated water used by viniculture to be 1.5 million acre-feet per year.[1] If, according to this study, savings are estimated to be up to 61 percent of water per vineyard on average, that would lead to statewide water savings of approximately 915,000 acre-feet per year, or 297-billion gallons per year. This corresponds to nearly 403-million kilowatt-hours of electricity savings.[2]

Based on the potential electricity savings of 403-million kWh and an average electricity rate of $0.1564 per kWh, the total savings for wine grapes alone can amount to $63 million for California ratepayers.

[1] Source: http://www.arb.ca.gov/fuels/lcfs/workgroups/lcfssustain/hanson.pdf.

[2] Assuming power need of 440 kWh per acre-foot (Source: C. Burt et al., PIER Program report).

LIST OF ACRONYMS

Term/Acronym	Definition
ASHRAE	The American Society of Heating, Refrigeration and Air-Conditioning Engineers
Brix	Degrees Brix
CDFA	California Department of Food and Agriculture
CEC	California Energy Commission
CIT	Center for Irrigation Technology
CSU	California State University
CWGA	California Winegrape Growers Association
EPIC	Electric Program Investment Charge
EPRI	Electric Power Research Institute
ET	Evapotranspiration
GHG	Greenhouse Gas
HVAC	Heating, Ventilation and Air-conditioning
K	Vine Water
NDVI	Normalized Difference Vegetative Index
PAI	Plant Aware Irrigation
PG&E	Pacific Gas and Electric Company
S	Sugar per Berry
SCE	Southern California Edison
SP	Smart Point
T	Transpiration
TAC	Technical Advisory Committee
UC	University of California
VPD	Vapor Pressure Deficit
WDI	Water Deficit Index

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APPENDIX A: Fruition Sciences Approach

Plant Based Measurement versus Atmospheric Measurement

To measure water stress, three main technologies are commercially available. Water-potential measurement at a plant-based level (a destructive technique) and vine sap flow (a nondestructive and real-time technique) have been used for more than 10 years in vineyards (Scholasch et al., 2018). At an atmospheric level, eddy covariance and surface renewal methods have been used to characterize the amount of water vaporized in the atmosphere, which relates to plant transpiration (Rienth and Scholasch, 2019).

Historically in California, water potential has been used to assess plant water stress. In fact, Spinelli et al., 2016 report that "according to a recent Almond Board of California survey, stem water potential is currently being used as an irrigation management tool by 40% of almond growers." However, recent scientific advances have highlighted technical limitations related to the use of water potential to assess plant water stress level and trigger irrigation accordingly.

Since air moisture deficit and soil moisture deficit both influence plant water potential, in the particular case of California, where heat waves are frequent, interpretations of water potential readings can be complex. When measurements are performed on hot and dry days, researchers may find it challenging to assess whether irrigation is needed, even soon after irrigation was applied. During heat wave days, atmospheric vapor pressure deficit (VPD) is higher. VPD measures how much air moisture and air temperature contribute to increased water demand. High VPD can be the source of embolism within a plant's vascular tissues. In turn, embolism creates a hydraulic disconnect between the leaf and the plant water status (Charrier et al., 2016).

Preliminary field observations show that water-potential variations in response to irrigation and heat wave can go in opposite directions, which potentially leads to overly irrigating when water potential is assessed on high VPD days. In fact, over the main irrigation period (May 15 through October 15), an average number of 40 to 50 days of heat wave has been historically reported in Napa Valley over the last six years. In comparison, the average in Bordeaux, France is less than 10 days, and less than six days for five out of the six previous years (based on a regional climatic studies reported by Scholasch, 2019 https://ucanr.edu/repository/view.cfm?article=177703).

Plants close their stomata in response to decreasing water potential, which reduces the amount of water use. Plants' hydraulic failure results from the tension between air and soil water deficit, creating embolism. "Xylem embolism can result from early stomatal closure relative to thresholds of hydraulic dysfunction" (Blackman et al., 2019). Furthermore, Charrier et al., 2016 have demonstrated that in the range of -10 and -15 bars, which is industry standard in California for irrigation threshold in viniculture, leaf petioles can lose between 40% and 80% of their hydraulic conductivity. Over that same range of water potential, shoot hydraulic conductivity loses less than 20%. This phenomenon is called "hydraulic segmentation" and can be compared as if the leaf would act as a hydraulic "fuse." Leaf hydraulic disconnect avoids the propagation of embolism to the whole plant. For that reason, due to embolism, leaf water status is not always connected to plant water status. Notably, the same authors have demonstrated that irrigation does not reverse embolism. Therefore, embolism can cumulate over the course of the season leading to a leaf gradually becoming more hydraulically disconnected from the shoot. Consequently, as the season progresses, and particularly as more heat waves are being experienced, growers should expect more hydraulic segmentation between leaf and shoot. As such, the use of leaf water potential measurement to assess plant water status is less reliable in a more arid climate.

