Master of Wine Research Paper

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A Study of Water Monitoring Technology In the Drought Affected Counties of San Luis Obispo, Santa Barbara, and San Diego:

Current Usage, Attitudes Towards Technologies, and Factors that Influence Adoption

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1. Summary

This study examined relevant water monitoring technologies (WMT), attitudes towards these technologies, and factors that influence their adoption by surveying 101 wine grape growers who own and/or manage vineyards in San Diego[1], Santa Barbara, and San Luis Obispo counties. In addition, twenty-seven semi-structured trade interviews were conducted to determine the scope of the research and to further clarify findings. Initial research revealed three predominant WMT categories: soil, plant, weather/Precision Viticulture (PV). Data was collected using an online survey. Findings uncovered an overall adoption rate of 45%.

This study is of value to wine grape growers and developers of WMT by illuminating which WMT are in use and why. Understanding factors that promote or hinder adoption of WMT among these growers uncovers practical needs and limitations that, if addressed, could encourage more widespread adoption.

[1] Including the Ramona Valley, an American Viticulture Area located within San Diego County.

Figure 1: *Location of Santa Barbara and Santa Barbara AVAs in California.*

Figure 2: *Location of San Diego County and Ramona Valley AVA.*

2. Introduction

Water management in California sits firmly at the forefront of public policy. Groundwater accounts for between 40 and 60% of total water supply in California and more than 60% in drought years. In 2016, California's drought resulted in an economic loss of $603 million and 4700 jobs, and a net water shortage of 2.6 million acre-feet of groundwater from over-pumping (Howitt et al 2015; Medellin-Azuara et al 2016; Water Education Foundation 2015; Croyle et al 2014*).* Consequently, California legislators passed the landmark Sustainable Groundwater Management Act (SGMA) in 2014.

The SGMA is the first legislation to regulate approximately 96% of groundwater use in California through the management of 127 medium-and-high-priority groundwater basins. It requires local agencies to implement sustainability plans by 2020 in these priority basins to prevent further chronic water level lowering, worsening groundwater storage reduction, seawater intrusion, water quality degradation and land subsidence (Water Education Foundation 2015*;* Croyle et al 2014*)*.

On April 7 2017 Governor Jerry Brown issued Executive Order B-40-17 marking an official end to the drought state of emergency in California (United States Geological Survey California Water Science Center 2017). However, even though surface water levels have been temporarily refilled, groundwater aquifers will take years to recover (United States Geological Survey California Water Science Center 2017). Groundwater will remain regulated for years to come.

As California lawmakers fully enforce ground water use regulations through public policy, the practical aspects of water monitoring technologies (WMT), including irrigation and vine water status monitoring, become even more important to viticulturists.

3. Literature Review

Water management and conservation are top priorities in California. As a result, institutions such as the University of California Cooperative Extension Farm Advisors (UCCE) and the University of California Agriculture and Natural Resources Department provide much research on this topic. These institutions offer online information, resources, and services to help wine grape growers manage water resources more efficiently, including step-by-step guidance on how to use various WMT: plant-based (pressure chamber, sap flow sensors, dendrometry), soil-based (tensiometer, electrical resistance blocks, neutron probes, soil moisture sensors), and weather-based (reference evapotranspiration (ET) data from CIMIS[2] weather stations) WMT.

In addition, researchers have published much literature comparing and contrasting these WMT. Peters, Desta & Nelson (2013) review the reliability, cost and usability of soil moisture sensors (volumetric and matric) while offering practical recommendations on their most effective use. Mabrouk (2014) similarly presents the effectiveness of pressure chambers.

Other studies sourced through online journals compare and contrast practical application of Precision Viticulture (PV[3]) technologies with plant and soil-based technologies. These innovative technologies include remote sensing or infrared

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[2] California Irrigation Management System (CIMIS) weather stations collect weather data by measuring the solar radiation, air temp, wind speed and direction, relative humidity and soil temperature in over 150 stations throughout the state of California (California Department of Water Resources 2016).

[3] Precision Viticulture (PV) is part of Precision Agriculture but is specific to viticulture. Precision Agriculture was developed in the 1990s and is defined as “a management strategy that uses information technology to bring data from multiple sources to bear on decisions associated with crop production’ (National Research Council, 1997).

imaging and use of the Normalized Difference Vegetation Index (NDVI). PV helps wine grape growers make irrigation management decisions easier and more effective by addressing the vine water status of the entire vineyard (Acevedo-Opazo, Tisseyre & Ojeda 2008; Tisseyre, Ojeda & Taylor 2007; Matese & DiGennaro 2015; Goode 2005; Skelton 2007). These studies argue that using a combination of PV technologies in tandem with soil, plant and weather-based systems is the most effective approach to improving irrigation scheduling (Acevedo-Opazo et al 2008; Tisseyre, Ojeda & Taylor 2007)

While the reviewed literature reveals the most widely available soil, plant, weather and PV WMT, it does not reveal which WMT available are actually used among viticulturists. This lack of information makes it difficult to determine which technologies are relevant in this study. One study uncovered in research explored the adoption of Best Management Practices (BMPs) used by wine grape growers throughout Northern and Central California. Newhouse, Wan and Wightman (2014) surveyed the adoption of technologies categorically (weather, soil, plant) as opposed to individually. It also excluded remote sensing, surface renewal, dendrometry and private weather stations. These limitations made it difficult to pinpoint relevant technologies in use in the counties pertinent to this study.

Few studies exist exploring the adoption of WMT in California viticulture. Even fewer studies connect drought conditions to adoption of these technologies in viticulture. The aforementioned Newhouse, Wan and Wightman study (2014) did explore the adoption of Best Management Practices (BMPs) used by wine grape growers in California following one year of drought (2014). They found that low adoption rates correlated to limited resources and lack of information but did not determine drought was a causal factor. Furthermore, the reliability of this data is questionable with possible methodology bias, as surveys were administered immediately after a researcher-organized water management workshop.

The scope of literature reviewed was thus broadened to include the adoption of water conservation methods in general by farmers in different agricultural sectors and regions around the world. Findings reveal that socioeconomic and agro-ecological factors influence the adoption of water-related technologies.

Socioeconomic factors affect the adoption of water conservation practices in farming (Escalera, Dinar & Crowley 2015; Goldhammer et al 2006). In a study on the adoption of water-related technologies in the California avocado industry, Escalera, Dinar and Crowley (2015) found that better-informed and more experienced growers are more likely to use water conservation practices including WMT.

Agro-ecological factors such as low water availability due to drought conditions, water costs, and farm size further impact the adoption rate of water-related technologies (Escalera, Dinar & Crowley 2015). The Escalera, Dinar and Crowley study (2015) reveals that agriculturists of large avocado orchards with less water availability are more likely to use conservation practices. A study by Schoengold and Sunding (2011) connects the adoption of irrigation technology (sprinkler systems, drip irrigation) to rising water prices among agriculturists in Southern California. Daberkow and McBride (2004) show that US agriculturists of larger sized farms are more likely to use precision agriculture technologies than smaller farms. Schuck et al

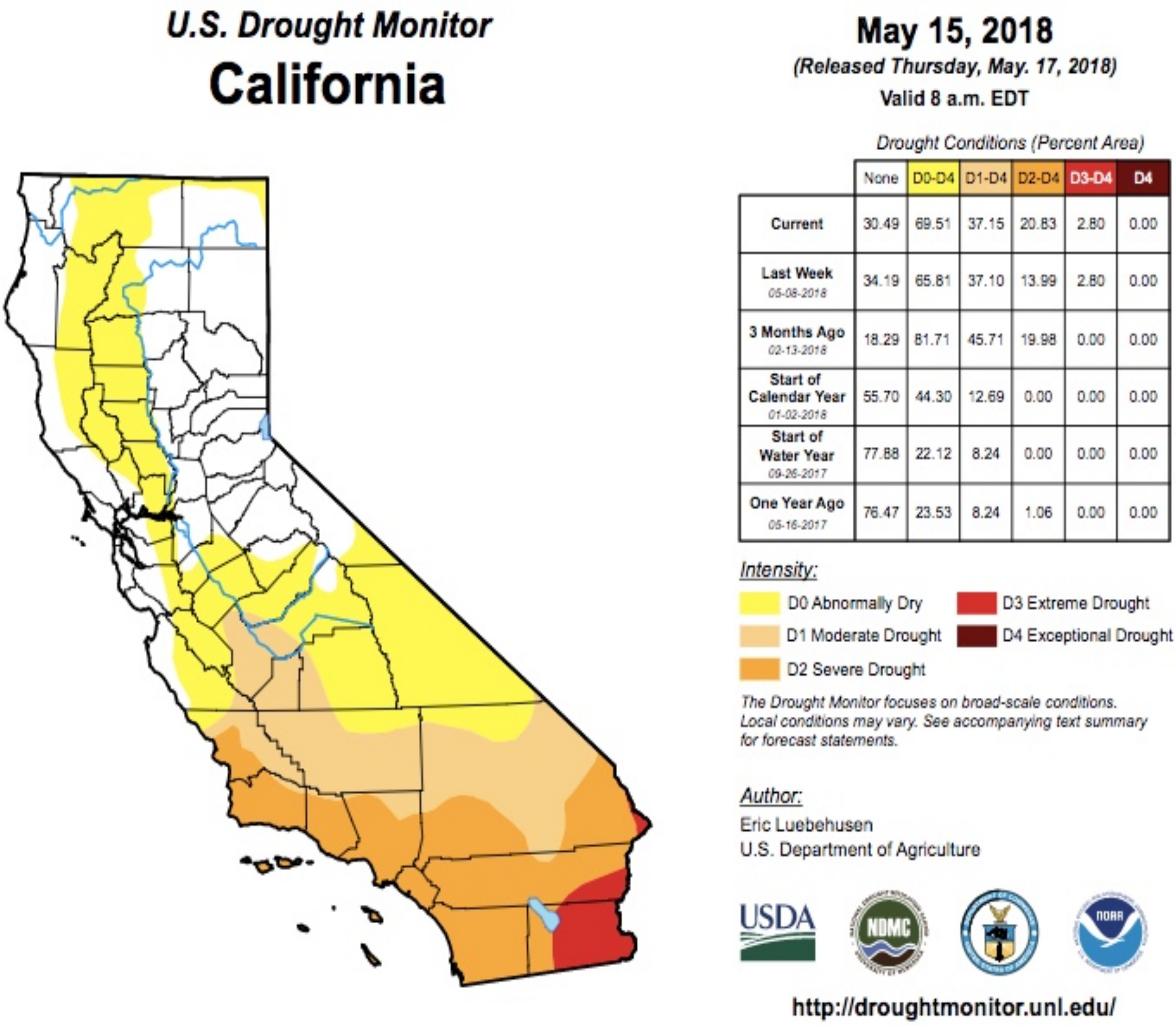
(2005) link drought conditions to changing irrigation technology systems. It was found that a significant number of irrigators responded to the 2002 Colorado drought by investing in more efficient irrigation systems.

No previous study has explored wine grape grower perceptions of WMT, nor factors influencing their adoption in the drought impacted wine regions of San Diego, Santa Barbara, and San Luis Obispo. Furthermore, the literature does not reveal any possible connections between water-restrictive SGMA regulations and adoption rates of WMT.

4. The Impact of Drought in the Central Coast and Southern California

The Central Coast and Southern California[4] are among the most drought-impacted regions in the state due to combined net water shortages of nearly 3.5 thousand acre-feet (Medillin-Azuara et al 2016). [5] As shown in Figure 3, these numbers put San Diego, Santa Barbara, and San Luis Obispo counties in the D2 “Severe Drought” zone (Artusa 2018). As a result, agriculturists have had to rely on dwindling groundwater supplies for their irrigation needs (Battany 2016, pers comm).

