DISCLAIMER

This project was conducted with financial assistance from a grant from the Metropolitan Water District of Southern California (Metropolitan) and the Southern California Gas Company through Metropolitan's Innovative Conservation Program (ICP). The ICP provides funding for research to help document water savings and reliability of innovative water savings devices, technologies, and strategies. The findings of this project, summarized in this report, are solely from the project proponent.

ICP Project: New technologies for improved agriculture water use efficiency

Final Report

Agreement No. A0-5263

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Submitted on December 24, 2021

Introduction and scope

Irrigating right amounts of water during the growing season is important for optimizing crop results and water use. Farms can save water early in the season by monitoring the soil moisture (water storage for the Winter rains) and start the irrigation season only when the rain water has been depleted.
Similarly, keeping track of crop water use during the peak water use months (June, July, August) is important to avoid under-irrigation and crop loss due to water stress. A potential 30% yield loss due to insufficient irrigation would amount to USD 1 Billion loss in crop value for the California wine industry.

This project aimed to validate technologies by offering case study examples to improve agriculture water use efficiency. The technologies include:

- In situ sensor based soil water potential & soil moisture measurement
- Remote sensing (satellite) based soil moisture measurement of the root zone
- CIMIS weather station based estimated actual crop water use using default crop coefficients
- Remote sensing (satellite) derived actual crop water use using a surface energy balance
- Variable irrigation automation using daily actual crop water use data

Vinduino will determine the effectiveness of each technology used in this project based on:

- irrigation water efficiency (yield/gallon)
- reduction of applied water
- reduction of labor

The project recorded in situ soil moisture sensors data together with satellite remote sensing data for crop fields selected for this project. Fields are selected for having the same grape varietal, and automated or manual irrigation. At the end of the season, crop results will be recorded as well as the amount of irrigated water used.

This project monitored 8 vineyard blocks and 3 avocado irrigation blocks during the 2021 growing season.
All locations used remote satellite sensing covering a total of 110 acres and in-situ soil moisture sensors.
Crop yield and quality as influenced by the type of irrigation operation (manual or automated) was monitored by bi-weekly sap analysis and end-of season harvested fruit weight.

	Purpose	**Technology 1**	**Technology 2**
Soil moisture	How often to irrigate	In situ sensors	Remote sensing (satellite)
Crop water use	How much to irrigate	CIMIS ETo x Kc	Remote sensing (satellite)
Irrigation	Crop yield and quality	Manual operation	Automated

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Conclusions Summary

Soil Moisture

Satellite soil sensor data was compared against soil moisture sensors in the fields, pressure bomb measurements, and field observations.
Remote soil moisture measurement using satellite data did not provide useful guidance for the best frequency of irrigation. During the project we found that “Product A” provided a consistently wrong indication of fields being too dry and in need of additional irrigation, even in well watered situations..

Although physical sensors require hardware in the field, installation, and maintenance, their data is regarded closer to the truth, especially when averaged over multiple sensors.
The team concludes that remote satellite soil moisture data is not sufficiently mature to be a viable alternative for soil moisture sensors in the field.

Crop Water Use

Crop water use was estimated using tools available to the average grower. In this project we used soil moisture trend, frequent pressure bomb measurements (plant water stress), and recorded the applied volumes of irrigation water per field. This project had no access to research grade measurement of evapotranspiration, such as flux towers.

Remote Satellite “Product A” crop evapotranspitation (ETc) data was consistently 50% lower in vineyards, but did closely follow the actual water use in the avocado grove. This technology appears to work better in orchards.

The most consistent crop evapotranspitation (ETc) estimates for vineyards and orchards came from using IrriSat crop coefficient (Kc) in combination with reference evapotranspiration (ETo) data obtained from Spatial CIMIS (California Irrigation Management Information System, a network of weather stations in California).
Outside of the early season where weeds dominate the planted area, IrriSat Kc tracks closely with manual Kc estimates and can save labor and accuracy by automatic collection of Kc data.

ETc estimation in combination with soil moisture sensing as feedback provided usable results for irrigation volume guidance. In the tested avocado grove, managing irrigation volume by keeping soil moisture at the same level proved to be equally effective as the evapotranspiration method.

Using automated irrigation, valve operation can be controlled with one minute accuracy. This eliminates the “human error”, sometimes deviating hours from the desired irrigation time, introduced by manual operation of irrigation valves. Water meter feedback allows for flow rate calibration of the used emitters

Irrigation Crop yield and quality

As part of the study we tested plant sap and soil samples on alternate weeks, so on one week we would do sap analysis and the following week we would do soil analysis. Our goal of the analysis was to see if we could detect a relationship between plant metabolic activity and chemo-typical expression and soil plant interface relationships as the vines provided additional carbon source and quorum sensing molecules to the soil microbiome.
Yield comparisons on grapes are not relevant within the first year of an experiment as grape physiology sets the potential apical cells for the following year’s fruit clusters just post fruit set of the current year. Hence, the genetic potential for yield is set over a year and a half in advance and is not a reliable marker except in long-term study.

It has been our experience in vineyards that when adjusting plant nutrient balance through foliar and fertigation mixes, the changes in the soil do not occur until the second or third season. This same trend proved to be consistent as is indicated by the soil health calculations of Block Nine Wilson Creek, which has been in a program of plant sap analysis and nutrient supplementation for four years versus the experimental van der Lee blocks one through four which have been in a program of plant sap analysis and nutrient supplementation for less than one year.

The Wilson Creek block nine was consistently higher in virtually all soil health categories however we did see plant critical points of growth similarity between the blocks that gives us a level of confidence that we will see a correlation result in the future. As far as seeing a specific correlation between the irrigation scenarios of irrigating one time per week, two times per week, or four times per week, the current data does not offer any indication that there is much of a difference. However we did not expect to see much per our prior experience with the timeline of creating biological regeneration and our primary goal in establishing these testing protocols was to make sure that we had worked out a system of testing and correlation between sap analysis and soil plant analysis.

Labor Savings Estimate

Irrigation

Assuming a typical irrigation management area of 2 acres, and 2 irrigation cycles per week, we estimate the following cost savings per growing season for an off-premise vineyard:
Irrigation season: April to October, = 56 events to open irrigation valves, and 56 events to close. For simplicity, we exclude off season irrigation events. Cost per valve operation: $ 15 (labor and transport).
Total irrigation operation cost per season per irrigation management area: $ 1,680.

Soil moisture monitoring

Manual monitoring of soil moisture using tensiometers requires on-site access for meter reading and maintenance at least once per week. Following previous assumptions for labor and transport cost, and 28 events for weekly on-site sensor reading during the growing season, the cost for soil moisture monitoring per season irrigation management area: 28 * $15= $420.

Appendix A, Study Setup

Study site locations and description

<u>Lassley vineyard</u>
Address: 32850 Vista de Oro Temecula, CA92591

This vineyard has 15.3 planted acres with Cabernet sauvignon vines.
This will be used as a control site for manual irrigation.
For soil moisture measurement full "Product A" (satellite) coverage will be compared with 3 x in-situ soil moisture sensor stations and CIMIS ET data.

<u>Scaldione vineyard</u>
Address: 36051 E Benton Rd Temecula, CA92590

This vineyard has 13.1 planted acres, of which 3.7 acres with Cabernet sauvignon vines.
This will be used as a control site for manual irrigation.
For soil moisture measurement full "Product A" (satellite) coverage will be compared with 4 x in-situ soil moisture sensor stations and CIMIS ET data.