The sap flow measurement technique has been adopted to overcome the challenges and technical limitations of water potential measurements. Two technologies exist to measure sap flow. The Thermal Dissipation Probes method, which is intrusive, is not suitable for commercial use (Vergeynst et al., 2014). The stem heat balance method, however, is considered a reference method to measure vine transpiration (Kustas et al., 2018, Rienth and Schoalsch, in review). It provides continuous and nondestructive measurements that can be performed even if sap trajectory through the stem is tortuous. The measurements are nonintrusive and can directly quantify water stress relative to plant potential transpiration (Pons et al., 2008). It does not confuse transpiration decline with aerodynamic conductance (g_a) decline, caused by wind-speed variations. Because the measurement represents single plants, reduction in T/ET_{ref} is not overridden by high leaf area index from other plants. For those reasons the use of nonintrusive sap flow sensors has been successfully adopted as a practice to drive irrigation strategies (Scholasch, 2018). However, the sap flow methods have some drawbacks. As a single plant measurement is performed, plant-based maximum vine transpiration (potential) is known, but it is difficult to say how representative it is for the whole vineyard scale. Furthermore, in the same vineyard, researchers found that a larger plant size displaying a higher leaf area uses a greater amount of water on a daily basis (Kustas et al., 2018).

The atmospheric method presents an interesting alternative to evaluate water use throughout an orchard or a vineyard. However, California studies in a commercial almond orchard have shown that atmospheric measurements have a low potential for water savings due to a low coupling between atmospheric evapotranspiration (ET) and tree stress (Spinelli et al., 2018).

In vineyards, atmospheric measurements show some limitations to assess vine transpiration and vine stress. First, vine transpiration measurements are difficult to obtain, because vineyard soil heterogeneity increases land surface temperature variability (Knipper et al., 2018.). Second, the partitioning between soil evaporation, cover crop, and vine transpiration is complex (Jiao et al., 2018; Kustas et al., 2018). More specifically, when compared to vine transpiration, atmospheric measurements performed via surface renewal were reported to underestimate vine transpiration before veraison (9%) and to overestimate vine transpiration around veraison (12%) by Poblete-Echeverría et al. (2017). Third, the principle of atmospheric measurement to be measuring water stress from a decrease in ET is also complex under varying wind speeds. Spinelli et al. (2016) reported that with wind speeds exceeding 5 meters per second, it is easier to diagnose a water stress related reduction in ET, whereas on a calm day, low wind and high-water stress may both reduce ET. Fourth, due to the intrinsic variability in soil composition affecting plant leaf area development, vegetative indexes may override water stress indexes. In practice, spots with higher vegetative development may override the effect of water deficit from weaker spots. Also, since water stress level is defined relative to a level of plant potential transpiration, researchers may find it difficult to define what is potential transpiration from a heterogeneous vine population.

Details of the Plant Aware Irrigation System

The Fruition Sciences approach consisted of measuring vineyard data and performing analytics in real time. To that end, different technologies were combined into analytical web-based software. By fusing results obtained through different analytical methods, the approach highlighted synergies between them. The technologies used characterized temporal and spatial variations in plant and fruit indexes. Entire vineyard data collected was combined into a single platform for analysis called Fruition analytics.