[4] The Central Coast includes San Luis Obispo and Santa Barbara. Southern California includes San Diego/Ramona valley (Medillin-Azuara et al. 2016).
[5] In 2016, groundwater availability in the Central Coast was reported at negative 2.9 thousand-acre feet and surface water at zero thousand acre-feet. In Southern California, the numbers were also low at negative 0.6 thousand acre-feet of groundwater and zero thousand acre-feet of surface water (Medillin-Azuara et al 2016). Surface water includes streams, rivers, lakes, reservoirs, and annual runoff (the amount of rain and snowmelt drainage left after evaporation and transpiration) (United States Department of Agriculture, National Resources Conservation Service, 2017).



	None	D0-D4	D1-D4	D2-D4	D3-D4	D4
Current	30.49	69.51	37.15	20.83	2.80	0.00
Last Week 05-08-2018	34.19	65.81	37.10	13.99	2.80	0.00
3 Months Ago 02-13-2018	18.29	81.71	45.71	19.98	0.00	0.00
Start of Calendar Year 01-02-2018	55.70	44.30	12.69	0.00	0.00	0.00
Start of Water Year 09-26-2017	77.88	22.12	8.24	0.00	0.00	0.00
One Year Ago 05-16-2017	76.47	23.53	8.24	1.06	0.00	0.00

Figure 3: *Santa Barbara, San Luis Obispo and San Diego/Ramona in the "D2 "Severe Drought" zone (Luebehusen, E. 2018).*

Local ordinances and legal regulations further restrict the dwindling supply, underscoring the necessity for water monitoring in this region. To protect the Paso Robles Groundwater Basin from further depletion, in 2013 the San Luis Obispo County Board of Supervisors passed Ordinance No. 3246, putting a moratorium on new or expanded irrigated crop production. The Santa Maria Valley basin, straddling

Santa Barbara and San Luis Obispo counties, is one of the twenty-two Department of Water Resources highly regulated "adjudicated" basins[6].

Despite restrictions on groundwater supply in Southern California, widespread adoption of WMT is not uniform. Water conservation expert Dr. Mark Battany[7] has expressed confusion over adoption rates and has stated that usage of Reference Evapotranspiration Rate (ET) data provided by CIMIS weather stations in the region is "quite low." [8] This study's survey results support Dr. Battany's claims with an overall adoption rate of 45%.

5. Research Questions

This study identifies current WMT available and presents the most relevant WMT in use in San Diego, Santa Barbara and San Luis Obispo counties. It also identifies wine growers who are or are not using WMT and grower perceptions of WMT. Finally, this study examines factors influencing widespread WMT adoption that uncover areas for improvement in policy and communication. It does so by investigating and analyzing the following questions:

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[6] Adjudicated basins are regulated by the county's superior court where specific pumping extraction requirements for these basins are allocated limiting water access and use (Water Education Foundation 2015).

[7] Dr. Mark Battany is the Viticulture Farm Advisor for the University of California Cooperative Extension in San Luis Obispo and Santa Barbara Counties. He personally oversees and maintains CIMIS stations and is a leader in water irrigation technology reseach and development (UC Cooperative Extension Viticulture/Soils Farm Advisor, San Luis Obispo County).

[8] ET is the sum of evaporation of water from soil surfaces plus transpiration from the leaves of plants. The Reference ET (ETo) rate is used to help wine grape growers determine when and how much to irrigate. It reflects the amount of water used by well irrigated mowed grass or alfalfa field. Therefore, ETo does not directly measure any individual grape growers vineyard. CIMIS weather stations provide this information for free to all irrigators (University of California Division of Agriculture and Natural Resources 2017; McClellan 2016, pers comm).

1. Which technologies are available in the market? Initial interviews and reviewed literature uncover twelve technologies as presented in Table 1.

Table 1: *Current WMT available in California viticulture*

Current WMT in Use				
Soil-Based	Soil moisture sensors (dielectric, TDT, TDR, capitance)	Neutron Meters	Tensiometers	Electrical Resistance Blocks
Plant-Based	Pressure Bombs	Leaf Porometer	Dendrometry	Microchip Sensors
Weather-Based/ Precision Viticulture (PV)	CIMIS Weather Stations	Private Weather Stations (Ranch Systems)	Surface Renewal (Tule)	Remote Sensing/PV (Infrared Radiometer, LiDAR, NDVI Images)

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2. What are the most relevant technologies currently in use in San Diego, Santa Barbara and San Luis Obispo? Survey results reveal seven relevant WMT.

3. Who (i.e. which growers) have and have not adopted technologies and which technologies are they using?

4. What are grower perceptions of these technologies?

5. What factors (drought, cost of water, size of vineyards) influence WMT adoption in these counties?

6. Is there a correlation between SGMA water regulation and the adoption of technologies?

6. Methodology

6.1 Exploratory trade interviews

Twenty-seven semi-structured qualitative interviews on water monitoring and drought awareness in California were conducted between October 2016 and May 2018 (Appendix 11.1). These interviews uncovered grower attitudes towards available WMT, the drought and SGMA regulations.

Interviewees included viticulturists, researchers, technology companies, and farm bureaus in California. To capture different perspectives on the topic, different trade professionals were consulted: large wine grape growers, researchers, small wine grape growers, managers, owners and grape grower associations. Wine grape growers interviewed owned and/or managed vineyards in one of the three counties studied. Interviewees answered standardized sets of open-ended questions conducted by phone, via email or in person (Appendix 11.2).

6.2 Survey design

An online survey was chosen as the best approach to most conveniently target wine grape growers. This method allowed for optimal respondent participation in a short time period. The highly structured, pre-tested online survey was created using the paid-for service Propeller Insights proprietary platform. The 31-question survey was designed for completion in 8-10 minutes (Appendix 3). The majority of questions were multiple-choice, matrix or Likert-scale type. Qualitative and quantitative market research experts were consulted to assist in questionnaire design.[9]

[9] Survey design consultants included; Dub Research qualitative survey optimization expert Kerry Hecht and quantitative survey optimization expert Teri Sorenson, and quantitative specialist Mark Engel of Engel Research. Sheri Sauter Morano with the Institute of Masters

The population size of 493 was sourced from San Diego, Santa Barbara and San Luis Obispo counties. Surveys were sent via email by combined sends to the population. Follow-up emails and phone calls were made to 194 of the sample size to ensure survey completion goals were met. The survey was live for six weeks, starting February 15 and ending March 31 2017. The data collected were principally quantitative in nature. In summary, a total of 101 completed responses representing 20% of the sample size was obtained. Survey respondents by region are presented below.

***Table 2**: Survey responses by region and total.*

Grape Growers	San Diego	Santa Barbara	San Luis Obispo	Total
Population	157	83	253	493
Completed Responses	36	11	59	106
Completed Responses (% of Population)	22.9%	13.2%	23.3%	21.5%

6.3 Selection of sample size

To gather a sample size that represented different wine grape growers, this study intentionally selected different counties in Southern California. Over 90% of wine grape growers in San Diego County are owners who farm less than 20 acres (Kahle 2016, pers comm). In Santa Barbara, over 90% of vineyards are managed by large companies overseeing more than 100 acres (Clow 2016, pers comm). Finally, San Luis Obispo represents a heterogeneous mix of management approaches and sizes

of Wine was consulted to help in the survey question design and Pat Merrill of Merrill research also advised on survey question design.

(Zelinski 2017, pers comm).[10] These counties are all considered “extreme” drought zones (Artusa 2018).

The sample size of wine grape growers was sourced through varying methods. The San Diego County wine grape grower contact list was created with contact information provided by the local San Diego County Vintners Association and Ramona Valley Vintners Association based on the membership roster and in-person interactions. Santa Barbara and San Luis Obispo contacts were gathered by cross referencing the regional Pesticide Use Permit List (provided by the California Department of Weights and Measurements) with contact information from the Independent Grape Growers of the Paso Robles Area (IGGPRA), San Luis Obispo Wine County, Paso Robles Wine Country Alliance and Santa Barbara County Vintners Association. To distribute the survey, the associations sent newsletter e-blasts to its members. For the full population, follow-up phone calls and personal emails were utilized.

6.4 Survey limitations

Survey questions did not address all possible demographical factors known to affect technology adoption rates such as the education level, gender and age of a wine grape grower. The survey focused on grower attitudes to different technologies but did not ask about attitudes to using technology in general, which could also provide a deeper understanding of why some growers use technology and others do not. These limitations should be addressed in future studies on this important subject.

[10] Dr. Lowell Zelinski has both Ph.D. in Soil Science and an M.S. in Ag Science. He is the current president of the Independent Grape Growers of Paso Robles and has over 30 experience in viticulture..

7. Findings and Analysis

7.1 The role and importance of WMT

Water moves through the soil, the vine, and into the atmosphere. Numerous factors (weather patterns, soil type, water quality, irrigation approach, slope, canopy demands, plant health, rootstock, cover crops, vine density) influence this soil-plant-atmosphere continuum making it difficult to characterize the total water use in a vineyard. A combination of plant, soil and weather/PV technologies is recommended to most accurately measure water availability at these different points to help a grower make precise, appropriate water management decisions about when and how much to irrigate (University of California Agriculture and Natural Resources, 2016; Grant 2014; Burt 2012; Westover & Beal 2014). The more comprehensive measures growers' use, the more precise can be their irrigations. As a result, they can reduce overall water consumption and increase the grape quality (Newton, pers comm 2017; Westover & Beal 2014; Burt 2012). This is particularly important to the drought-afflicted regions of this study.

7.2 Identifying relevant WMT available and in use

This study successfully determined the most relevant WMT currently available and in use among wine grape growers in San Diego, Santa Barbara, and San Luis Obispo counties. A series of descriptive statistics was used to explore usage trends among the 101 completed survey responses. Among the respondents, 45 adopt WMT (TA) and 56 do not (NA). The most relevant technologies were noted with current use (between 2016 and 2017) among at least 20% of the sample.

7.3 Soil-based WMT available

Soil-based technologies are based on the premise that available moisture in the soil affects the moisture status of the vine. These technologies indirectly assess a vine's water status by measuring water available for a vine to uptake through the soil (University of California Agriculture and Natural Resources 2016; Acevedo et al 2008). The measurements help growers determine how often and how much to irrigate and are often used in tandem with plant or weather technologies (Grant 2014; Peters 2013).

Two types of sensors are available: volumetric and matric. Volumetric sensors including soil moisture or dielectric sensors (capitance, Time Domain Reflectometry [TDR], Time Domain Transmissometry [TDT]) and neutron meters measure the soil's water content, indirectly informing grape growers when and directly informing how much to irrigate (University of California Agriculture and Natural Resources 2016; Peters 2013). In contrast, matric sensors, such as tensiometers and electrical resistance (gypsum blocks), measure the soil water potential, or water tension in the soil, indirectly informing grape growers when to irrigate but not how much (University of California Agriculture and Natural Resources 2016; Greenspan 2017, pers comm). However, through observation and experience it is possible to use matric sensors to determine how much to irrigate although they are not as accurate as volumetric sensors (Peters 2013). Current soil monitoring technologies are described in Table 3.

Table 3*: Description of soil-based technologies.*

Description of Soil-based Technologies			
Volumetric		**Matric**	
Soil moisture sensors (dielectric, capitance, TDT, TDR)	**Neutron Probes**	**Tensiometers**	**Electrical Resistance Blocks**
Use high frequency electro-magnetic waves to reflect the dielectric constant or volume of water in the soil.	Indirectly measure the soil water volume by using radioactive materials.	Measure the water tension (how tightly water is held) in the soil.	Measure the electrical resistance or conductivity between two electrodes.
Advise how much and when to irrigate.		**Advise when to irrigate and can help determine how much.**	
Data sourced from: Peters, 2013; University of California Agriculture and Natural Resources 2016; Grant 2014; Greenspan 2016, pers comm; Chavez 2012.			