<u>van der Lee vineyard</u>
Address: 36615 E Benton Rd Temecula, CA92592
This vineyard has 4 planted acres with Cabernet sauvignon vines.
This will be used as a test site for 4 x automated irrigation irrigation blocks.
For soil moisture measurement full "Product A" (satellite) coverage will be compared with 1 x in-situ soil moisture sensor stations and CIMIS ET data.

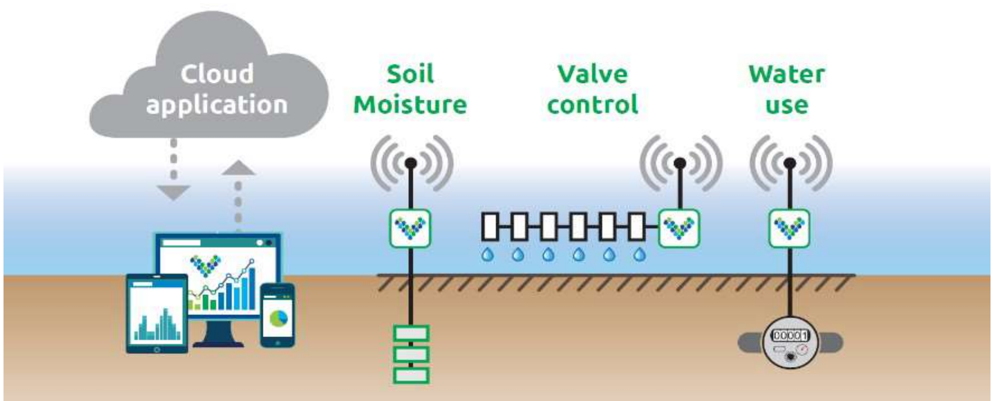
<u>Wilson Creek vineyard</u>
Address: 36615 E Benton Rd Temecula, CA92592
This vineyard has 64 planted acres, with a wide range of grape varietals. We will use two comparable blocks with Cabernet Sauvignon vines as control block (Block 4, 2.6 acres) and test block for irrigation automation (Block 9, 3.1 acres)
This will be used as a test site for 4 x automated irrigation irrigation blocks.
For soil moisture measurement full "Product A" (satellite) coverage will be compared with 9 x in-situ soil moisture sensor stations and CIMIS ET data.

M&H Avocado Ranch
Address: 48725 Via Vaquero Temecula, CA 92590
This avocado grove has 13.1 planted acres with a total of 1609 trees. This will be used as a test site for 3 x automated irrigation irrigation blocks. Here is no control block, so we will need to rely on historical data for water use and crop yield
For soil moisture measurement full "Product A" (satellite) coverage will be compared with 6 x in-situ soil moisture sensor stations and CIMIS ET data.

Equipment description

Wireless network

Vinduino uses a long range wireless digital network, operating in the license-free 915 MHz band. The radio technology used is known as “LoRa”. It is optimized for long range (up to 10 miles) communication of small data packets (such as sensor in formation or valve commands), in an energy efficient way. Units in the field operate with energy from a small built-in solar panel.
For this project we have set up our own internet network servers and operate multiple access points to provide sufficient wireless coverage of all the locations. Wireless access points are installed at the following locations: Lassley vineyard, M&H Avocado, Van der Lee vineyard, and at Wilson Creek.
The access points connect the sensor and controller nodes to a cloud application on the Internet.



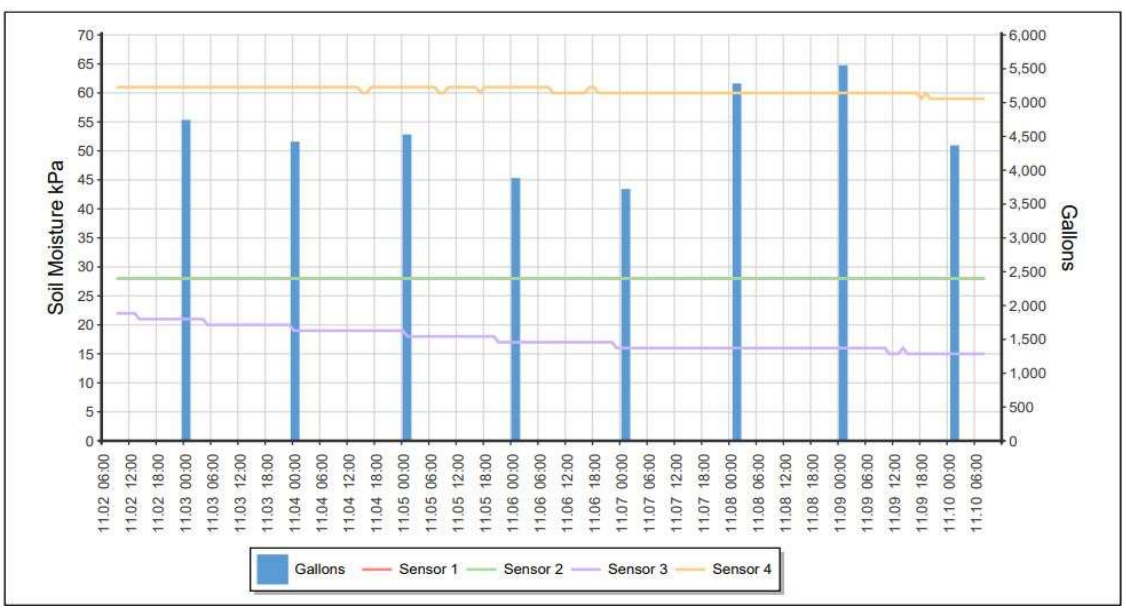
For more information about Lora : https://blog.semtech.com/winemakers-enjoy-the-fruits-of-their-labor-with-vinduinos-lora-based-sensors

Soil moisture sensors

The Vinduino soil moisture sensor node (left in below picture) can connect up to 4 x soil moisture sensors. For this project we only need 2 sensors (Watermark SS200) per location, installed at 2 and 3 feet depth. This is where vines typically take up most of the available water. Avocado has shallow roots, and we installed sensors there at 12” and 18”.
The station works on a solar charged battery, and reports sensor data every 15 minutes.
For this project we have an interest in shallow and deep soil temperature, so the stations and cloud software will be customized to support 2 waterproof temperature sensors.

Soil moisture data is being captured and recorded in the Evineyard and eOrchard cloud application.
Below chart is an example of soil moisture information (kPa) taken from Van der Lee vineyard block 2.
Sensor 2 is at 2 feet, sensor 3 is at 3 feet depth. Because of the integrated water meter feature, we can provide combined reports showing soil moisture and applied irrigation water volume.