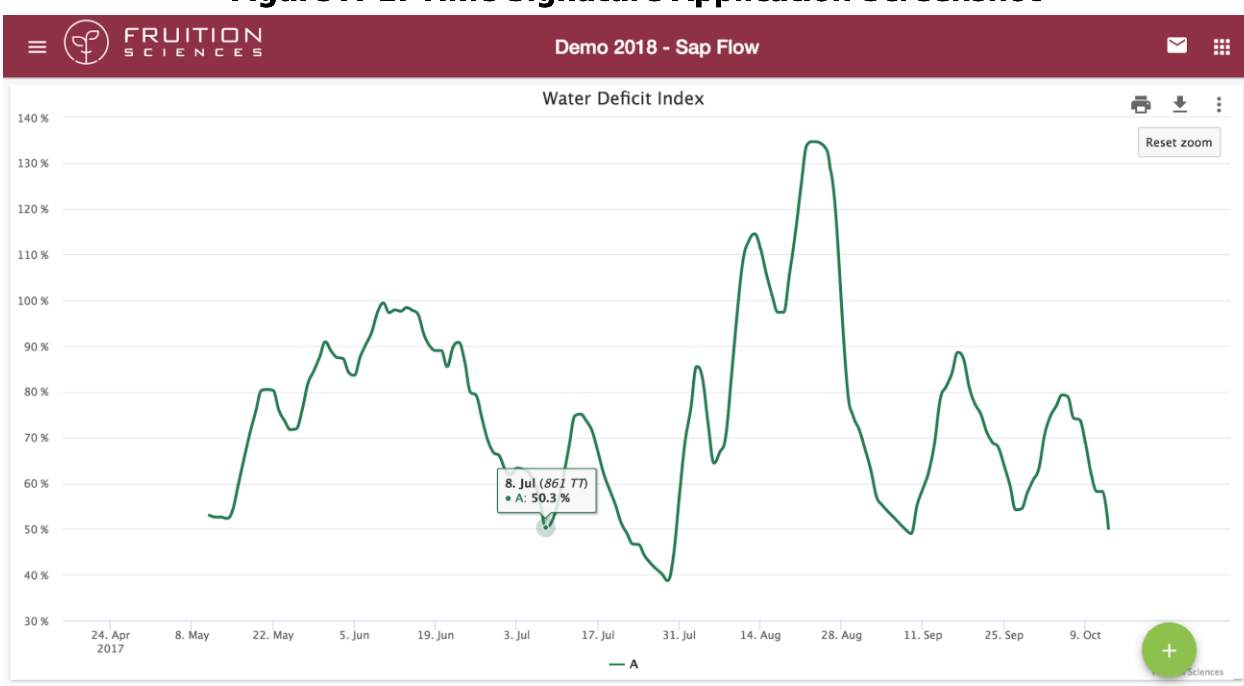
Technologies Used for Field Monitoring

Web Application

Sap flow data alone cannot lead to any irrigation action. However, by developing a web application linking sap flow data to other sources of information describing spatial and temporal changes in key production indices, sap flow data can be turned into action. Analyzed vineyard data results were presented via three web-based applications:

1. Time Signature Application: Designed to enable users to compare time profile of climatic parameters, as well as plant and fruit indexes across various locations and multiple years. Figure A-1 shows a typical profile for any vineyard parameter (here the water deficit index perceived by the plant).

Figure A-1: Time Signature Application Screenshot

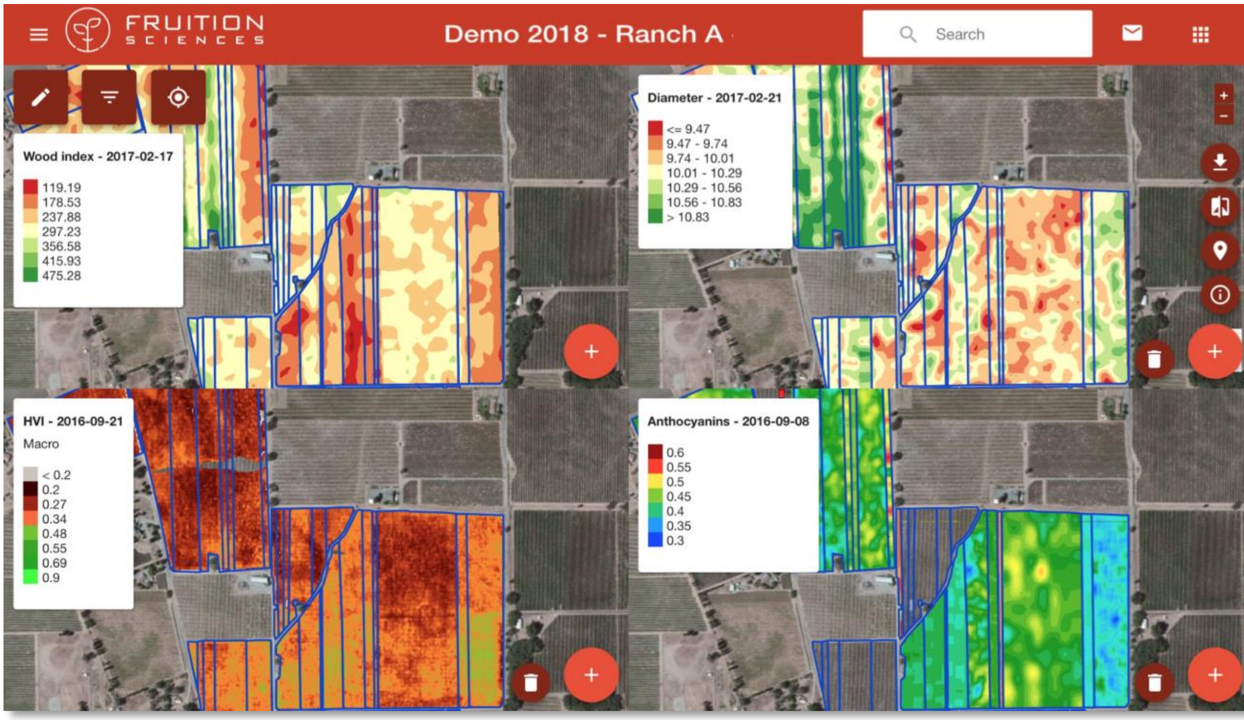


Typical profile for any vineyard parameter (here the water deficit index perceived by the plant).

Source: Fruition Sciences

2. Mapping Application: Designed to enable users to compare maps obtained via different mapping tools and technologies, such as spectral imagery and aerial view, fluorescence and multiplex map, and laser and Physiocap map. Figure A-2 shows a typical aggregation of maps corresponding to the vineyards spatial structure of relevant parameter such as wood index, shoot diameter, lead area (HVI); Anthocyanins (i.e. fruit color concentration).