7.3.1 Relevant soil-based WMT in use

Table 4 illustrates that volumetric soil moisture sensors are the only soil-based technology considered relevant (*n* = 31, 69%). Matric electrical resistant blocks (*n* = 6, 13%), and tensiometers (*n* = 7, 16%), and volumetric neutron meters are among the least used (*n* = 3, 7%) and therefore not relevant.

Table 4: *Frequency table for adoption of soil-based technologies among growers*

Soil-based Technologies in Use	*n*	*% of growers using technology*
Soil moisture sensors (capitance, TDT, TDR sensors)	**31**	**69**
Tensiometer technology	7	16
Electrical resistance blocks technology (eg. Gypsum blocks)	6	13
Neutron meter technology	3	7

There are several reasons for these findings. In general, soil-based technologies are highly sensitive to soil conditions and only measure one point at a time. As a result, readings can be inaccurate requiring additional data from plant or weather WMT to most effectively ascertain a vineyard's water status (Peters 2013). As reflected in their low adoption rates, matric sensors (electrical resistance blocks and tensiometers) are the least reliable because of their high sensitivity to dry or saline soils (University of California Agriculture and Natural Resources 2016; Greenspan 2017, pers comm; University of California Agriculture and Natural Resources 2016; Pritchard et. al 2004). This is particularly problematic in regions like Paso Robles, Santa Barbara and San Diego/Ramona where dry soils and salinity are commonplace due to sustained drought conditions and over-pumping of groundwater (Battany 2010; Battany 2012; Battany et al 2015; Martin 2014). Low adoption of volumetric neutron meters could be explained by the fact that they require use of radioactive materials necessitating installation and management by a trained, licensed operator who must recertify every two years. Thus their mainstream adoptability is limited to researchers (Grant 2014).

In these drought stricken regions, where dry and saline soil conditions prevail, volumetric sensors (dielectric, capitance, TDT, TDR) are highly used (n=31, 69%). An exploration of why these sensors are relevant resides in section 8.2.

7.4 Plant-based WMT available

Whereas soil-based systems inform a grower when or how much to irrigate based on water available in the soil, plant-based technologies measure the actual physiological status of the vine itself to assess more directly how vines are responding to the amount and frequency of applied water (Westover & Beal 2014). This makes plant-based systems more effective for determining when to irrigate (Acevedo-Opazo et al 2008; McGourty 2015). This category consists of four technologies described in Table 5: pressure bombs, leaf porometers, dendrometry and microchip sensors.

Table 5*: Description of plant-based technologies.*

Description of Plant-based Technologies			
Measures leaf or stem of a vine only		**Measures entire vine**	
Pressure Chamber/Bomb	**Leaf Porometer**	**Dendrometry**	**Microchip/Sap Flow Sensors**
Measures the plant's sap tension from the xylem of a leaf or stem. This provides a reading of the leaf or stem's energy potential.	Measures the stomatal conductance (how open or closed the stomata are) and therefore provides direct information into the vine's state of water stress.	Measures the transpiration rate, or changes in the water content of a vine, by measuring how much the trunk shrinks and swells	Measures the sap flow during transpiration with sensors installed on stems.
Data sourced from: Acevedo-Opazo et al 2008; McGourty, 2015; Greenspan 2011; Heinzen 2017, pers comm; Zelinsky 2016, pers comm; Scholasch, 2015; Greenspan 2016, pers comm; Matthiassen 2016, pers comm.			

7.4.1 Relevant plant-based WMT in use

Table 6 shows survey results revealed mixed adoption of plant-based technologies, with usage of pressure bombs (*n* = 14, 31%) and leaf porometers (*n* = 9, 20%) suggesting they are relevant and low usage of dendrometry (*n* = 1, 2%) and microchip sensors (*n* = 1, 2%) suggesting they are not.

Table 6: *Frequency table for adoption of plant-based technologies among growers*

Plant-based Technologies in Use	*n*	*% of growers using technology*
Pressure bombs	**14**	**31**
Leaf porometer	**9**	**20**
Dendrometry	1	2
Microchip sensors	1	2

The low adoption of both dendrometry and microchip sensors is compelling. According to a Papi and Storchi study (2012), data from dendrometers are not reliable post-veraison when bark growth thickens. This clearly limits their effectiveness for irrigation decisions (Heinzen 2017, pers comm). Furthermore, trunk variability in a vineyard can make it difficult for microchip or sap flow sensors to accurately assess the water status of an entire vineyard. The high of using multiple units could also limit adoption for both these technologies[11] (Acevedo-Opazo, et al 2008, Greenspan 2015).

In conclusion, the most relevant plant-based technologies available and in use in these regions are pressure bombs and leaf porometers. An exploration of why these sensors are preferred appears in section 8.2.

[11] Microchip sensors cost $5000USD/year for a 40 acre vineyard (Matthiassen, pers comm 2017). Automated dendrometers cost $650/unit. Number of units vary by size and variations of a vineyard (Phytogram by Agriculture Electronics Company).

7.5 Weather and Precision Viticulture (PV) WMT available

Four different weather-based technologies were identified in the research. Weather stations (CIMIS, private weather stations) calculate Reference ET[12][13] by measuring atmospheric and soil factors (solar radiation, air temperature, wind speed, relative humidity, soil temperature, and wind direction). Weather stations can only estimate water loss in a vineyard (University of California Division of Agriculture and Natural Resources 2017). Surface renewal by Tule Technologies calculates Actual ET[14] from a vineyard making it the most accurate technology to determine both when and how much to irrigate according to irrigation expert Dr. Mark Greenspan (Greenspan 2017, pers comm).[15] PV/Remote Sensing (Infrared Radiometer, Normalized Difference Vegetation Index [NDVI], Light Detection and Ranging [LiDAR]) uses sensors to obtain and interpret information, such as canopy vigor, size and soil conditions, from a vineyard's surface at a distance (Greenspan 2016). This can help a growers assess the vine stress of an entire vineyard, indirectly indicating when to irrigate and

[12] Reference ET refers to the amount of full water used by a standardized grass or alfalfa field upon which the CIMIS station is located (CIMIS, 2008). Therefore, ETo does not directly measure any individual grape growers vineyard nor does it measure actual water loss. This information is used to anticipate what will or has happened in the past – it does not provide information about the actual water use or status of crop. Furthermore, irrigators have to use crop coefficients (Kc), to convert standardized ETo into actual evapotranspiration (ETc) for their vineyard- which can result in inaccurate readings University of California Division of Agriculture and Natural Resources, 2017; "CIMIS Overview," 2016; University of California Division of Agriculture and Natural Resources, 2008; McClellan 2016, pers comm).

[13] To clarify, CIMIS weather stations and private weather stations differ in where they gather measurements. Private weather stations are more reliable because data is taken from the vineyard where the unit is installed. In contrast, CIMIS is based on a weather station not directly located on the vineyard in question. Both use the Reference ETo model to estimate the evaporative demand (Greenspan pers comm 2017).

[14] Tule Technologies is currently the only provider of surface renewal. Surface renewal measures the Actual ET (in contrast to Reference ET). This is the actual amount of water that is vaporized and transpired from the field being measured. It is a new technology released to the public in 2014 (Lansing 2014; LaBarge 2016, pers comm; Shapland 2015).

[15] Dr. Mark Greenspan specializes in irrigation and irrigation technology with over 25 years of scientific viticulture research and field experience. His work is frequently published in Wine Business Monthly and is a valuable source of information for this study.

more specifically, where (Lansing 2014). Many grape growers use weather and PV-based technologies in tandem with more direct soil and plant-based approaches.

***Table 7**: Description of weather and PV-based technologies.*

Table 7: Description of Weather and PV-based Technologies					
Weather Stations		**Surface Renewal**	**PV/Remote Sensing**		
Advises how much and when to irrigate			**Auxiliary Method on where to irrigate**		
CIMIS	**Private**	**Surface Renewal**	**NDVI**	**Infrared Radiometry/ Thermography**	**LiDAR**
California state funded resource provides Reference Evapotranspiration Rate (ETo) data from over 150 weather stations. Measurements are references and not from the grower's actual field.	Measures weather conditions of a particular site to determine Reference ET.	Integrates soil, plant and atmospheric factors to calculate actualwater loss from vineyard surfaces (ground and vine canopy).	An Index that shows the response of a vine's canopy to red and near-infrared spectral bands	Sensors that use electromagnetic radiation to measure blue, green, and near-infrared light wavelengths.	Uses lasers to illumin-ate a target and measure the light reflected back.
Data Sourced from: University of California Division of Agriculture and Natural Resources, 2017; "CIMIS Overview," 2016; University of California Division of Agriculture and Natural Resources, 2008; McClellan 2016, pers comm; Pregler, 2007; "Agricultural Solutions," 2017; Newton 2016, pers comm; Lansing, 2014; LaBarge, 2016 pers comm; McGourty, 2015; Amaral 2017, pers comm; Goldhammer, et al 2006; Matese, 2015; Greenspan, 2016; Lodi Growers Association*, 2017;* Smit, J., Sithole, G., and Strevor, A. 2010*;* Acevedo-Opazo et al, 2008; Greenspan 2017, pers comm; Matthiassen 2016, pers comm.					

7.5.1 Relevant weather and PV WMT in use

As illustrated in Table 8, all weather and PV technologies have an adoption level over 20% and are therefore all considered relevant. Private weather stations (*n* = 31, 69%) are the most frequently used weather-based technology. CIMIS weather stations showed moderate categorical usage (*n*=18, 40%). Both surface renewal (*n*=11, 24%) and remote sensing (*n*=10, 22%) are the least used technologies within the category.

Table 8: *Frequency table for adoption of weather-based/PV technologies among growers*

Weather and PV Technologies in Use	*n*	*% of growers using technology*
Private weather station technology	**31**	**69**
CIMIS stations	**18**	**40**
Surface renewal/Tule Technologies	**11**	**24**
Remote sensing	**10**	**22**

Unlike plant and soil-based technologies that require data interpretation of multiple single-point measurements to accurately characterize vineyard water status, weather-based technologies can conveniently provide automated data characterizing an entire block or portion of a vineyard or multiple vineyards at one time. This is most likely why all technologies in this category are relevant. An exploration of why these technologies are preferred appears in section 8.2.

In conclusion, the most widely used or relevant WMT available and in use in San Diego/Ramona, Santa Barbara and San Luis Obispo counties are soil moisture sensors, private weather stations, public weather stations, pressure bombs, surface renewal, remote sensing and leaf porometers. An exploration of who uses these technologies, which technologies they use, and grower perceptions of why some are preferred over others appears below.

8. WMT Usage Trends

8.1 Adoption rates and WMT usage trends

To address this question, a series of descriptive statistics and cross-tabulations are used to examine the grower subgroups that have (TA) and have not adopted (NA) technology as well as adoption behavior differences and preferences among TAs (n=45). Findings are explored below.

8.1.1 WMT adoption trends and ownership style

The relationship between owning or managing a vineyard and using WMT was statistically significant ($\chi^2(1) = 24.52$, $p < .001$). Managers (n = 13, 79%) and the combination of owner/managers (n = 13, 62%) are more likely than owners (n = 13, 23%) to adopt technology.[16] The cross-tabulation is presented in Table 9.