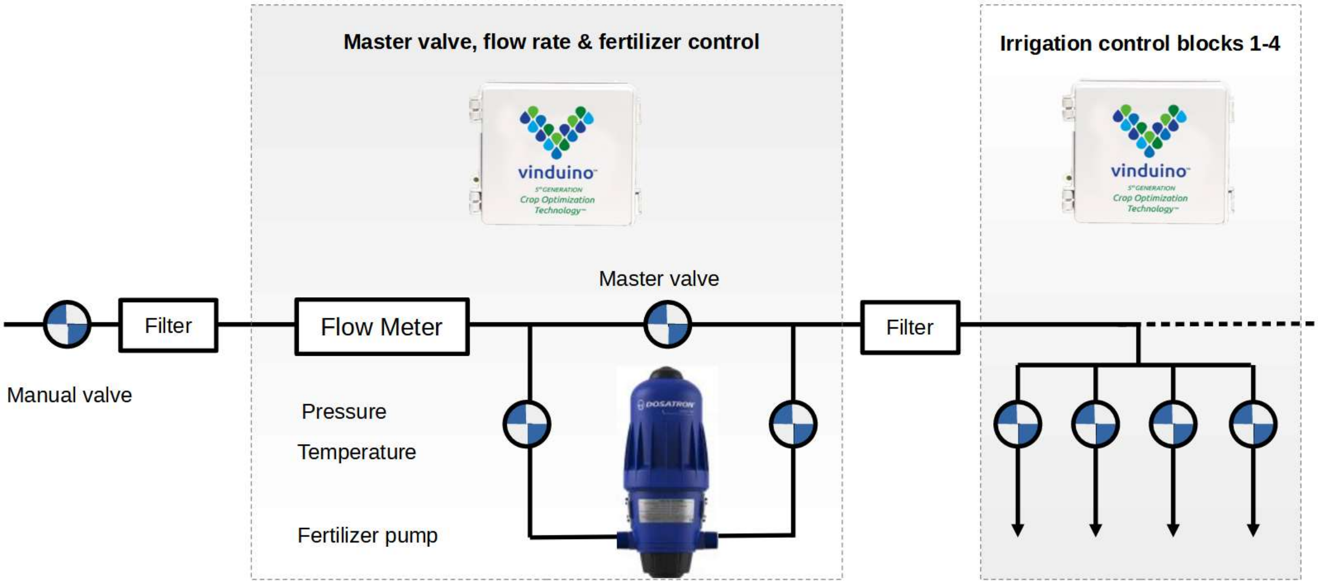
Soil Moisture Level and Irrigation for Sensors CS Block 2



Irrigation automation

Using the LoRa network, we can control irrigation and fertilizer. One wireless node (right in above picture) can control up to 4 irrigation valves and one master valve. Irrigation events can be set on-line to start at any day and time.
Reference ET data obtained from the CIMIS weather station network, or "Product A", is used to optimize irrigation time to match the vines daily water use. Alternatively, a grower can opt to set a fixed irrigation time.

Optimally, multiple controllers can work in concert to automate master valve (or pump) control, fertilizer control and irrigation control. Below is a schematic diagram and picture of the installation used at Van der Lee vineyard.

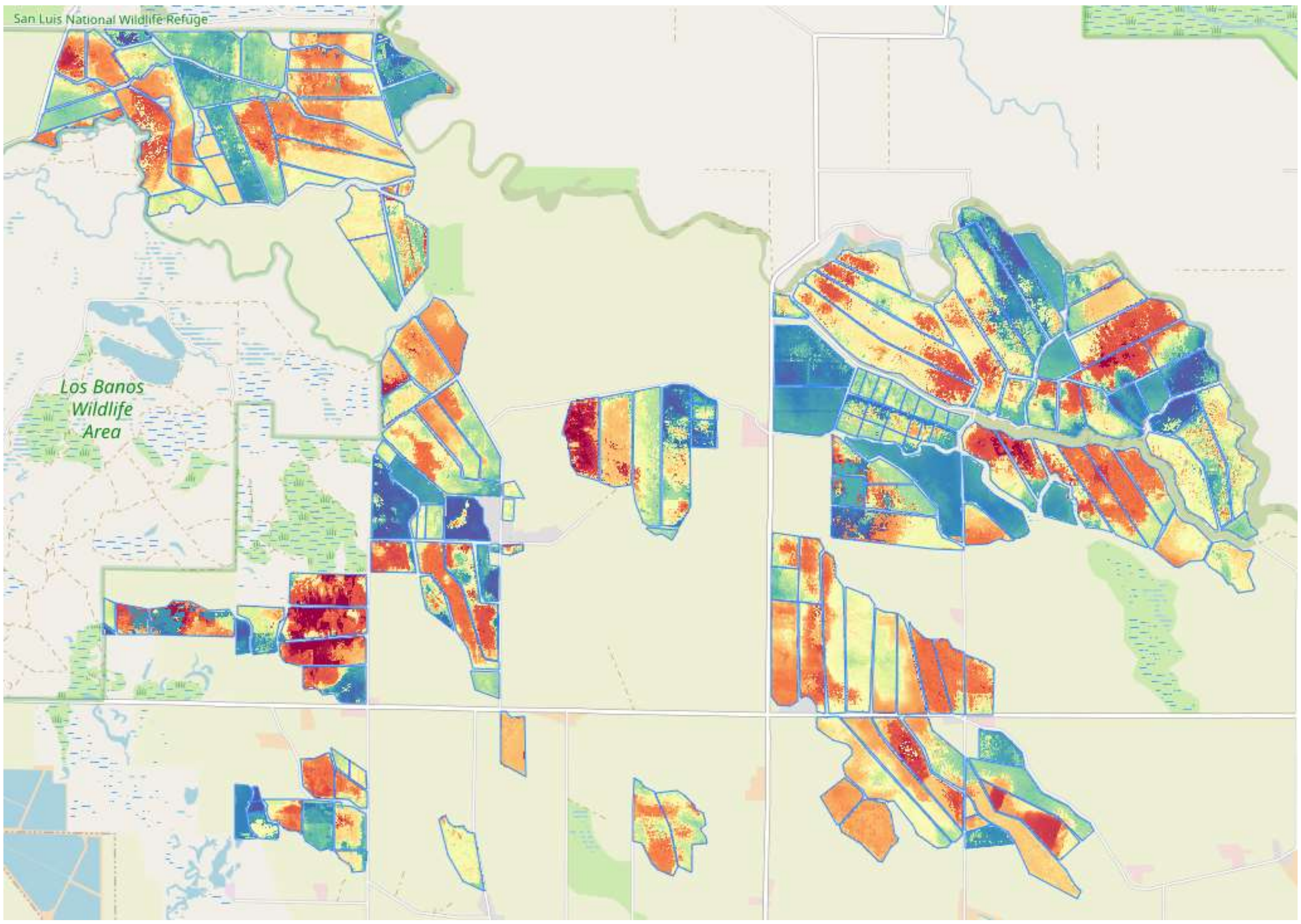


Satellite data

Satellite data products potentially offer game changing cost and performance advantages over traditional sensors in the field.
Product A, is the first product to provide highly detailed soil water potential and soil moisture data in the root zone on the basis of thermal images using satellite remote sensing technology. In addition the actual crop evapotranspiration and a crop production estimation is delivered.

As comparison we also included the free IrriSat satellite service, which product features spatial information to support farmers with making irrigation decisions.

Below picture shows an example of spatial satellite remote sensing of root zone soil moisture in the field of a California 11,000 acre farm. Red is considered to dry, blue colored field are considered too wet.