Figure A-2: Mapping Application Screenshot

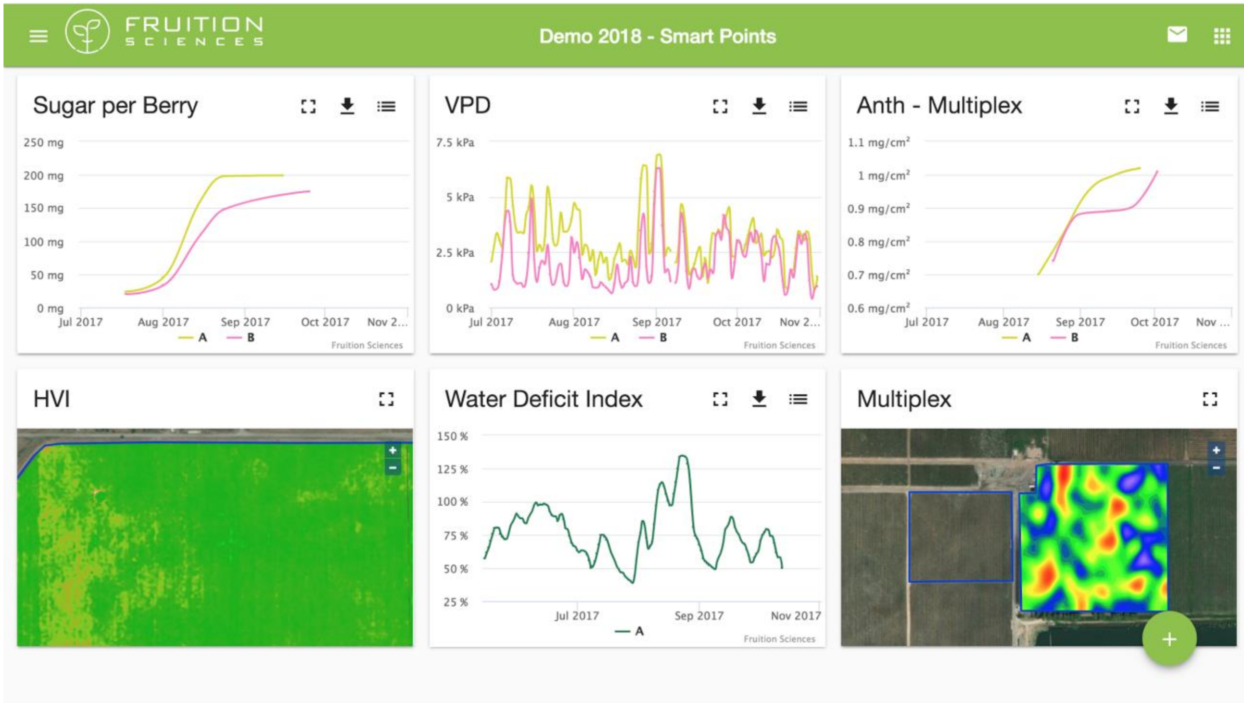


Typical aggregation of maps corresponding to the vineyard spatial structure of relevant parameter such as wood index, shoot diameter, leaf area (HVI); Anthocyanins (i.e. fruit color concentration).

Source: Fruition Sciences

3. Dashboard Application: Designed to combine maps and signature for at-a-glance comparison of spatial and temporal information. Figure A-3 shows a typical vineyard dashboard displaying multiple information sources (spatially and temporally explicit).