Table 9: *Cross-tabulation between owning and/or managing a vineyard and using WMT.*

	Use WMT				
Own and/or manage a vineyard	Yes *n*	No *n*	Total *n*	$\chi^2(1)$	*p*
				24.52	<.001
Owner	13 (23%)	43 (77%)	56		
Manager	19 (79%)	5 (21%)	24		
Both Manager/Owner	13 (62%)	8 (38%)	21		
Total	45 (45%)	56 (55%)	101		

Ghadim, Pannel and Burton (2005) found that “the perceived risk or uncertainty that new technology tools won’t be worth the investment or are too difficult to use prevent

[16] Managers exclusively manage vineyards. Owners exclusively own vineyards. Owner/managers simultaneously both own and manage vineyards.

adoption.” Managers offer paid-for services and can factor technology costs and the additional labor/time needed to properly implement into their fee schedule, making WMT adoption less risky. This contrasts with owners who handle vineyard operations themselves and may have fewer resources to allocate towards WMT, heightening the technology investment risk. Owner John Backer explains, “It’s just me, using contract labor (who really don’t care) and I’m also the winemaker, business operator, head of marketing, person doing all the maintenance, etc.” He must prioritize his return on investment for his time and effort to use a technology that can be a “hassle” (Backer 2017, pers comm). Owner Donald Hofer echoes Becker, “Adoption of a new technology is often a gamble for an owner as it may cost a lot and not bring anything useful to their operation” (Hofer 2017, pers comm).

Also, owners may not see the value of WMT in situations where they are on-site daily visually assessing any vineyard changes. Managers may not be on-site daily. Using technology that provides a better understanding of what is transpiring in their absence helps them to justify their decisions to their clients (Heinzen 2017, pers comm; Backer 2017, pers comm; Zelinsky 2016, pers comm).

Not only are managers more likely to use technologies than owners, the average manager uses more than twice as many technologies (3.7) as an owner (1.8) and approximately 1.2 times more than an owner/manager (2.2). Additionally, managers use a wider variety of technologies than owners or owner/managers. While all respondents favor soil moisture sensors and private weather stations, more than half also use pressure bombs, CIMIS stations and surface renewal systems and remote sensing, demonstrating more technological diversity compared with owners and owner/managers. Table 10 reflects these differences in use of relevant technologies (as defined in section 7).

Table 10: *Cross-tabulation of relevant technologies in use and owning/managing a vineyard*[17]

	Own and/or Manage and Adopt WMT		
Relevant Technologies	Own (*n=13)* *n*	Manage (*n=19)* *n*	Own and Manage (*n=13)* *n*
Soil moisture sensors	**7 (54%)**	**14 (74%)**	**10 (77%)**
Pressure bombs	2 (15%)	**10 (53%)**	2 (15%)
Leaf porometer	2 (15%)	5 (26%)	2 (15%)
Private weather stations	**8 (62%)**	**14 (74%)**	**9 (69%)**
CIMIS stations	4 (31%)	10 (53%)	4 (31%)
Surface renewal/Tule	0 (0%)	**10 (53%)**	1 (8%)
Remote sensing	1 (8%)	**8 (42%)**	1 (8%)
Total number of technologies in use by cohort	24	71	29
Average number of technologies in use by cohort	1.8	3.7	2.2

Behavioral differences between the groups suggest that owners and managers have different farming needs. A study by Escalera et al (2015) found that the more landscape variability (steep slopes, soil differences) a site had, the more likely avocado farmers were to adopt WMT. Data show that managers are more likely to manage more than one vineyard (*n*=18, 75%) compared with owners (*n*=7, 13%) and to manage larger vineyards (more than 100 acres) (*n*=15, 63%) compared with

[17] Please note, due to the multi-select nature of an individual grower's response (reflecting their use of multiple technologies), the percentages do not total 100.

owners (*n*=4, 7%).[18] Larger vineyards and multiple vineyards are more likely to have more landscape diversity (soil types, elevation, slope), necessitating the use of more diverse technologies.

Technology adoption motivations between the groups may also differ. There is competitive pressure to stay relevant among companies who commercially manage vineyards (Newton 2017, pers comm; Heinzen 2017, pers comm). Managers thus are more likely to use the newest available technologies to improve their 'marketability,' and a wider variety of technologies compared with owners (Newton 2017, pers comm); (Zelinsky 2017, pers comm).

8.1.2 WMT adoption trends and experience growing grapes

Data show that the likelihood of adopting WMT increases as years of experience growing grapes increases. The majority of growers who own vineyard(s) for less than 10 years do not use technology (*n*=26, 77%). Owners who have owned for more than 10 years are split between using (*n* = 15, 50%) and not using technology (*n*=15, 50%). Growers who have managed vineyard(s) for less than 10 years are also split between using (*n*=11, 52%) and not using (*n*=10, 48%) technology. However, growers who have managed vineyard(s) for 10 or more years are heavily favored towards using technology (*n* = 21, 87%). Cross-tabulations between years owning or managing vineyard(s) and using water technology are presented in Table 11.

[18] Calculations are based on total number of exclusive managers surveyed (24) and total number of exclusive owners surveyed (56).

Table 11: *Cross-tabulation between years owning and managing a vineyard and using WMT.*

	Adopt WMT				
Years owning	Yes *n*	No *n*	Total *n*	$\chi^2(1)$	*p*
				5.79	.016
Less than 10 years	11 (23%)	36 (77%)	47		
10 or more years	15 (50%)	15 (50%)	30		
Total	26 (34%)	51 (66%)	77		
Years managing	Yes *n*	No *n*	Total *n*	$\chi^2(1)$	*p*
				6.72	.010
Less than 10 years	11 (52%)	10 (48%)	21		
10 or more years	21 (87%)	3 (13%)	24		
Total	32 (71%)	13 (29%)	45		

Adrian, Norwood, and Mask (2005) found that the more experience growers have, the more confident they are about the perceived usefulness and their ability to use technology, resulting in a higher adoption rate. It is plausible that experienced growers have endured more drought situations and hence are more aware of WMTs' ability to more precisely manage water use.

Data reveal that the manager model is more adoptive of more and diverse technologies. As owners become more experienced and more confident, however, they also start to diversify their selections. These findings are expressed in Table 12.

Table 12*-Cross-tabulation between relevant technologies and years owned or managed among TA (n=45).*

	Years Owning Vineyard		**Years Managing Vineyard**	
Relevant Technologies	Less than 10 years (*n*=11) *n*	10 or more years (*n*=15) *n*	Less than 10 years (*n* = 11)	10 or more years (*n* = 21)
Soil moisture sensors	**9 (82%)**	**8 (53%)**	**8 (72%)**	**16 (67%)**
Pressure bombs	1 (9%)	3 (20%)	2 (18%)	10 (48%)
Leaf porometer	1 (9%)	3 (20%)	1 (9%)	6 (29%)
Private weather station	**7 (64%)**	**10 (67%)**	**7 (64%)**	**16 (76%)**
CIMIS stations	2 (18%)	**6 (40%)**	3 (27%)	11 (52%)
Surface renewal/Tule	0 (0%)	1 (7%)	3 (27%)	8 (38%)
Remote sensing	0 (0%)	2 (13%)	2 (18%)	8 (33%)
Total number of technologies in use by cohort	20	33	26	74
Average number of technologies in use by cohort	1.8	2.2	2.3	3.5

On average, owners with 10 or more years experience use more technologies (2.2) than owners with less experience (1.82). This trend is echoed among more experienced managers who use significantly more technologies (3.5) than managers with less experience (2.3).

Private weather stations and soil moisture sensor technologies are the most favored among growers at all experience levels. However, more experienced owners and managers are more likely to use remote sensing, surface renewal, pressure bombs, and CIMIS compared with less experienced owners and managers. It is plausible that as growers gain experience, they are more likely to be more aware of available technology options and more likely to use them (Antolini et al 2015). In contrast, growers with less experience are often less knowledgeable on different available technologies and as a result use fewer (Daberkow & McBride 2004). This presents an opportunity for technology companies to better target market outreach and education efforts towards less experienced growers.

8.1.3 The need for multiple WMT is a barrier to adoption

It is important to point out that regardless of cohort type, all TAs (*n*=45) use on average more than one technology, supporting the assertion that to most accurately characterize the water status of a vineyard, a combination of technologies is needed. Manager Mike Myers explains, “Every technology does generally have a weakness that is best supplemented by another technology” (Myers 2018, pers comm). Because some technologies better inform when to irrigate, and others how or where to irrigate, multiple technologies are used. Difficulty understanding which technology combinations can most reliably inform the when, where and how much to irrigate is a plausible barrier to adoption among NAs.

Growers without technology or plant physiology backgrounds or with limited time to research options may be less likely to adopt WMT (Hofer 2017, pers comm; Zelinsky 2017, pers comm). Owner and non-adopter John York notes, “It’s not only the extra technology cost, but also the additional time to figure out how to use it and then actually keep up with the applications” (York 2017, pers comm). Cost, time and labor implications required when using multiple technologies could make it difficult for less experienced or resource-strapped growers to determine WMTs’ true cost-benefits.

This study recommends targeted educational efforts on the benefits of WMT to encourage more widespread adoption among less experienced owners and managers. Better assessment tools to help growers determine which technology combinations best meet their needs would be invaluable to growers lacking time or expertise. There is also an opportunity to design and develop more automated WMT that combines atmospheric, soil and plant measurements in a single source and informs growers both when and how much to irrigate. Tule Technologies recently created surface renewal, which offers this to growers. It is discussed in section 8.3.

8.2 Grower perceptions of the most relevant technologies in use

This study surveyed grower perceptions of relevant technologies to illuminate their effectiveness as an irrigation decision-making source for ease of use, affordability, and reliability of data. Findings highlight insightful, pragmatic user preferences that can lead to more meaningful grower policy recommendations, technology development and further academic research.

Using a 5-point Likert scale, the survey allowed growers to rank technologies as "Extremely," "Very," "Somewhat," "Not Very," and "Not At All" for the corresponding attributes (effectiveness, cost, ease of use, reliability). To present results concisely, the responses "Extremely" and "Very" were combined and presented as "Effective," "Reliable," "Not Expensive" and "Easy to use." "Not Very" and "Not at All" were presented together as "Not effective," "Not reliable," "Not easy to use" and "Expensive." "Somewhat" was presented by itself. Therefore, three rankings are presented instead of five.[19] Ratings of the most relevant technologies currently in use by TAs (*n*=45) are presented with perceptions of NAs (*n*=56) who have never used these technologies to better understand why growers adopt certain WMT and identify potential barriers limiting their use.[20]

8.2.1 Soil moisture sensors

Soil Moisture Sensors		
Usage	Most adopted among TA (*n*=31, 69%). ✓ Used by all growers. ✓ Particularly high use among less experienced owners (82%, *n=9*) and managers (77%, *n*=10).	
Effectiveness	TA-Effective 77% (n=24)	NA-Somewhat effective 46% (*n*=12)
Reliability	TA-Reliable 65% (*n*=20)	NA-Reliable 43% (*n*=9)
Affordability	TA-Somewhat expensive 58% (*n*=18)	NA-Somewhat expensive 74% (*n*=14)
Ease of Use	TA-Easy to use 90% (*n*=22)	NA-Easy to use 37% (*n*=7)
Recommendations	✓ Develop sensors with a larger zone of influence to reduce the number needed in a vineyard and save costs and improve accuracy. ✓ Once installed, sensors send data automatically via telemetry – convenient for any grower.	
Potential barriers to adoption	✓ Small zone of influence (1-4”) requires multiples sensors to characterize water status of a vineyard. ✓ Sensors average $200-300 each. Multiple sensors are required for accuracy – ideally placed every 10 acres-increasing costs. ✓ Sensitivity to soil variations can result in inaccurate readings - requires careful selection of where for proper installation to most accurately represent a vineyard.	
Data sourced from: University of California Agriculture and Natural Resources 2016; Peters 2013; Greenspan 2017, pers comm; Anjum 2018, pers comm.		

[19] See Appendix 11.4 for all cross-tabulations between relevant technologies and their perceived attribute ratings.
[20] Please note, the (n) varies due to a different number of TA and NA users for each technology. Also for NAs, growers had the option of selecting “I don’t know” for each of the attributes, so (*n*) varies between attributes within each technology. This is a limitation to the reliability of the findings.