Data collection plan

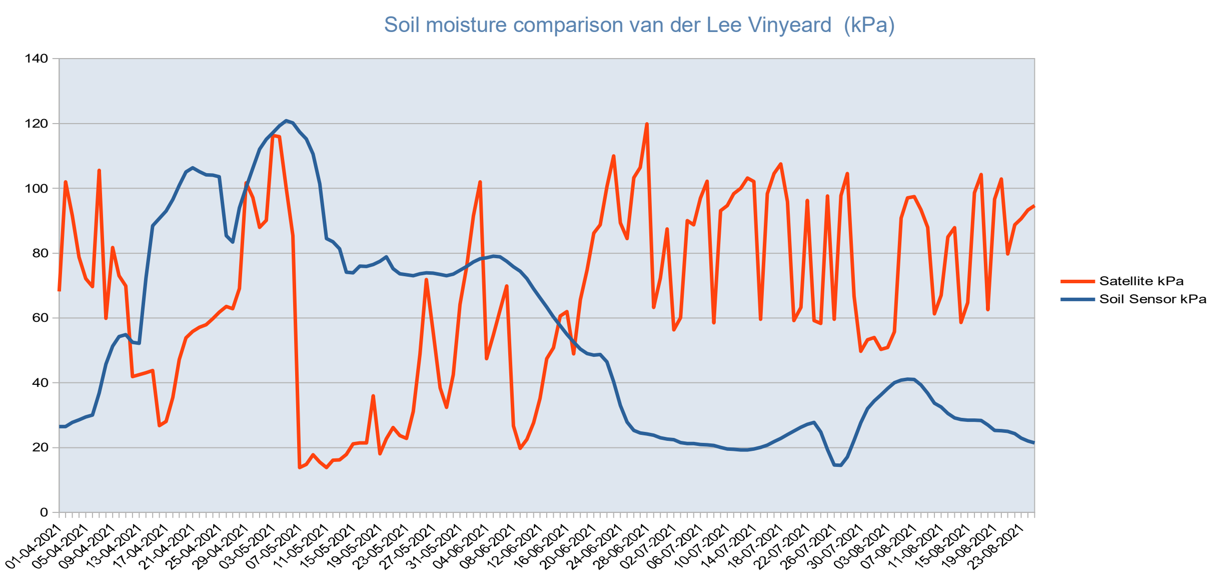
		WC-4	WC-9	VDL-1	VDL-2	VDL-3	VDL-4	LSLY	SCD	M&H
	Varietal	Cab Sauv	Cab Sauv	Cab Sauv	Cab Sauv	Cab Sauv	Cab Sauv	Cab Sauv	Cab Sauv	Avocado
	Acres	2.6	3.1	1	1	1	1	15.5	3.7	13.1
Irrigation related										
Irrigation volume (Etc)	CIMIS	yes	yes	yes	yes	yes	yes	yes	yes	yes
	Irriwatch	yes	yes	yes	yes	yes	yes	yes	yes	yes
Controlled Irrigation	Vinduino system	control	automated	automated	automated	automated	automated	control	control	automated
Irrigation frequency		2 x a week	2 x a week	2 x a week	2 x a week	4 x a week	1 x a week	2 x a week	2 x a week	as needed
Pressure bomb analysis		weekly	weekly	weekly	weekly	weekly	weekly	---	---	---
Soil moisture + temp	Vinduino system	yes	yes	yes	yes	yes	yes	yes	yes	yes
Bi-weekly sap analysis		yes	yes	yes	yes	yes	yes	yes	yes	
Soil health										
Haney soil respiration		monthly	monthly	monthly	monthly	monthly	monthly	1 x	monthly	
Soil analysis 1 x	Gross essay			yes	yes	yes	yes	yes	yes	
	CEC			yes	yes	yes	yes	yes	yes	
	Saturated paste			yes	yes	yes	yes	yes	yes	
End of season data	Yield/acre									
	Yield/HCF									
	HCF/acre									
	Brix/pH/TA									
	Fruit quality									

Appendix B, Data & analysis

Vineyard data

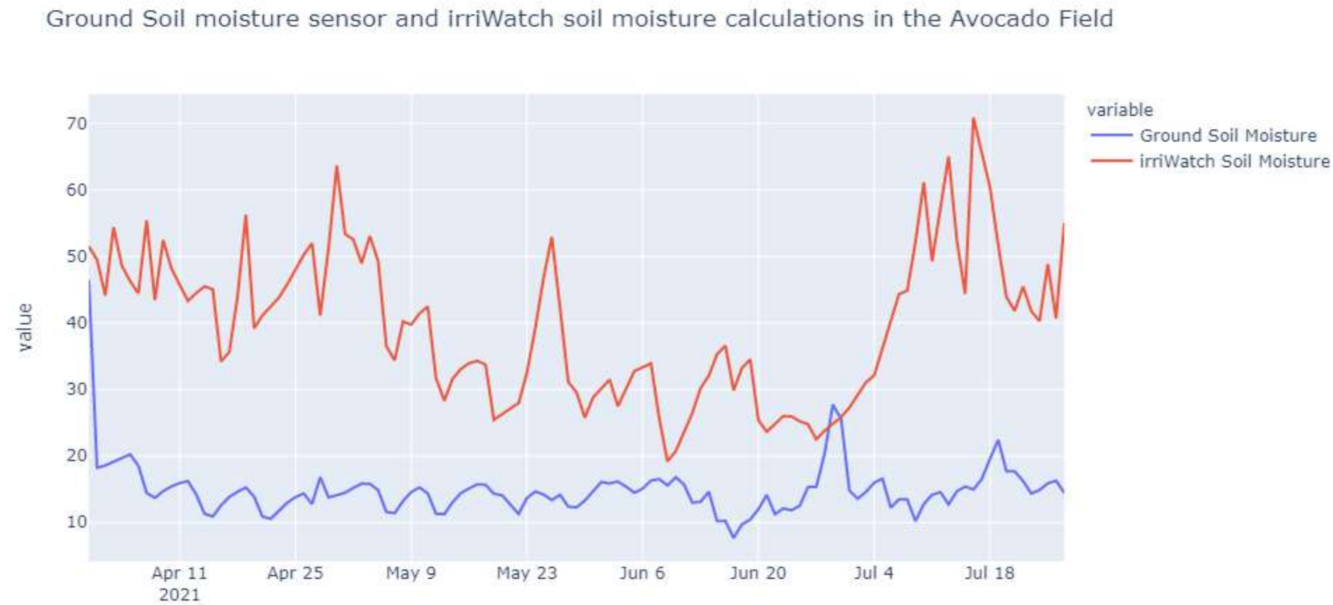
Comparing Satellite and in-situ sensors at Wilson Creek field 4, we find that the satellite data shows low available water levels in the Spring and Mid-Summer. For vineyards, good practice for avoiding plant water stress is to keep the soil water potential level below 50 kPa. The soil sensors indicate that this practice was met during the whole monitored season. This was confirmed with pressure apparatus measurements.
For this field, the satellite data was indicating too low soil moisture, and following this data for irrigation would lead to over-irrigation.

A similar comparison between the satellite estimated root zone soil moisture and field based sensors is shown in below chart. This chart represents data from the Van der Lee vineyard where the sensor soil moisture data is calculated from the average of 8 sensors installed in the wine grape root zone at 4 locations. The satellite data represents the whole vineyard. Also here we see that from June onwards, the satellite data consistently shows low soil moisture (= high kPa numbers), where the actual sensor data, supported by pressure bomb test, show low water stress/sufficient plant available water.



Avocado data

The shown in-situ soil water potential is the average of 12 actual sensors (12 and 24" deep) at 6 locations. During the season the soil moisture was well managed (blue line) between 20-30 kPa. The satellite data provided consistently higher numbers without apparent correlation to the soil sensor data.



Soil Moisture data, Conclusions

From the test data observed in all field and crops, we find that the "Product A" satellite data obtained gave a consistent wrong indication of the fields being too dry and in need of additional irrigation. The soil sensor data was compared against pressure bomb measurements, soil moisture sensors, and field observations. The team concludes that the soil moisture data as reported by the "Product A" satellite system is not usable for irrigation management applications.

A potential advantage of using remote satellite sensing technology is that there is no hardware, installation, and maintenance needed. Also, remote sensing allows for spatial information, in this case offering a 30 x 30 meter resolution. Unfortunately, the data accuracy was not usable for irrigation management purposes.

Local soil moisture sensors are still the best source of irrigation management data, especially when averaged over multiple sensors and locations.