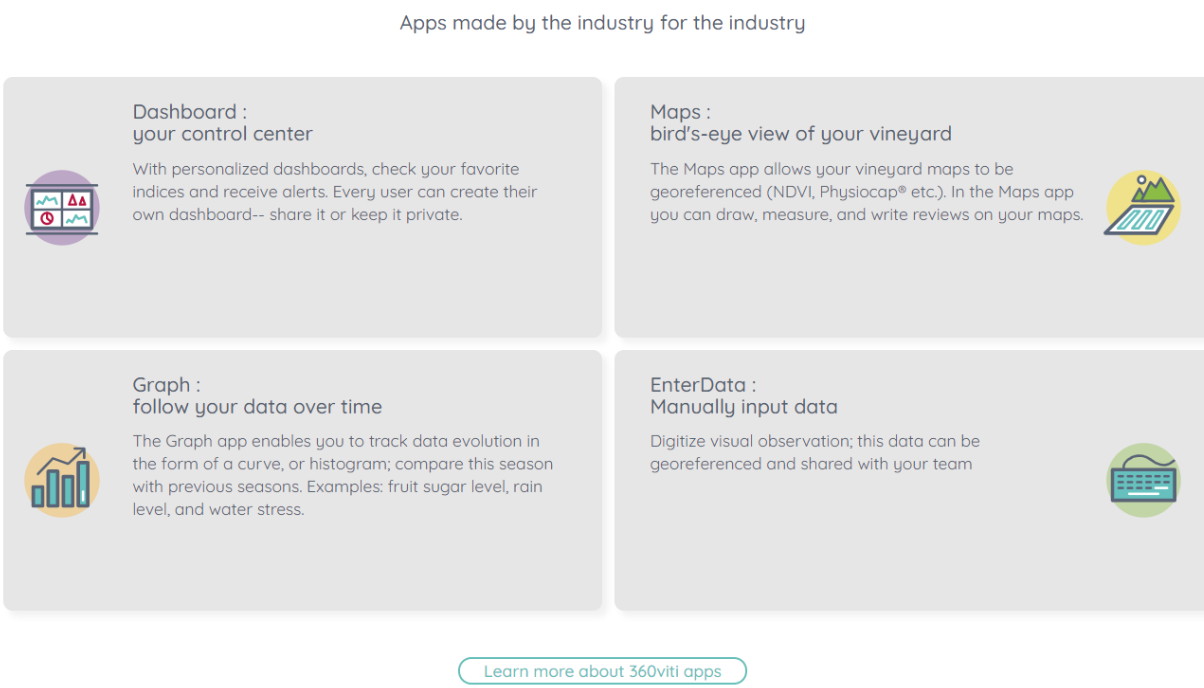
Figure A-3: Dashboard Application Screenshot



Typical vineyard dashboard displaying multiple information sources (spatially and temporally explicit).

Source: Fruition Sciences

Figure A-4: 360viti Apps



Examples of apps offered by Fruition Sciences, Dashboard, Graphs, Maps.

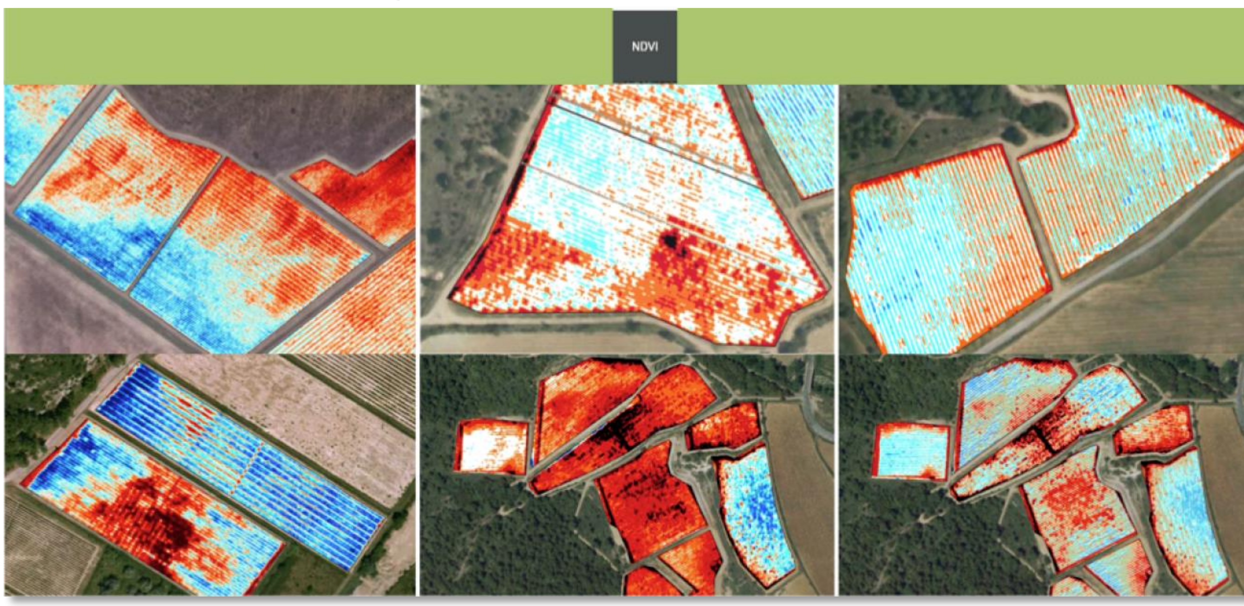
Source: Fruition Sciences

Mapping Tools

Aerial Photographs

Aerial pictures over multiple fields were obtained at different dates during the season and integrated within the application to compare with historical maps. Normalized Difference Vegetation Index (NDVI) and Hyper Spectral Narrow Band Vegetation Index (HVI) maps were used to show the spatial structure of leaf area ground coverage. Both NDVI and HVI maps describe spatial variations of a vegetation index related to chlorophyll content above the ground. NDVI was obtained using a multispectral camera; HVI images were obtained using a hyperspectral camera. The analysis of successive aerial pictures taken over the same field revealed potential variations in leaf area spatial distribution in response to management operations such as irrigation. Thanks to aerial pictures, plant water use variations measured at an individual scale can be interpreted in the context of the spatial distribution of leaf area measured at the whole field scale. Aerial maps were used to interpret and compare water use time variations as a function of leaf area size. Examples of aerial maps in Figure A-4 show the spatial distribution of the NDVI index using Fruition Sciences analytics.