Understanding how much water is in the soil, and therefore how much is available to the vines, is important in drought conditions. This is reflected by a high overall use of volumetric soil moisture sensors. Results point to a correlation between positive scores on effectiveness, reliability and ease of use and widespread adoption of this technology among TAs. The moderate cost does not seem to impact TA adoption among TAs. Interestingly, growers who most use this technology are less experienced owners and managers suggesting that the need for multiple units resulting in moderate costs and care in site selection does not inhibit less experienced users. It is plausible that these are adoption barriers among NAs who perceive this technology less favorably than actual users.

An explanation for soil sensor technology preference is that these technologies have been available to viticulturists for decades and are considered a trusted, well-known information source (Greenspan 2017, pers comm). This supports the theory posed earlier that less experienced growers are more risk averse – i.e., soil moisture sensors are “tried and true” technologies which less experienced growers are more likely to use.

8.2.2 Private weather stations

Private Weather Stations		
Usage	Most adopted among TA (*n*=31, 69%). ✓ Used by all growers. ✓ Is the one of the most used technologies widely used by all cohorts (62%, *n*=8),	
Effectiveness	TA-Effective 65% (*n*=20)	NA-Effective 64% (*n*=7)
Reliability	TA-Reliable 71% (*n*=22)	NA-Reliable 70% (*n*=7)
Affordability	TA-Expensive 42% (*n*=13)	NA-Expensive 28% (*n*=3)
Ease of Use	TA-Easy to use 90% (*n*=28)	NA-Easy to use 70% (*n*=7)
Recommendations	✓ Recommended to all growers, especially because of it's multi-functionality. ✓ ETo only provides an estimate of the evaporative demand. Recommended to use with plant and/or soil-based sensors for most accurate irrigation scheduling. ✓ Can be affordable with basic systems starting at $259 (Kestrell 5000).	
Potential barriers to adoption	✓ Complex calculations and data analyses are required to determine ETc to use for irrigation scheduling posing a barrier among NAs. ✓ Although costs can be affordable, with basic systems starting at $259 (Kestrell 5000), their zone of influence maxes at 1000 feet necessitating use of multiple units particularly in vineyards with high in-field variability[21] ✓ Complex systems that reach half a mile like Ranch Systems cost $20,000 or $451/month for 5 years can be costly.	
Data sourced from: McGourty 2015; Greenspan 2016; Pregler 2007; Tisseyre et al 2007; Ranch Systems 2018.		

Most modern weather stations do more than just provide irrigation scheduling information; they can also provide irrigation and frost and heat alerts, indicate disease pressure levels, and monitor well depth (Greenspan 2016). It is unsurprising that this multi-functional technology is among the most used technology among all cohorts (tied with soil moisture sensors). Using ETo for irrigation scheduling is also "tried and true" which could also support its widespread usage (Greenspan 2017, pers comm).

[21] In field variability is defined as a vineyard with different aspects, elevation, microclimates, and soil types.

It is compelling that both NAs and TAs share similar favorable attitudes towards this technology. Both groups rated it positively as reliable, effective and easy to use for irrigation decision-making. Cost perceptions vary. Nearly half of TAs (42%) and a third of NAs (28%) considered it expensive. Expensive systems can be fully automated and provide extensive data. Simpler less costly systems have much less functionality and are not automated. State and federal programs such as EQUIP and SWEEP provide cost-saving grant funding for growers who install weather stations to adhere to water efficiency standards (Greenspan 2016; State Water Efficiency and Enhancement Program, 2016). Only 8% of all growers surveyed (*n*=101) currently use either of these programs; the reasons are unclear. Failure to utilize available resources could indicate growers' lack of awareness of available cost-saving solutions. This is another opportunity for policy and technology developers to better inform growers and promote a wider adoption.

8.2.3 CIMIS weather stations

CIMIS Weather Stations		
Usage	Third most adopted (*n*=18, 40%) ✓ Used among managers (53%, *n*=10), owners (40%, *n*=6) and managers (53%, *n*=10) with more than 10 years experience.	
Effectiveness	TA-Somewhat Effective 44% (*n*=8)	NA-Somewhat effective 50% (*n*=15)
Reliability	TA-Reliable 65%, (*n*=11)	NA-Somewhat reliable 48% (*n*=11)
Affordability	TA-Not expensive 83% (*n*=15)	NA-Not expensive 100% (*n*=20)
Ease of Use	TA-Easy to use 83% (*n*=15)	NA-Easy to use 67% (*n*=16)
Recommendations	✓ This is a free resource that can provide useful information to help a grower determine how much and when to irrigate –best used as an auxiliary source. ✓ California Department of Water Resources should increase the number of stations available to growers.	
Possible barriers to adoption	✓ Reference ETc is a theoretical model. Data collected does not directly measure a grower's vineyards conditions–data therefore are not 100% reliable. ✓ Complex calculations are required to determine a vineyards needs (Kc) making the data less reliable. ✓ ETc data of the field may not be close to a grower's vineyard. This limits the effectiveness of the technology to growers who are located next to a station.	
Data sourced from: Croyle et al 2014; McClellan 2016, pers comm; Cahn 2017; State of California 2016.		

CIMIS is rated "somewhat effective" among both groups. This is because these weather stations measure the Reference ET taken from a well-watered grass field – not the actual vineyard. Crop coefficient equations (Kc) are then required to correlate ET data to grape vines, resulting in readings that can only estimate water use in a vineyard (Greenspan 2017, pers comm). To improve accuracy, CIMIS is best used in tandem with more direct soil or plant-based technologies. Furthermore, CIMIS data is only effective to growers whose vineyards are located near one of the 150 stations (McClellan 2016, pers comm). For example, San Diego County's only station, Bandy Canyon, is approximately 20 miles from Ramona Valley. It is well known that California's coastal regions experience dramatic weather variations within a few miles. Therefore, CIMIS is ineffective unless a vineyard is located nearby and shares similar weather conditions. Data generated from these stations, however, are a reliable information source for growers in proximity, which presupposes that TAs rating the tool as more reliable are close to stations.

While complex equations are involved in converting Reference ET data to usable information, the majority of growers rated this technology as easy to use possibly because the majority of its adopters are more experienced owners and managers who may have more experience using CIMIS. Because the technology is free, it is unsurprising that it is the third most used despite its being only somewhat effective.

Considering that CIMIS is a free resource that rated favorably among users, it is highly recommended as an auxiliary information source for all growers located near one of the 150 stations. In the past 10 years four new stations have been added to the Central Coast and two have been updated (Cahn 2017). This is promising and suggests that demand growth for this technology. As the SGMA regulations take effect, it is predicted that even more stations will be updated or added.

8.2.4 Pressure bombs

Pressure Bombs		
Usage	Fourth most adopted (n=14, 31%) ✓ Used among managers (53%, *n*=10) and managers with more than 10 years experience (48%, *n*=10).	
Effectiveness	TA- Effective 64% (*n*=9)	NA-Somewhat effective 56% (*n*=15)
Reliability	TA-Somewhat reliable 50%, (*n*=7)	NA-Reliable 52% (*n*=14)
Affordability	TA-Somewhat expensive 43% (*n*=6)	NA-Expensive 52% (*n*=13)
Ease of Use	TA-Somewhat easy to use 36% (*n*=5)	NA-Not easy to use 48% (*n*=14)
Recommendations	✓ Accurately characterizes vine's water stress level for precise timing of irrigations – recommended to reliably schedule irrigations.	
Possible barriers to adoption	✓ Data collection is a manual process that requires much precision and consistency and exact collection times and is prone to user error. ✓ Time consuming manual data collection (2 samples for 4-6 vines will characterizes 10-15 acres) makes this impractical for many. ✓ Equipment is expensive ($3000 for PMS Instruments). Weighs around 30 pounds making it less practical to carry around. ✓ There is confusion around which of 3 methods of collecting data is the most reliable – limiting to more experienced growers.	
Data sourced from: Acevedo-Opazo et al 2008; McGourty, 2015; Greenspan 2016; Bogart 2013.		

Despite high upfront costs, unreliable collection conditions and difficulty in using pressure bombs, they are the fourth most frequently used technology surveyed. Because this tool has been around for decades, usage preference is likely linked to familiarity (Greenspan 2016). However, adoption is limited to managers and managers with more than 10 years experience who are more likely to have the resources to properly implement it.

Manager Jeff Newton, a pressure bomb proponent, explains that they can effectively gauge the vine's water stress level. He is thus able to implement more precisely timed irrigations and as a result has seen higher quality fruit (Newton 2017, pers comm)[22]. However, data collection is a manual process that requires precision and consistency and is prone to user error (Acevedo-Opazo et al 2008), making it less reliable among users with less experience as reflected by the overall lower NA scores.

This study does not foresee pressure bomb adoption in their current form to expand much beyond managers and experienced managers. To reliably use this tool requires experience and time that many growers lack. If pressure bombs were lighter weight and be less prone to user error, perhaps they would gain traction.

[22] Jeff Newton has a MA in economics in addition to studying viticulture at UC Davis. He founded Coastal Vineyard Care management company in 1983 and currently manages over 1500 acres. He is a highly respected grower well known in Santa Barbara and San Luis Obispo.

8.2.5 Surface renewal/Tule Technologies

Surface Renewal/Tule Technologies		
Usage	Fifth most adopted (*n*=11, 24%) ✓ Used among managers (53%, *n*=10) and managers with more than 10 years experience (38%, *n*=8).	
Effectiveness	TA-Effective 82% (*n*=9)	NA-Somewhat effective 67% (*n*=4)
Reliability	TA-Reliable 73%, (*n*=8)	NA-Reliable 67% (*n*=4)
Affordability	TA-Expensive 45% (*n*=5)	NA-Expensive 50% (*n*=3)
Ease of Use	TA-Easy to use 100% (*n*=11)	NA-Not easy to use 50% (*n*=3)
Recommendations	✓ Combines soil, plant and weather-based measurements into 1 information source - recommended to all growers as a way to save labor from manual collection technologies - i.e., pressure bombs. ✓ Is a service-calculations are provided to a grower and maintenance is included - ideal for less “tech savvy” growers who want usable information at their fingertips. ✓ Offers automated irrigation scheduling-saves time.	
Possible barriers to adoption	✓ Is a new technology and therefore still perceived as risky-limits widespread adoption. ✓ Is moderately expensive (Annual $1500 subscription fee includes all maintenance and reporting). Each unit can read up to 10 acres - multiple stations needed in larger vineyards.	
Data sourced from: Shapland 2014; Tule Technologies 2018; LaBarge 2017, pers comm; California Association of Winegrape Growers 2014.		

Despite overall high scores in effectiveness, reliability and ease of use, surface renewal is only the fifth most used technology. This is likely because it is newer (released in 2014) and therefore not widely known (only six NAs had heard of it). Currently, adoption is limited to managers and experienced managers. As described earlier, managers are more likely to use newer technologies to stay competitive and experienced managers are likely more aware of technology trends.

One hundred percent (100%) of TAs perceive surface renewal as easy to use. Sensors installed directly into irrigation lines allow growers to automate irrigation. A subscription-based service, its automated email reports alert growers precisely when and how much to irrigate (LaBarge 2017, pers comm). NAs are clearly unaware of how this technology functions as they perceived it as just “somewhat” easy to use.

A large majority of TAs (83%) positively rated this technology as effective. As mentioned previously, it is the only technology that combines soil, plant and weather measurements to accurately determine a vineyard’s irrigation needs and thus informs both when and how much to irrigate as one information source. The only drawback is cost. Both NA and TAs perceive surface renewal as expensive. It would be interesting to explore in a future study whether its true cost is higher when compared against the cost of using multiple WMTs together, such as soil moisture sensors, private weather stations and pressure bombs.