Crop water use data, analysis

The amount of required irrigation water is often determined by calculating the estimated plant water use.
The standard practice to calculate daily plant water use is to find the local reference evapotranspiration (ETo) and multiply this by the crop coefficient. (ETc = ETo x Kc).
While there are multiple sources for the reference ETdata, such as the CIMIS weather station network in California, the crop coefficient is often done by making a manual estimate or text book lookup.

For this grant, we have used the method developed by Larry E. Williams (UC Davis). The relationship of canopy size and sunlight exposure to grapevine water consumption has been extensively studied by Dr. Larry Williams in California. His research has shown that grapevine crop coefficients can be readily estimated for a vineyard by estimating the percentage of the vineyard area that is shaded. The percent shaded area must be estimated during the solar noon hour (between 12:30 and 1:30 pm,) by measuring the average width of shaded area beneath the vine row. We have found that this method also works for tree crops.

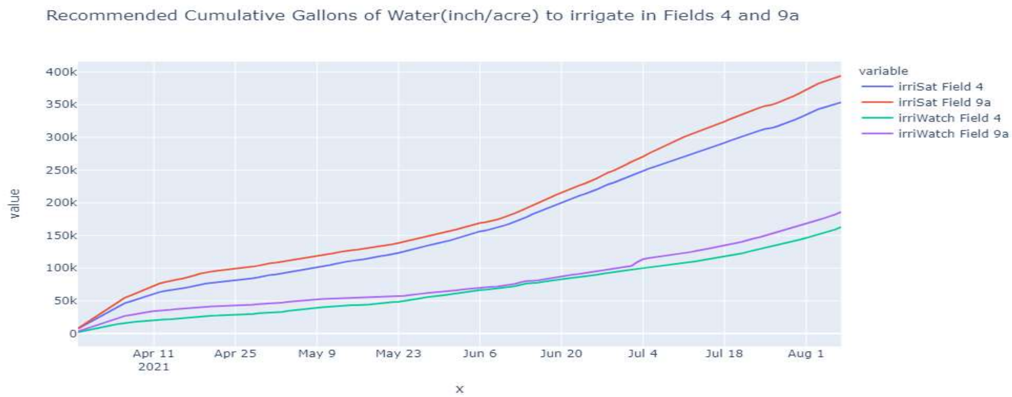
Both ETo and Kc variables can introduce inaccuracies for the estimated plant water use. Using the ETc method in combination with soil moisture monitoring will help a farmer accurately dial in the correct irrigation amount and approach the best irrigation practice.
The satellite system used for this grant provides ETc as a direct output. In this report we compare the results from using two satellite systems and the “traditional” ETc = ET0 x Kc calculation.

When practicing deficit irrigation, growers can choose to temporarily irrigate less than the estimated water use in order to introduce beneficial water stress. Deficit irrigation amounts may range from 90-50% replacement of full water use. For this report, we assume that the farmers use 100% ET irrigation.

Vineyard data

Wilson Creek winery Fields 4 and 9, recommended cumulative irrigation volume

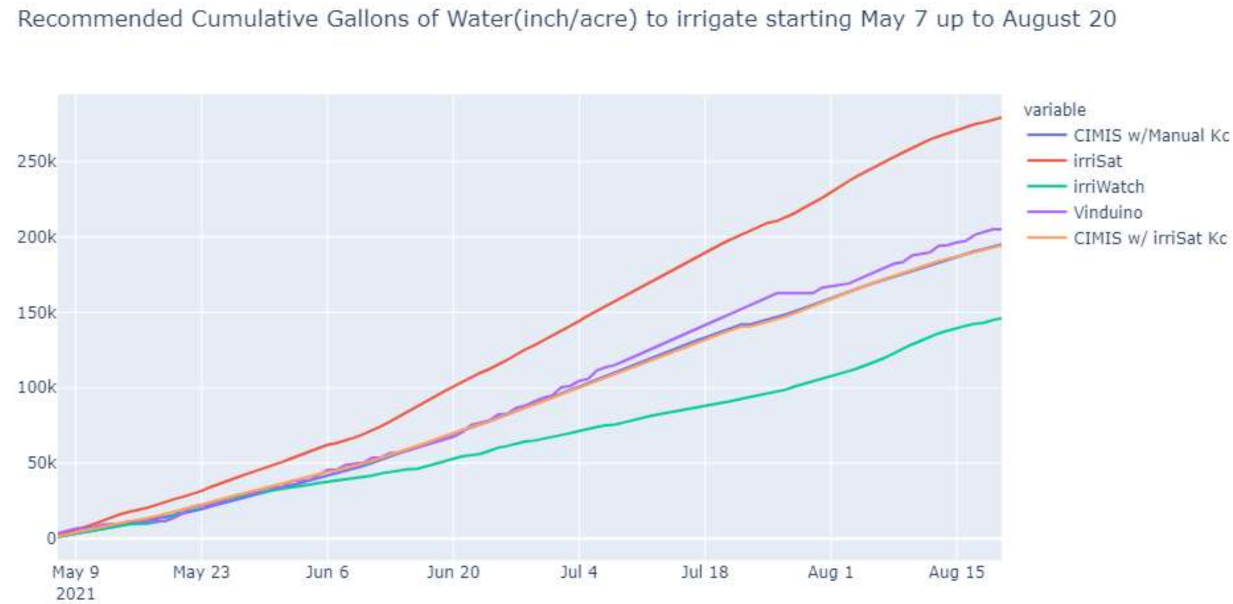
The difference between recommended irrigation volumes between Irrisat and "Product A" satellite systems is a factor 2. The "Product A" irrigation volume is based on direct ETc output, where the IrriSat ETc is calculated by CIMIS ETo x IrriSat Kc.



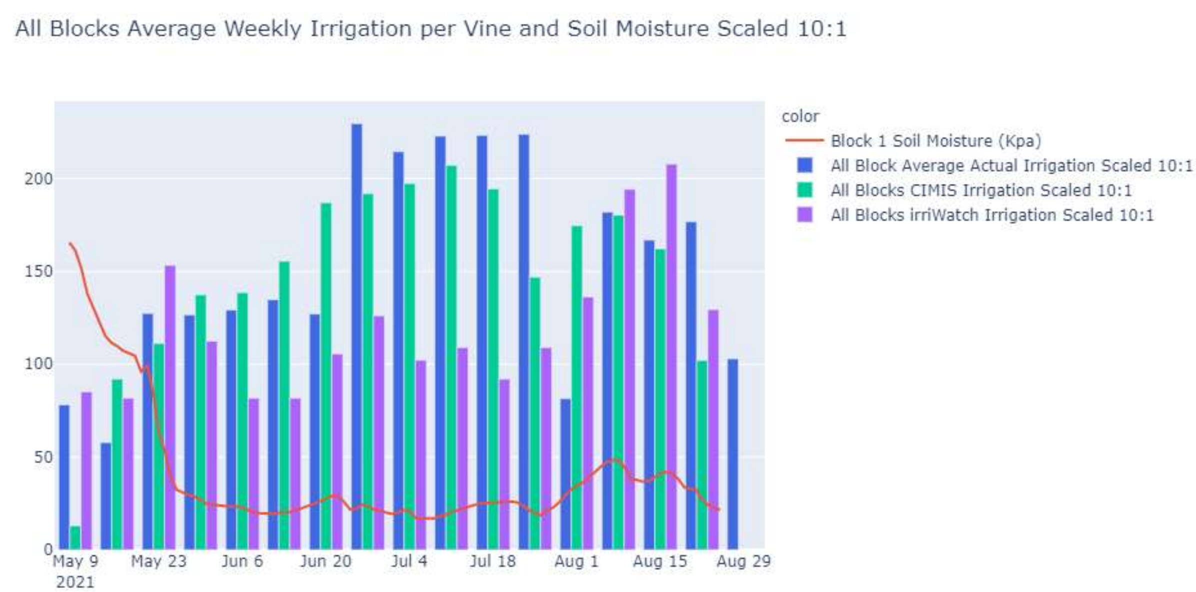
One reason why the two satellite systems disagree by such a large amount may be the crop coefficient estimated for both systems being off by the same ratio. See below chart.
The IrriSat system uses NDVI to estimate crop coefficient, and the "Product A" system uses the more comprehensive SEBAL model.