Figure A-5: Aerial Map Screenshot



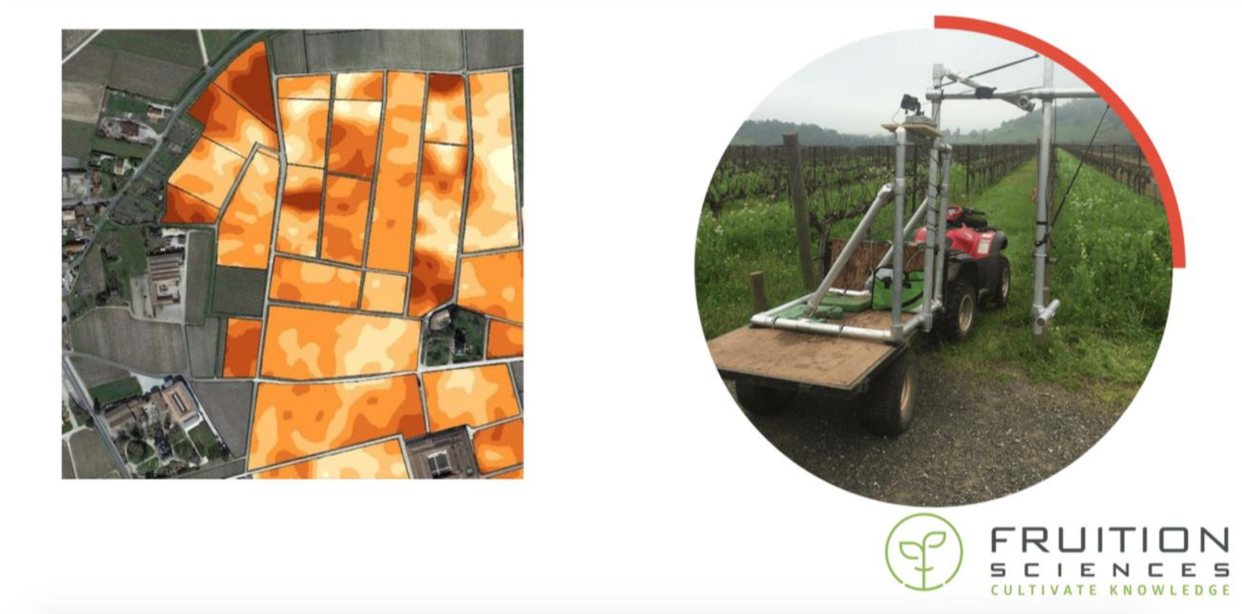
Examples of aerial maps showing the spatial distribution of NDVI index using Fruition Sciences analytics.

Source: Fruition Sciences

Physiocap Measurements

Physiocap measurements were performed during the winter to characterize vineyard spatial structure prior to the introduction of PAI treatment. The maps generated described spatial variations observed in the amount of shoots per vine, the diameter of shoot (mm^2), and the wood index (mm^2/m^2), which reflects the amount of stem section per unit of ground area. These indices were useful to show the shape and size of uniform areas when no leaves were on the plant. Unlike aerial pictures, Physiocap maps reflected the spatial distribution of plant perennial structure. Physiocap maps were used to optimize field-sampling strategy considering field heterogeneity, and to interpret and compare water use time variations as a function of plant perennial size. Figure A-5 illustrates how the Physiocap maps were created.

Figure A-6: Physiocap Mapping (Left) and Device (Right)