Surface renewal offers much potential as an easy-to-use, highly accurate solution for all types of growers. This study recommends that Tule Technologies expand its outreach efforts to better inform potential users on functionality and cost saving benefits that could potentially offer a one-source solution for all types of growers.

8.2.6 Remote sensing/PV

Remote sensing		
Usage	Sixth most adopted (*n*=10, 22%) ✓ Used among managers (42%, *n*=8) and managers with more than 10 years experience (33%, *n*=8).	
Effectiveness	TA-Effective 70% (*n*=7)	NA-Somewhat effective 50% (*n*=7)
Reliability	TA-Reliable 60%, (*n*=6)	NA-Somewhat reliable 79% (*n*=11)
Affordability	TA-Somewhat expensive 50% (*n*=5)	NA-Somewhat expensive 36% (*n*=5)
Ease of Use	TA-Easy to use 90% (*n*=9)	NA-Easy to use 50% (*n*=7)
Recommendations	✓ Useful for large vineyards to determine where there are areas lacking water. ✓ When used in tandem can provide a reliable source of information to determine more precisely where to irrigate, eliminating unnecessary irrigations. ✓ Images offer visibility into an entire vineyard, not just the perimeter - useful to growers where accessibility into parts of a vineyard are difficult.	
Possible barriers to adoption	✓ Images generated cannot be used to determine the cause of vigor discrepancies - limits their ability to inform when or how much to irrigate. ✓ Time consuming data analysis is required to compare images to other data points from other modalities such as plant, soil or weather-based technologies to determine when and how much to irrigate – therefore, best used as ancillary information. ✓ Costs for NDVI technology are quoted at $5-8/acre with a minimum of $500 (60+acres), limiting their use to larger vineyards. ✓ Since images capture data at one specific time, multiple images are required to track changes over time, increasing costs.	
Data sourced from: Matese 2015*;* Greenspan 2016; Greenspan 2017, pers comm; Acevedo-Opazo et al 2008.		

Remote sensing is the sixth most frequently used relevant technology surveyed. Users of this technology rated it high in all categories except cost. This is because images are taken at one specific time. In order to track changes over the course of a growing season, multiple images are required, thus increasing costs. Images generated cannot directly inform a grower when or how much to irrigate, thus making TAs high scores in reliability, and effectiveness compelling. Perhaps growers rated it highly in its role as an auxiliary technology. In that case, it can provide very useful information on where to irrigate.

Remote sensor users, much like users of surface renewal and pressure bombs, are exclusively more experienced managers, most likely because this is a very modern technology that is still being refined (Greenspan 2016). NAs lower overall scores can be explained by the time-consuming data analysis required.

As improvements in imaging capabilities enhance its ability to determine the exact cause for vine vigor variability, remote sensing could become a reliable single information source for growers to determine both where and when to irrigate. Dr. Mark Greenspan (2016) has also noted that its price keeps decreasing.

8.2.7 Leaf porometers

Leaf Porometers		
Usage	Seventh most adopted (*n*=9, 20%) ✓ Used among managers (42%, *n*=8) and managers with more than 10 years experience (33%, *n*=8).	
Effectiveness	TA-Effective 56% (*n*=5)	NA-Somewhat effective 50% (*n*=10)
Reliability	TA-Reliable 56%, (*n*=5)	NA-Reliable 53% (*n*=8)
Affordability	TA-Somewhat expensive 44% (*n*=4)	NA-Somewhat expensive 36% (*n*=5)
Ease of Use	TA-Somewhat easy to use 44% (*n*=4)	NA-Easy to use 58% (*n*=7)
Recommendations	✓ Ideal for growers who have time or labor resources to collect data - this technology is precise and can help save water.	
Possible barriers to adoption	✓ Requires time-consuming manual frequent single-point measurements to accurately assess vine water status of a canopy – limits collection to larger growers who may have more resources. ✓ High one-time upfront cost ($2850/unit-Decagon SC-1) may be cost prohibitive for some. ✓ Measures plants response to irrigations- informing when to irrigate but does not inform how much- therefore best used in tandem with other modalities. ✓ Precise collection conditions –prone to user error if inexperienced. ✓ Data is not automated and requires analysis to utilize.	
Data sourced from: Acevedo-Opazo et al 2008; Hofer 2017 pers comm; Heinzen 2017, pers comm; Greenspan 2011; Matthiassen 2016, pers comm; Bogart 2006.		

It is unsurprising that leaf porometers are the seventh most frequently used technology surveyed. Similar to pressure bombs, data collection is time consuming and manual. To gather enough reliable data with which to make irrigation decisions, an average of 32 different vine leaf samples with four measurements per vine is recommended. This takes over three hours (Acevedo-Opazo et al 2008). Owner Donald Hofer explains, “Pressure bombs and leaf porometers indicate plant moisture status but it's a lot of work to get the data” (Hofer 2017, pers comm). This is a barrier among growers without viticulture teams or time to devote to collection. Additionally, precise collection conditions and an ability to identify ‘vine representative leaves’ require experience.

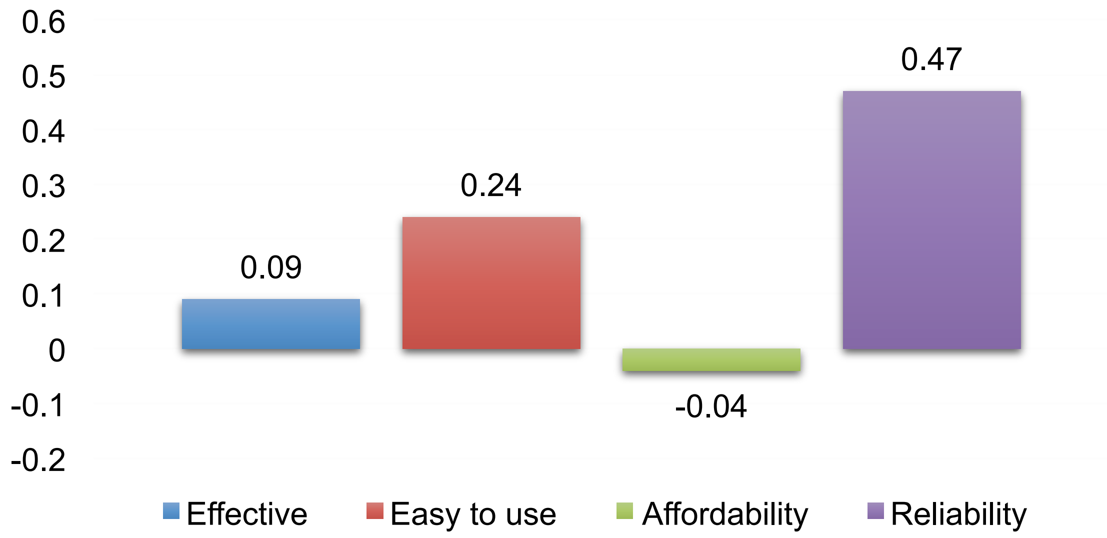
Despite the high one-time upfront cost (Decagon’s SC-1 is quoted as $2850), this technology can be used in any size vineyard and is reusable. However, time and labor costs involved in collecting usable data limit it to managers and experienced managers with the necessary resources (Heinzen 2017, pers comm; Greenspan 2011; Matthiassen 2016, pers comm; Bogart 2006). It is interesting to note that NAs perceive this technology as slightly easier to use than TAs, confirming their inexperience with using it.

Leaf porometers are currently impractical for many due to the precise collection times and conditions. As a result, this study does not predict adoption to increase beyond experienced managers.

8.2.8 Correlations between technology attributes and usage

Correlations between the adoption of a WMT among TAs (*n*=45) and their positive response to attributes are presented in Graph 1.

Graph 1: Correlation between adoption of technology among TAs and their positive response for that attribute



Interestingly, there is a negative correlation (-0.04) between technology perceived affordability and its adoption among TAs. TAs surveyed are more likely to adopt technologies perceived as unaffordable and suggests a lack of understanding about actual technology costs: the opportunity cost of using vs. not using WMT (short-term and long-term), different cost models, and the need for technology combinations. This makes it difficult to determine the real cost of WMT. This perception could link to different business approaches on cash-flow management – an agricultural mind-set (owners living "hand-to-mouth") vs. a business mind-set (management companies well financed to make investments) – and could cause differences in calculating costs among TAs. Understanding the real cost of using technology is complicated and merits further research.

Instead, technology adoption was most strongly correlated with reliability (0.47), followed by ease of use (0.24). There was no significant correlation between a technology's perceived effectiveness and its use among adopters. These findings suggest that TAs appear to select WMT based on their perceived reliability and ease-of-use. Owner John Backer explains, “Easy tools use micro-climate methods, hard tools measure at a single plant or site level” (Backer 2017, pers comm). This explains the overall categorical preference for weather-based technologies over plant and soil. Understanding that reliability and ease of use are technology selection drivers can help technology developers improve designs to better match a grower’s practical preferences and needs.

In summary, this study foresees an opportunity for growth among remote sensing, private weather stations, surface renewal and CIMIS technologies. It does not predict that use of pressure bombs or leaf porometers will expand beyond managers or experienced managers. “Tried and true” soil moisture sensors will remain in high demand for all growers. Finally, reliability and ease of use seem to be the main drivers for technology selection among TA – not costs. True costs, however, are confusing to determine and do not reliably correlate to adoption.

8.3 Factors That Influence WMT Adoption

Many factors influence whether a wine grape grower adopts WMT. This study has already presented the influence of ownership style and experience. It has also explored how grower perceptions of technology attributes are linked to their adoption preferences and has identified barriers to adoption among NAs. This section focuses on how agro-ecological factors including the vineyard size and water supply (drought conditions) impact adoption. It also explores whether the cost of water impacts WMT adoption and the relationship between the perception and impact of SGMA regulations and technology adoption. To give direction to the research, four hypotheses are defined:

1 Growers who own and/or manage larger vineyards are more likely to use water technologies.

2 Growers with drought-impacted vineyards will be more likely to use WMT.

3 Growers who pay more for water will be more likely to use WMT to reduce water costs.

4 Growers who are aware of the SGMA regulations will be more likely to use WMT.

8.3.1 Vineyard size influences WMT adoption

Previous studies have found that agriculturists of larger sized farms are more likely to use technologies (Adrian et al 2005; Daberkow & McBride 2004; Pierpaoli et al 2013; Pannel et al 2006). For further examination, this study surveyed how many acres wine grape growers owned and/or managed and whether or not they used technology.

Table 13: *Cross-tabulation between acreage of land owned and managed and using WMT*[23]

	Use WMT				
Acreage of land owned	Yes *n*	No *n*	Total *n*	$\chi^2(3)$	*p*
				6.60	.086
Less than 20 acres	15 (26.8%)	41 (73.2%)	56		
20-99 acres	6 (42.9%)	8 (51.7%)	14		
100-249 acres	4 (66.7%)	2 (33.3%)	6		
250-499 acres	1 (100%)	0 (0.0%)	1		
Acreage of land managed	Yes *n*	No *n*	Total *n*	$\chi^2(4)$	*p*
				15.79	.003
Less than 20 acres	6 (40.0%)	9 (60.0%)	15		
20-99 acres	6 (60.0%)	4 (40.0%)	10		
100-249 acres	4 (100/0%)	0 (0.0%)	4		
250-499 acres	2 (100.0%)	0 (0.0%)	2		
More than 500 acres	14 (100.0%)	0 (0.0%)	14		

The relationship between acreage of land owned and WMT use was not statistically significant ($\chi^2(1) = 6.60$, $p = .086$). This is likely because the sample size was skewed towards smaller growers with less than 100 acres. Future research with a more balanced sample size of small and large owners is recommended. However, the relationship between acreage of land managed and WMT use was statistically significant ($\chi^2(3) = 15.79$, $p = .003$). Growers who manage more than 100 acres (*n*=20, 100%) are more likely than managers who manage less than 100 acres (*n*=25, 48%) to use WMT. This supports the hypothesis that as vineyard size increases, so does the likelihood of WMT use.