Van der Lee vineyard Fields 1-4, recommended cumulative irrigation volume

Actual and calculated irrigation is shown below, where we feel that the actual applied irrigation volume is close to the truth as confirmed by soil moisture and pressure bomb measurements. The satellite technology recommendations are either much higher (Red= IrriSat) or much lower (Green). Following solely the satellite irrigation guidance would lead to either significant over- or under-irrigation for this vineyard.

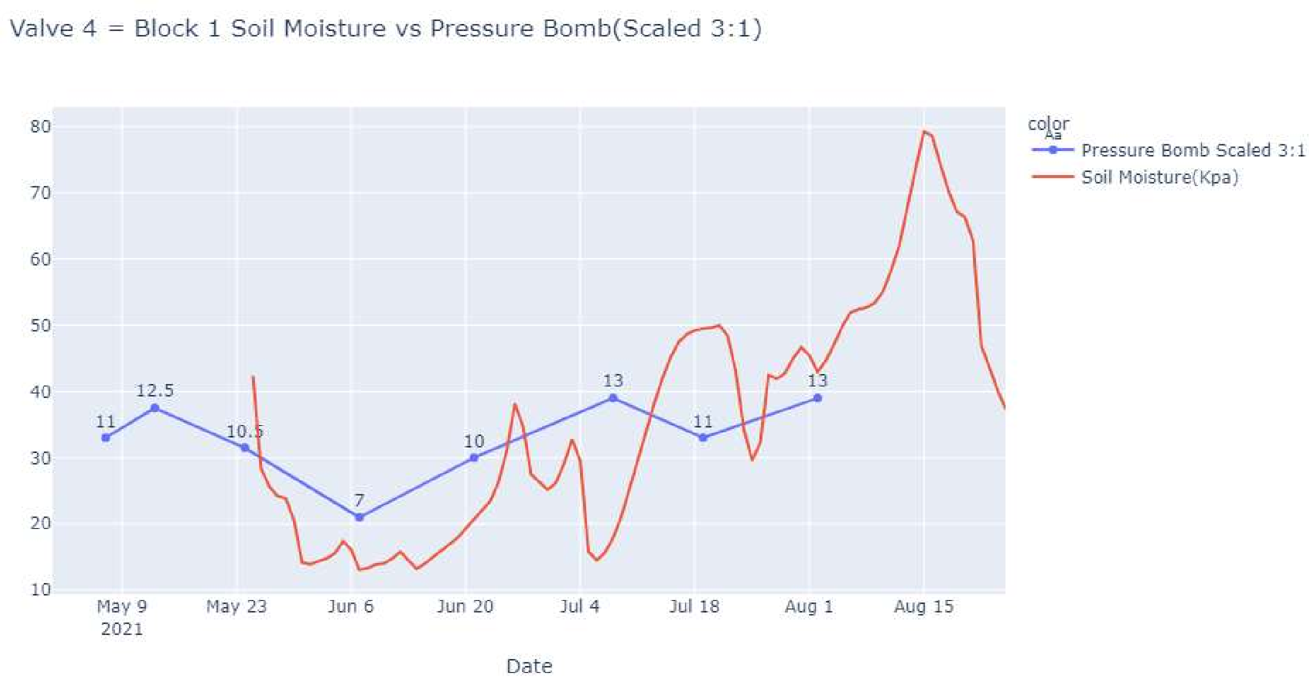


The Van der Lee vineyard was monitored and irrigation in 4 separate blocks. Blocks 3 & 4 were irrigated 2 x per week, Block 3 was irrigated 4 x per week, and Block 1 received 1 x per week irrigation water. Weekly volumes were the same. Actual irrigation (blue column) was based on CIMIS ETo and manual estimate of Kc (green line). "Product A" recommended 50% of the actual irrigation volumes during the hottest period of the season. All individual blocks show the same trend, so we’re showing the average off all 4 block for brevity.



We found that the crop coefficient data from IrriSat closely aligns with the manual method of calculating the crop coefficient by measuring the shaded area per plant. This provides the option of using satellite Kc data vs the error-sensitive manual estimate method. Early in the season, weeds dominate the satellite Kc in both reviewed satellite technologies.

Pressure bomb vs soil moisture data for block 1-4, shows a coarse correlation between soil water tension (sensor) and leaf water tension (pressure bomb). It is used here to show that the soil moisture data corresponds with plant water stress and can be used as a reliable indicator of plant available water status. Additional data from the other fields were reported in deliverable #2.