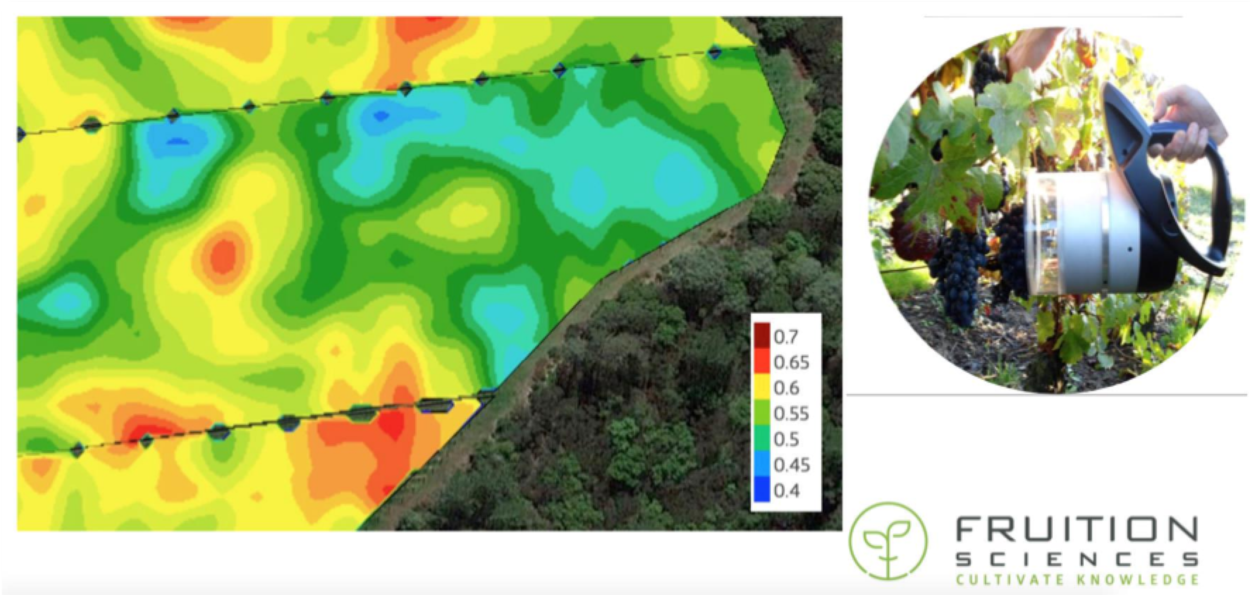
Map showing wood index and view of device for field data collection.

Source: Fruition Sciences

Multiplex Measurements

Multiplex maps were used to optimize the field-sampling strategy for monitoring berry ripening. By illuminating berries with specific wavelengths such as show in Figure A-6, the team defined total anthocyanins accumulated per berry skin surface area ($mg \cdot cm^{-2}$). Total anthocyanins are compounds responsible for the density of berry coloration accumulated during the fruit ripening period. Maps were generated by scanning according to a systematic grid (including approximately 2,500 clusters per acre) showing the spatial variations of berry color concentration. Sugar accumulation and color accumulation were related during fruit ripening.

Figure A-7: Multiplex Mapping (Left) and Device (Right)



Map showing fruit skin color concentration (total anthocyanin concentration) obtained by fluorescence measurement collected in the field.

Source: Fruition Sciences

Signature Tools

Climatic Measurements

Climatic measurements were performed via weather stations installed in the field. Key parameters such as temperature, vapor pressure deficit, light, and rain were continuously monitored.

Berry Weight and Sugar Concentration

Berries were sampled manually, and measurements were performed in the lab. Results were displayed and analyzed via the web application.

Sap Flow Sensors

Figure A-7 shows a schematic view of sap flow sensor.

Vertical conducted heat loss (Q_v) was decomposed as:

$$Q_V = q_u + q_d$$

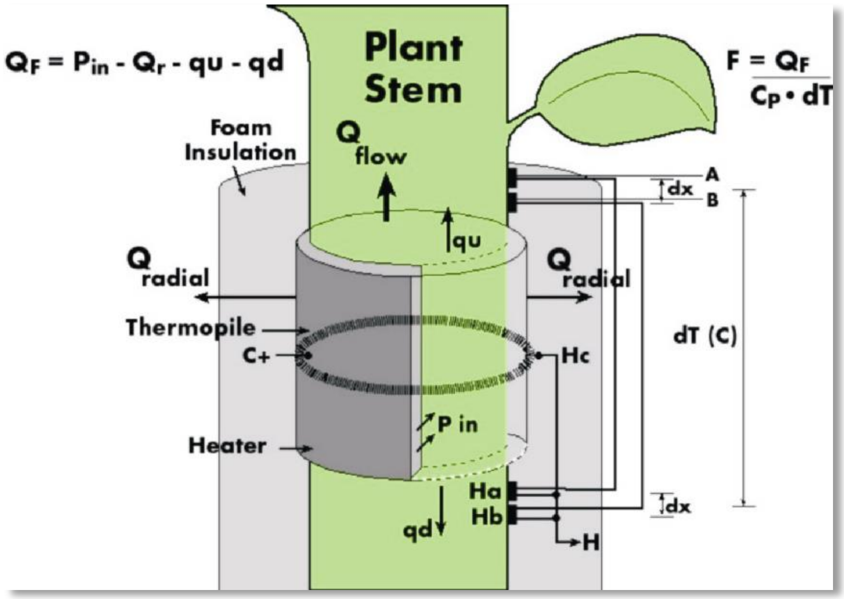
Where

$Q_V = vertical\ conducted\ heat\ loss\ (J)$

$q_u = upper\ heat\ loss\ (J)$

$q_d = downwards\ heat\ loss\ (J)$

Figure A-8: Schematic View of Sap Flow Sensor



Picture shows heat fluxes measured inside the sap flow sensor.

Source: Dynamax, Inc.