[23] Note that the total *n* is higher than 101 due to growers both owning and managing different sized vineyards.

There are several plausible reasons for this finding. Growers with larger vineyards require more water than smaller ones. As a result, they are more impacted by water rationing or shortages and respond by using WMT to better manage water needs. Because the water and cost saving benefits of using WMT are more significant due to economies of scale, larger growers are also more likely to invest the time and labor needed to learn how to use technologies compared with smaller growers (Daberkow & McBride 2004). For example, Coastal Vineyard Care in Santa Barbara has an entire viticulture "tech" team devoted to using technologies that collect data for crop analysis (Newton 2017, pers comm). Manager Jeff Newton reports not just cost savings per acre from more precise water applications, but also significant revenue increases from resulting grape quality improvement. Larger scale viticulture also necessitates automated data collection, resulting in fewer person-hours per acre, thus making adoption of technologies more cost and labor effective for large growers (Newton 2017, pers comm). If growers are able to save money, save water and increase revenues, then benefits outweigh costs.

This presents an opportunity to increase WMT among non-adopting smaller growers who may lack financial, labor or logistical resources. Educating more growers about government resources such as SWEEP or EQUIP grants to fund improved vineyard water efficiency, or expanding educational efforts about the WMT's cost-saving and revenue-increasing benefits could promote more widespread adoption.

8.3.2 Drought conditions influence WMT adoption

The relationship between drought conditions and WMT adoption is not well researched in viticulture. One study did find a positive correlation between using more water efficient irrigation systems among Colorado agriculturists in response to the 2002 Colorado drought (Schuck et al 2005). To examine this relationship, this study surveyed whether a grower's vineyard was impacted by drought and if they adopted technology.

Table 14: *Cross-tabulation between effect of drought and using WMT*

	Use WMT				
Vineyard effected by drought	Yes *n*	No *n*	Total *n*	$\chi^2(1)$	*p*
				10.11	.001
Yes	40 (54%)	34 (46%)	74		
No	5 (19%)	22 (81%)	27		

The relationship between the effect of drought and water technology use was statistically significant ($\chi^2(1) = 10.11$, $p = .001$). Among growers with drought-impacted vineyards, a slight majority (*n*=40, 54%) use technologies but surprisingly nearly half (n=34, 46%) do not. These non-adopters with drought-impacted vineyards are mainly owners (*n*=35, 74%) who overwhelmingly own or manage smaller vineyards (less than 100 acres) (*n*=32, 94%). Some of these growers don't feel that potential water savings gained from using WMT are worth the investment. Owner John York explains, "I don't think there is a lot we can do that would result in substantial [water] conservation. Most of our local operations are also quite small, so I don't think any changes in our irrigation practices will result in anything statistically significant" (York 2017, pers comm).

Most growers are not ignoring the drought — they just do not turn to WMT for solutions. All growers surveyed (n=101, 100%) use best management practices such as assessing shoot tips to determine vine water needs or using a shovel to assess soil moisture status. Soil salinity is one of the biggest problems caused by drought conditions. Without rainfall to wash salts away, buildup around the root zones negates grape quality and is problematic in these regions. WMT does not solve this problem, which could plausibly explain why these growers aren't motivated to use it. Instead, owners of smaller vineyards are responding to the drought by investing in drought and saline resistant rootstocks as a long-term solution (Backer 2017, pers comm) or replanting with varietals that can be dry farmed and harvested earlier (Sapier 2017, pers comm).

Many growers have modified or adopted new technologies in response to the drought. Manager Erin Amaral of Pacific Vineyard explains "Growers are making a lot of advances in farming practices and investing money in technology to better their practices. Growers do not want their wells to dry up and render their land unproductive" (Amaral 2017, pers comm). In response to the drought, she adopted surface renewal in 2017 and observed that it saved 40% of water consumption in one of her vineyards (Amaral, pers comm 2017). Owner Bob Tillman also responded to the drought by replacing pressure bombs with sap flow monitors. He was able to cut water consumption by 30% (Tillman, pers comm 2018).

The link between the drought and using WMT is not clear. Drought conditions do motivate growers to change their water management practices, but not all turn to WMT choosing non-technology solutions instead. Finally, WMT cannot solve for soil salinity.

8.3.3 The cost of water influences WMT adoption

Adoption of water conserving irrigation technology in response to increased water prices is established in literature (Schoengold & Sunding 2011). Escalera et al (2015) found a positive correlation between an increase in water costs among San Diego avocado farmers and use of WMT. To explore if growers surveyed also respond to high water prices by using WMT, growers were asked how much they paid per acre foot for their water usage and whether they adopted WMT.

Table 15: *Cross-tabulation between price paid per acre foot and using WMT*

	Use WMT				
Price per acre foot paid for water in 2016	Yes *n*	No *n*	Total *n=101*	$\chi^2(2)$	*p*
				0.89	.641
Less than $1,000 per acre foot	19 (56%)	15 (44%)	34		
$1000 to $1499 per acre foot	3 (38%)	5 (62%)	8		
$1500 or more per acre foot	3 (50%)	3 (50%)	6		
I don't know	18 (37%)	31 (63%)	49		
Prefer to not respond			4		

The relationship between price paid per acre foot for water and using water technology was not statistically significant ($\chi^2(2) = 0.89$, $p = .641$). Use of technologies did not correlate with higher water prices. It is plausible that as costs increase, growers are less likely to spend money. Technology is perceived as expensive (Greenspan 2017, pers comm; Kahle 2017, pers comm; Heinzen 2017, pers comm). Owner Micole Moore explains, "When costs go up, expenses have to be carefully evaluated and tough decisions are made, so it's harder to invest in new technologies" (Moore 2016, pers comm). Growers may be more aware of technology's costs than its benefits, an area where technology companies can improve. An easy-to-use calculation tool for potential adopters to estimate a tool's costs savings (by comparing their water usage to potential water usage-savings per acre) could be useful to communicate how WMT benefits outweigh costs.

However, it is difficult to determine potential cost savings and revenue increases from reducing water use if growers are unaware of their water costs and usage. Nearly half of all growers surveyed did not know how much they paid for their water in 2016 (*n*=49, 48%). Growers unaware of water costs are less likely to see the benefit of investing in expensive technologies to lower water cost and usage. The low adoption (*n*=18, 37%) of these "unaware" growers, who are mainly owners (*n*=32, 65%) of less than 20 acres (*n*=42, 86%), could correlate to the overall low adoption of WMT in this study (45%). Without more clarity on current water usage and costs, it is challenging to convince growers of the need or benefits of WMT.

This lack of awareness may be difficult to rectify. A majority of growers surveyed source their water via their own private wells (*n*=84, 83%). Currently in California, the only cost to pump water from a private well is the cost of electricity. To determine actual water use, wells must be metered. This is problematic because two-thirds of viticulturists surveyed in California do not meter their wells, resulting in low awareness of actual water use (Greenspan 2014). The only way to determine well water costs and savings is by cross-referencing well meter readings with the electrical bill. If more well owners were aware of their actual water use by metering, they would potentially be more likely to consider solutions to reduce water usage and save money on electricity (Newton 2017, pers comm).

Mandating metered wells has met with much resistance among growers (Zelinsky 2016, pers comm; Greenspan 2016). In certain adjudicated basins, such as in the Salinas Basin in San Luis Obispo, well metering is already mandated. It is expected that upcoming SGMA regulations will require all growers who irrigate to meter their wells (Zelinsky 2016, pers comm; Newton 2018, pers comm; Greenspan 2017, pers comm; Stollberg 2016, pers comm). California irrigation expert, Dr. Mark Greenspan, states, “As the SGMA takes effect [in 2020], all well users will be required to monitor and report draws on their wells “(Greenspan 2017, pers comm). As metering becomes mandated, growers should gain a better understanding of the true costs of well water pumping. This may incentivize growers to use WMT to lower water use and expense, resulting in more widespread adoption.

8.3.4 SGMA water regulations influence WMT adoption

To achieve the goals set forth by SGMA regulations to bring groundwater basins under “sustainably safe levels,” it is widely expected that SGMA regulations will restrict the quantity of water that well owners can pump (Greenspan 2017, pers comm; Stollberg 2016, pers comm; Newton 2017, pers comm; Heinzen 2018, pers comm; Sapier 2017, pers comm). Growers will need technology to help track and report water usage. Dr. Mark Greenspan explained “eventually, 100 percent of California growers that use groundwater will be monitoring their water use with flow meters” (Greenspan 2016).

To determine whether anticipated SGMA groundwater regulations have already influenced growers in how they manage water use, growers aware of SGMA (*n*=67, 66%) were asked if they had modified or were in the process of modifying their WMT to prepare for these regulations. Fewer than half (*n*=29, 43%) responded that they were. Unsurprisingly, demographics reveal that the majority of these “early modifiers” are experienced (*n*=20, 69%) managers (*n*=21, 72%). Manager Randy Heinzen explains, “We are focusing on technologies that in addition to helping us refine application amounts, also digitally record and store pump meters/field flow rate/system hours. Having permanent records for use is anticipated to help in meeting future SGMA requirements” (Heinzen 2017, pers comm).

Many growers who are aware of SGMA have not modified (*n*=38, 57%) most likely because regulations do not officially begin till 2020 or 2022[24], making it still too soon for growers to know how SMGA will affect them and what changes will be needed for compliance.

A third of growers surveyed have never heard of SGMA (*n*=34, 34%). The majority of these “unaware” growers are located in San Diego/Ramona County (*n*=26, 76%) and own farms of less than 20 acres (*n*=23, 88%). Because all growers, regardless of size, will be impacted by anticipated regulations and will likely need to report their water pumping volumes, this study recommends that policy makers improve and target education and outreach efforts to smaller growers like those in San Diego County where overall awareness is still low.

Even though currently only 43% of growers have modified their WMT protocols, this study anticipates a significant, widespread increase in WMT adoption when SGMA regulations take effect in 2020. More educational resources need to be made

[24] GSPs (Groundwater Sustainability Plan) must be submitted by 2020 for critically overdrafted basins. All other basins must have GSP (Groundwater Sustainability Plans) completed by 2022 (Howitt et al 2015).

available to help growers understand how to select technologies that meet the new standards. This could create business opportunities for savvy tech companies as new adopters enter the WMT market.

9. Conclusions

WMT helps growers to irrigate vineyards more precisely and use water more efficiently, which is critical in drought-afflicted San Diego, Santa Barbara, and San Luis Obispo counties. This study is the first to explore reasons for widespread low adoption of WMT (45%) despite restrictions and reductions on groundwater supply in these regions. It establishes the reasons behind usage of the most relevant WMT, and explores growers' perceptions and preferences regarding WMT including barriers to adoption. This study is also the first to explore the correlation between WMT adoption among Central and Southern California growers and external factors such as drought conditions, water costs and water restrictive SGMA legislation.

9.1 Perceptions of WMT and usage trends

Analyses discover that variations in business models and farming experience influence WMT adoption trends. Motivators to adopt abound for the service-oriented manager-model. Competition to gain clients incentivizes managers to use WMT as a way to stand out. Different client needs may also motivate diversity of their WMT selections as seen by adoption of newer (surface renewal, remote sensing) technologies. By contrast, owner-model businesses tend to lack incentives to invest valued resources to learn about "the right" technology combinations and their proper implementation. The risk that investment in their limited time, money and labor required may not yield financial savings or improved grape quality limits their willingness to adopt or try different technologies. This sentiment is reflected in their overwhelming preference for “tried and true” soil moisture sensors or private weather stations. Notably, as growers gain experience managing their vineyards, their awareness of available WMT options increases, as does their confidence in their ability to use them. This notion is supported by survey results pointing to adoption of more difficult-to-use WMT (pressure bombs, leaf porometers) among more experienced growers. More widespread adoption could be encouraged if technology companies offered more practical technology solutions to resource-strapped and less experienced growers. Outreach efforts targeted at streamlining the adoption process can also be helpful.