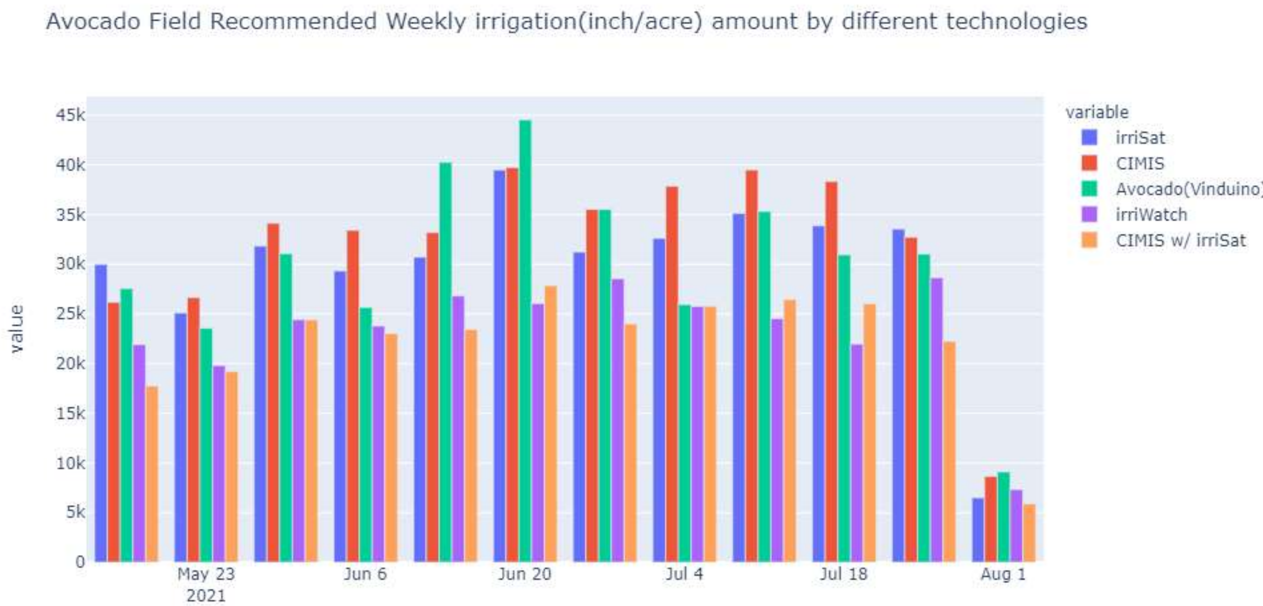


Scaldione and Lassley Fields, recommended cumulative irrigation volume

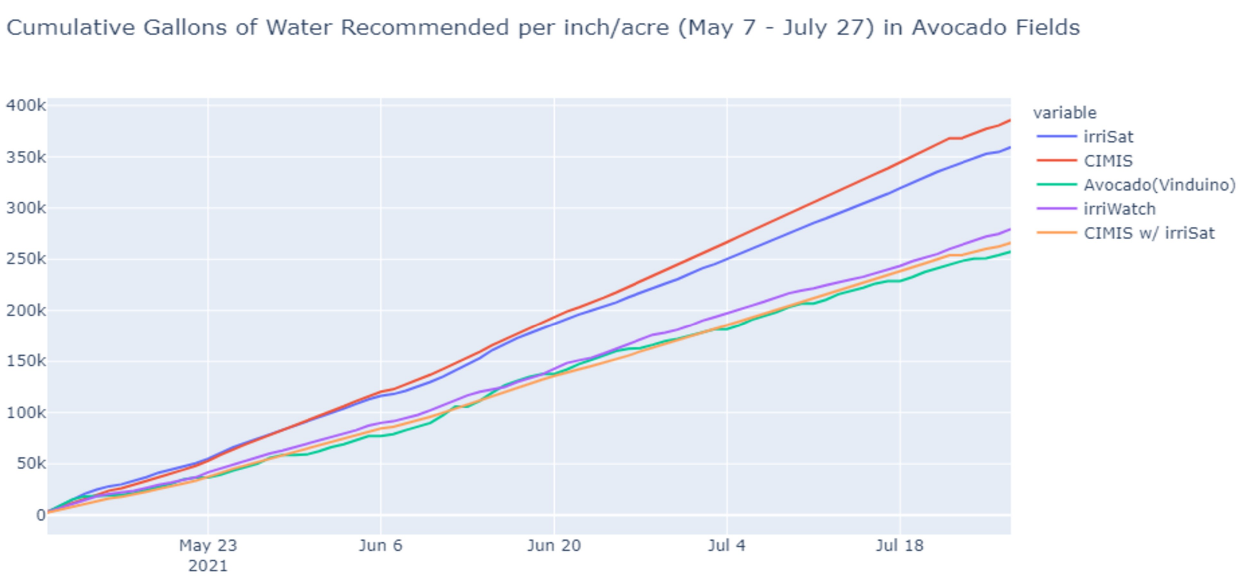
For the Lassley Field we took the average of 6 vineyard blocks taken from the "Product A" and Irrisat satellite data.
Also here the "Product A" irrigation recommendation trends towards the lowest volume, and Irrisat is in the upper guidance. Using IrriSat Kc x CIMIS ETo gives a result between IrriSat and "Product A". We estimate that this is the best available guidance, as supported by other field observations.

M&H Avocado grove, recommended cumulative irrigation volume

The irrigation in this avocado grove was managed by observation of the soil moisture, which was measured using 12 sensors at 6 locations (2 locations per irrigation zone). In the chart below, the actual weekly irrigation is measured with a dedicated water meter (green column).



Using a text book crop coefficient for avocado (0.85) together with CIMIS ETo data, gives the overall highest water use recommendation. "Product A" ETc data agreed with the actual soil moisture-based irrigation, although the soil moisture estimates were not in line with actual sensor measurements. Using the Irrisat crop coefficient together with CIMIS also tracked closely to the actual irrigation.



Conclusions,

recommended cumulative irrigation volume

A combination of ETc estimates and soil moisture sensing as feedback for irrigation management provided consistent results, while the team believes that these estimates were close to the truth.
Satellite based estimates of root-zone soil moisture proved not usable in vineyards and orchards.

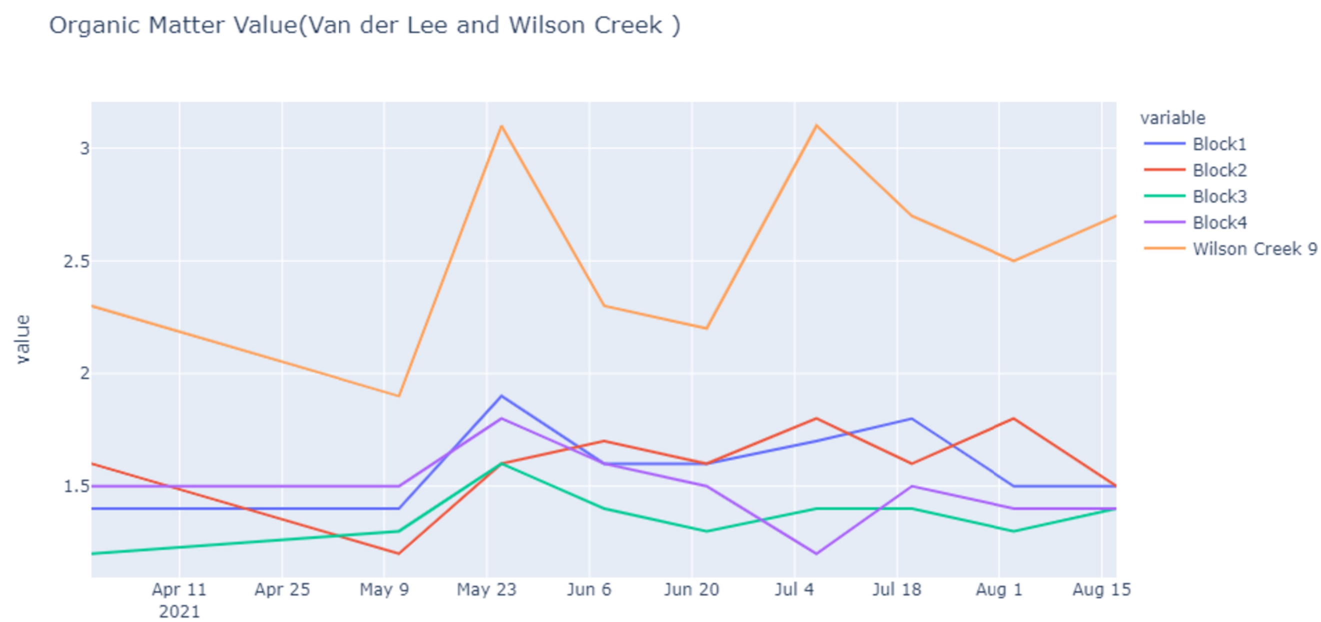
The most consistent ETc estimates for vineyards and orchards came from using IrriSat Kc in combination with Spatial CIMIS. Outside of the early season where weeds dominate the planted area, IrriSat Kc tracks closely with manual Kc estimates and can save labor by automating the collection of Kc data.