Heat energy losses through vertical conduction in the wood and radial losses through the insulation were measured and subtracted from the energy input. The remainder was the heat energy in the water passing through the heated zone. The heat energy in the water was directly proportional to the amount of water flowing as 4.18 kJ of energy was needed to increase the temperature of 1kg of water by 1°K. Thermocouples were positioned to be in direct contact with the xylem, but are not inserted into it. According to the stem heat balance method, sap flow was computed as follows:

$$F = \frac{(P_{in} - Q_v - Q_r)}{C_p} \times \Delta T \ ({}^{g}/_{s})$$

Where

$F = sap\ flow(g \cdot s^{-1})$

$P_{in} = heat\ applied\ to\ the\ stem\ (J)$

$Q_v = vertical\ conducted\ heat\ loss\ (J)$

$Q_r = radial\ energy\ from\ the\ stem\ (J)$

$C_p = constant\ for\ water\ heating\ capactiy\ (4.186 J \cdot g^{-1} \cdot {}^{\circ}C^{-1})$

$\Delta T = Temperature\ difference\ above\ and\ below\ the\ strip\ heater\ ({}^{\circ}C)$

Radial heat losses (Q_{radial}) defined as:

$$Q_r = K_r \times E$$

Where

$K_r(W \cdot mW^{-1}) = single\ sheath\ conductance$

$E(mV) = radial\ thermopile\ input$

Assuming negligible sap flow at night K_r was as follows:

$$K_r = \frac{(P - Q_v)}{E}$$

Grimme et al. (1995) found that K_r could be estimated from the daily minimum of apparent sheath conductance (K_a). Apparent sheath conductance (K_a) was evaluated for each gauged stem and for every measurement.

For each experimental site, sap flow was measured on the selected vines per plot using the Dynamax logger system (Dynamax, Inc.; Houston, Texas,). Each vine was equipped with one sensor. Prior to the sap flow sensor installation, the team removed the bark and smoothed the section with fine-grain sandpaper (index 150) to optimize contact between the wood and the heat strip. Canola oil was sprayed in two coats around the circumference of the trunk where the sensor was attached. After the solvent evaporated, the residue acted as a release compound, which prevented the sensor from sticking to the trunk. The residue also avoided the use of insulating compound directly on the stem. The thick layer of insulating compound was impervious to moisture and air, but when directly applied to the stem, it can cause the dying off of tissues. Around the stem or trunk section, the team applied the electrical insulating compound Dow Corning ®-4 (Dow Corning Corporation; Midland, Michigan). Then the thermocouples for sensing the respective temperature differentials were pressed against the outsides of the trunk or stem. To avoid irregular basal trunks or ground temperature gradient effects, sap flow gauges were installed at least 45 cm above ground level, insulated with a double layer of bubble wrap covered with aluminum foil. Then, the whole trunk was also covered with a layer of bubble wrap and reflective aluminum foil to minimize the effect of thermal fluctuations on the sap flow measurements caused by ground radiations. Output from each sap flow sensor was scanned and logged every 15 minutes. Sap flow rates measured on each vine were averaged on an hourly basis.

Total sap flow of each vine was calculated as the product of sap flux density and cross-sectional sap wood area at the point of measurement. According to the work of previous authors with vines of similar age, the whole cross-sectional area, excluding the bark, can be considered as sap wood. Various expert methods were applied to filter out weak or erroneous signals. Sap flow measurements were scaled at the plant level according to plant leaf area estimates corresponding to each sensor. The volumetric flux per vine ($g \cdot h^{-1}$) was converted into $mm \cdot h^{-1}$, taking into account the respective area of ground per vine. Figure 8 shows a sap flow sensor installed on a plant.

APPENDIX B:
Historical Irrigation and Yield Manual Records

Table B-1: Historical Total Irrigation Reported (mm)

Site-Block	2013	2014	2015	2016
Wente-Karl	173.7	287.4	552.3	275.79
Wente-Mel	163.4	228.2	513.6	228.47
Wente-Reuss	94.9	301.72	232.79	175.92
Wente-Smith	95.75	141.5	193.21	163.09
Gamble-8	—	—	—	—
Gamble-9	—	80	130	134
Gamble-11	—	—	—	—
Stanly-1C	—	—	—	—
Stanly-5J	—	—	—	—

Source: Winery Irrigation Records

Table B-2: Historical Yield Reported (tons/acre)

Site-Block	2010	2011	2012	2013
Wente-Karl	—	—	—	—
Wente-Mel	—	—	—	—
Wente-Reuss	—	—	2.44	5.87
Wente-Smith	—	—	1.22	10.67
Gamble-8	2.68	2.98	5.37	4.41
Gamble-9	0.99	2.45	2.59	3.10
Gamble-11	1.96	1.11	4.19	2.17
Stanly-1C	1.75	1.30	3.21	3.30
Stanly-5J	3.32	3.88	4.18	5.72

Source: Winery Grape Yield Records

Additional Appendices

Appendices C and D are available under separate cover (Publication Number CEC-500-2021-011-APC-D) by contacting Karen Perrin at Karen.Perrin@energy.ca.gov.