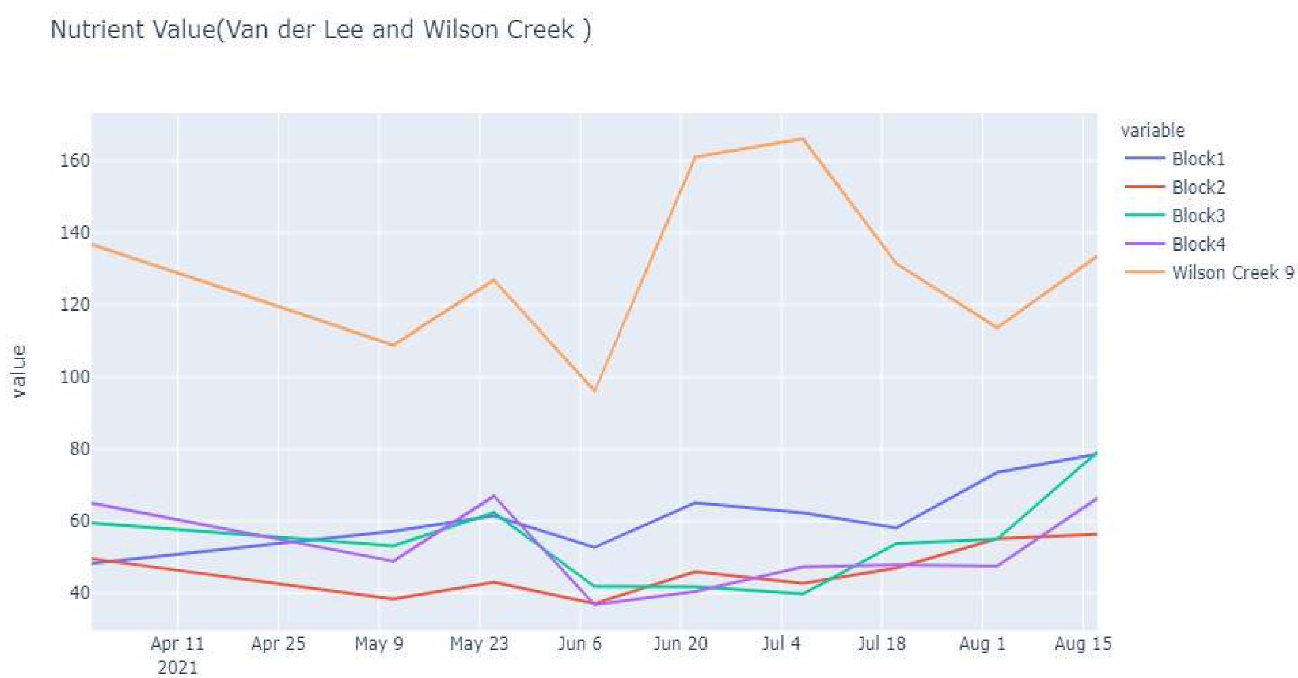
"Product A" ETc data was 50% lower low in vineyards, but did closely follow the actual water use in the avocado grove. This technology appears to work better with large canopy size orchards.

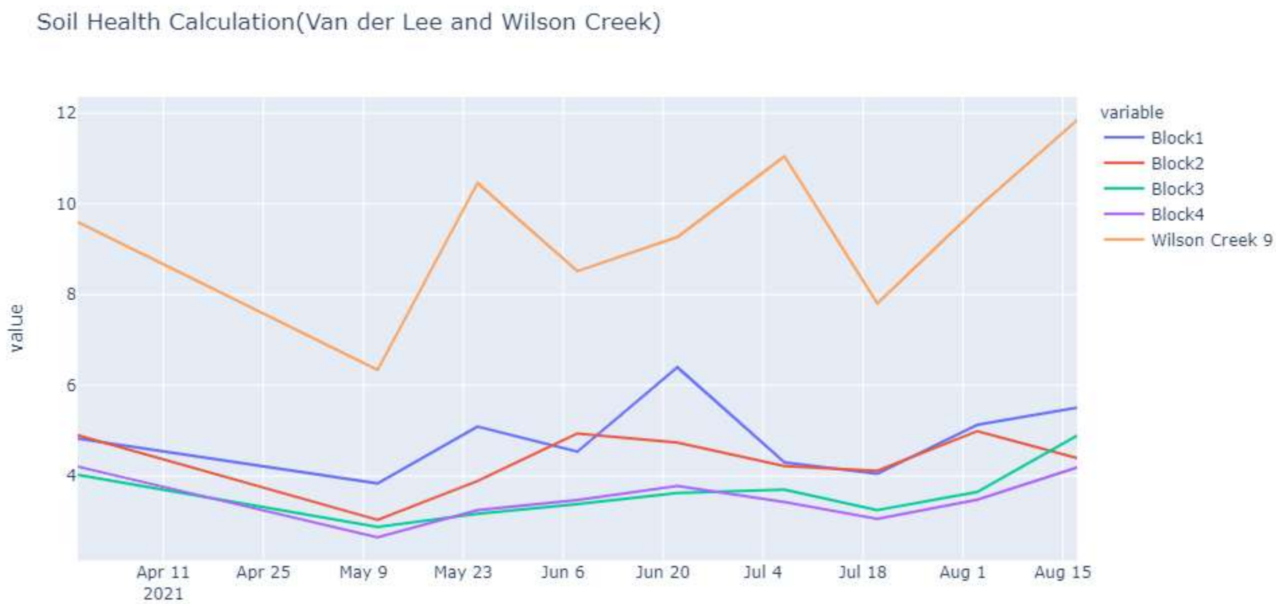
Irrigation Effects on Soil Health

<u>Soil Sample analysis Van der Lee and Wilson Creek Fields</u>

During the growing season we tried to establish how irrigation frequency, while maintaining the same weekly irrigation volume, affects soil and plant health. Block 1 was irrigated 1 x week, Block 2 received 4 irrigations per week. Block 3&4 + Wilson Creek 4 were receiving the standard 2 x per week irrigation frequency.







<u>Conclusions Irrigation Effects on Soil Health</u>
As part of the study we did plant sap analysis through Apical Laboratories in Canby Oregon, and Haney CO2 respiration, and biological nutrient availability through Regen Ag Laboratories Pleasanton, NE. We also performed several PCR analysis of gross quantitative speciation of microbiome species through Regen Ag Laboratories.

We tested plant sap and soil samples on alternate weeks. On one week we would do sap analysis and the following week we would do soil analysis. Our goal of the analysis was to see if we could detect a relationship between plant metabolic activity and chemo-typical expression and soil plant interface relationships as the vines provided additional carbon source and quorum sensing molecules to the soil microbiome.

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To this end we have made the following conclusions.

Plant sap analysis seems to be affected by lunar phases so rather than working on a biweekly calendar it would be more consistent to work on a 28-day lunar calendar of which we will do in the future.

The van der Lee block received mulch in mid July. Possibly more than irrigation regimes we suspect that soil temperature is a key variable and in future analysis we will carefully analyze soil temperature in the top three, six and twelve inches.

We also suspect that one of the primary effects of frequent irrigation versus less frequent irrigation has less to do with water availability than it does with the oxidative reductive impact of irrigation as well as the “Birch Effect” which is Drying and wetting of Mediterranean soils stimulates decomposition and carbon dioxide emissions.

Although the analysis of one year’s data is not sufficient to reveal biological trends in a complex perennial system, it has illuminated several key physical and biochemical markers as well as experimental design improvements.

When designing Irrigation studies, the figure of merit of “gallons per acre” needs to be expanded to include total yield per unit of irrigation with an indicator of quality. As seasonal peak temperatures increase in intensity, frequency, and length of season, the quality of wine grapes is declining due to oxidative stress, the consumption of photosynthetic sugars and lipids to keep the plant cool, and the loss of the ability of plants to photosynthesize at higher temperatures.

The technologies and techniques developed and refined for this study will lead to the following data points critical for monitoring the entire ecosystem affecting water use, and resilience to climatic stress:

- Soil temperature at 3, 6 and 12 inches
- Soil respiration and microbial gross speciation quantification
- Canopy temperature over time to calculate the potential loss of photosynthetic capacity of a C3 Plant in temperatures above 28C and monitor the effects of canopy management on evapotranspiration
- Soil pore saturation during irrigation as a possible effect on oxidative vs. reductive nutrient uptake
- Soil physical properties utilizing the USDA soil health matrix including water-holding capacity.