Functionality differences between WMT are also important to understanding user selection. Findings suggest that growers prefer technologies that are reliable and easy-to-use. This is reflected by the high adoption rate of weather-based technologies that generate automated data characterizing a large portion of a vineyard at once (private weather stations, CIMIS) and the low categorical adoption of point-based soil and plant WMT. Obstacles of unreliability due to soil variation and vine truck thickness and time-consuming data collections conditions are plausible barriers for adoption of dendrometers, microchip sensors, matric sensors and neutron meters. If less than half of WMT available in these regions (42%) are considered too unreliable or difficult to use, perhaps growers who have tried them in the past are dissuaded from trying others. Technology companies should aim to improve the reliability and ease of use to better meet the needs of growers.

Interestingly, findings suggest that there is a negative correlation between adoption rates and perceived affordability. This suggests that there is confusion about the true cost of WMTs among users and merits further research to fully understand. Among NAs, ratings of technologies they *do not* use are often incorrect, often skewed towards a favorable yet unrealistic opinion. This suggests that NAs do not understand how to use certain WMT and are therefore unclear how the benefits could potentially outweigh their cost or risks. More targeted outreach by technology companies could help reduce confusion around the functionality of technology and among NAs, and encourage more widespread adoption.

9.2 Factors that influence the adoption of WMT

In addition to differences in grower experience levels, business models, and functionality between WMT, the study uncovered that vineyard size, ignorance around water costs and future SMGA regulations influence WMT adoption. The link between using WMT to solve for drought conditions is not conclusive.

1 Size matters. The ROI of using WMT favors larger economies of scale. As a result, it is plausible that technology companies target their marketing efforts toward larger scale growers or management companies over smaller ones: servicing fewer clients who buy more makes business sense. This could suggest a market niche exists for technology solutions for smaller scale viticulturists.

2-There is no clear link between the drought and WMT adoption. WMT do not solve the biggest problem caused by the drought – soil salinity. The benefits to using WMT in these conditions may seem less clear-cut and growers may focus on solutions that better mitigate yield and grape quality instead.

3-Grower ignorance around water usage and costs limits WMT adoption. Unrestricted groundwater use means that historically there have been no financial or legal incentives to encourage water-monitoring practices. This is reflected by the overall low WMT adoption rate and underscores the need for water-monitoring regulations like the anticipated SGMA. Correlation of water cost and use is an area that merits further research and exploration.

4- While historically not a factor, imminent SGMA regulations to reduce water use have caused management companies to respond to anticipated tighter controls by modifying their WMT protocols. Many growers, however, have not. Policy makers will need to improve their outreach and education efforts to bridge this gap.

SGMA regulations impact all well users across all agriculture sectors. Therefore, all irrigators will be forced to make permanent changes to their irrigation practices. Many farmers may convert some land to viticulture because wine grapes require less water than other crops. This could potentially change California's agricultural landscape. It is also plausible that future compliance to SGMA standards could cause a significant increase in WMT adoption creating an opportunity for savvy technology companies to exploit as new WMT users enter the market.

9.3 Future predictions and recommendations

It is clear that the benefits of using WMT are not well understood. Confusion over which technologies inform when, how much and where to irrigate have been identified as barriers to adoption. It is recommended that technology companies invest in outreach efforts to better educate non-users on WMT functionality and the potential cost and water savings. Although surface renewal comes close, no one technology is simultaneously the most reliable, effective, cost-effective and easy to use. Results may prove useful for technology developers and other viticulturists to clarify which technologies matter and why and presents an opportunity for technology developers to exploit. It is plausible that a technology offering a combination of automatically generated, wirelessly transmitted data with an easy to use and cost-effective management platform could inspire NAs to take a risk.

This study advances the understanding of the practical aspects of WMT. The research is clear: evidence strongly supports the following factors as most influential when it comes to adoption: decision-maker's length of experience, their available time or labor resources, managerial role over owner role, decision-maker's confidence or perception of risk, and size of vineyard. The finding that drought conditions and water costs are not strongly correlated to adoption is significant and reveals a crucial knowledge gap regarding awareness of water usage and cost to close to increase WMT adoption. It is indicated that SGMA regulations mandating water usage reporting will likely solve this problem and increase demand for WMT. Understanding how vineyard size, drought, water costs, SGMA regulations and technology limitations influence WMT adoption identifies necessary policy and communication areas to improve as the future supply of groundwater available to viticulturists in California is reduced.

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11. Appendices

11.1 List of Industry Interviews Conducted

Last Name	Company, Title or Role, and Location	Interview Date
Amaral, E.	Pacific Vineyard Co., Vineyard Manager, San Luis Obispo	January 13, 2017
Anjum, F.	Gro Guru soil moisture sensors, Owner. San Diego.	March 8, 2018
Backer, J.	August Ridge Winery, Owner, Paso Robles	April 10, 2017
Battany, M. Dr.	UCCE Chief Viticulturist, San Luis Obispo and Paso Robles	October 25, 2017
Carr, R.	Carr Winery, Owner, Santa Barbara	October 18, 2016
Clow, F.	Santa Barbara County Vintners Association, Executive Administrator, Santa Barbara	October 28, 2016
Gispert, C. Dr.	UCCE Chief Viticulturist, Riverside and San Diego	October 28, 2016
Greenspan, M. Dr.	Advanced Viticulture & Contributing Writer to Wine Business Monthly, Sonoma County	January 10, 2017, April 15, 2017
Heinzen, R.	Vineyard Pro Services, Operating Officer, San Luis Obispo	January 5, 2017, March 6, 2017
Hofer, D.	Kiler Canyon Ranch, Owner, Paso Robles	April 10, 2017
Kahle, M.,	San Diego Vintners Association, Secretary & Woof n Rose Winery, Owner, Ramona	October 31, 2016, March 5, 2017
Kahle, S.	San Diego Vintners Association, Education Director & Woof n Rose Winery, Owner, Ramona	October 31, 2016, March 5, 2017
McGeary, A.	Shadow Mountain Winery, Owner, San Diego	October 31, 2016
LaBarge, S.	Tule Technologies (Surface renewal), Director of Sales and Customer Development, Calfornia	December 20, 2016, January 8, 2017
Larson, E.	San Diego Farm Bureau, Executive Director, San Diego	December 21, 2016
Matthiasson, S.	Premiere Vit, Owner, Sonoma	December 16, 2016
Myers, M.	Roberts Vineyard Services, Owner, San Luis Obispo	May 8, 2018
McClellan, R.	Highland Hills Winery, Owner, San Diego	January 13, 2017
McWilliams, L.	San Diego Vintners Association, President, & San Pasqual Winery, Owner, San Diego	January 13, 2017
Moore. M.	Ramona Valley Vintners Association, President & Ramona Ranch, Owner, Ramona	December 20, 2017, January 2018

Newton, J.	Coastal Care Associates, Owner, Santa Barbara	October 31, 2016, February 6, 2017, February 18 and March 17, 2018
Sapier, S.	Vineyard Grant James, Owner, Ramona	April 13, 2017
Snyder, R. Dr.	Biometerology Specialist UC Davis, California	December 15, 2016
Stollberg, J.	Maverick Farming, Owner, Santa Barbara	October 19, 2016, February 13, 2017, March 16, 2018
Tillman, B.	Alta Colina Winery, Owner, San Luis Obispo	May 7, 2018
York, J.	Ramona Valley Vintners Association, Former President & Hellanback Ranch, Owner, Ramona	April 15, 2017
Zelinksi, L. Dr.	Independent Grape Growers Association, President & Precision Ag, Owner	October 27, 2016, February 13, 2017, April 16, 2017, January 7th, March 5, 2018

11.2 Grower Interview Questions:

1- Where do you farm? How many acres? Experience?

2-Are you an owner or manager or both?

a. If both, do you approach your vineyard and your client's vineyards differently? If so, how?

3- Are you aware of the drought?

a. Is your vineyard Impacted by the drought?

b. Have you adopted new technology or changed your practices due to the drought?

i. Are you planning on it? Why/Why not?

4-Are you aware of SGMA?

a. Have you adopted new technology or changed your practices due to upcoming SGMA regulations?

i. Are you planning on it? Why/Why not?

5- What WMT are currently being used?

a. Has this changed due to drought? Due to SGMA? Neither?

6-Which technologies do you use? Why/why not?

a. Can you tell me their costs/efficiency/usability/brand names?

b. What combination of technologies do you use and why/why not?

c. How many technologies do you use? Why/why not?

d. What are disadvantages to using WMT?

7- Is there a higher adoption rate between large and small growers?

a. What are the barriers to adoption?

8-What implications from the drought do you perceive?

a. Do growers anticipate more strict or relaxed regulations?

b. Will the drought impact costs moving forward?

c. Will it motivate growers to be more water conscious?

d. Anything else?

9-Are technologies easy to find in the marketplace?

a. Which ones?

b. Why/why not?

10-Which Technologies do you recommend? Why?

11-Do you have any suggested resources/contacts I can reach out to?

11.3 Survey Questions

I am a Master of Wine candidate currently working on the third and final part of the exam – the Research Paper. For my Research Paper I am examining WMT used by grape growers in Santa Barbara, San Luis Obispo, and San Diego counties.

Your input on these technologies is essential to the completion of my project. I appreciate your input and help on this important and relevant matter. Thank you for your time!

1. Do you currently own or manage a vineyard that grows wine grapes? (CHECK ALL THAT APPLY)
   Currently own a vineyard
   Currently manage a vineyard
   Do not currently own or manage a vineyard (IF NO, TERMINATE)

NOTE: PLEASE CHANGE VERBIAGE OF REMAINING QUESTIONS TO OWN VS MANAGE BASED ON ABOVE RESPONSES

2. Do you [own/manage] more than one vineyard?
   Yes
   No

(IF YES TO Q2, ADJUST VINEYARD/VINEYARDS)

3. Where is the vineyard/are the vineyards located? (CHECK ALL THAT APPLY)
   Santa Barbara County
   San Luis Obispo
   San Diego/Ramona
   None of the above (TERMINATE IF NONE OF THE ABOVE)

4. Overall, what is the total acreage of vineyard land that you [own/manage]?
   Less than 20 acres
   20 to 99 acres
   100 to 249 acres
   250 to 499 acres
   500+ acres

5. For how many years have you [owned/managed] vineyard(s)?
   Less than 2 years
   2 to 9 years
   10 years or more

6. Do you currently or have you ever monitored your water usage in the vineyard?
   Yes
   No – Skip to Q8
   I Don't know-Skip to Q8

7. For how long have you been monitoring your water usage in the vineyard?
   The last 12 months

1 to 2 years
2 to 4 years
4 to 6 years
6 to 8 years
8 to 10 years
More than 10 years

8. Has your vineyard been affected by the drought in California?
   Yes
   No

9. Have you ever heard of California's Sustainable Groundwater Management Act (SGMA)?
   Yes
   No

   (IF YES TO Q9)
10. Have you modified or are you in the process of modifying your WMT because of the drought or in preparation for the new SGMA regulations?
    Yes
    No

11. Why haven't you modified your WMT because of the drought or in preparation of the new SGMA regulations?

12. What technologies have you ever used to monitor water usage in your vineyard?
    Tensiometer technology
    Dielectric Soil Moisture Sensors (eg. Capacitance and TDT, TDR sensors)
    Neutron meter technology
    Electrical Resistance Blocks technology (eg. Gypsum blocks)

    Pressure bombs
    Leaf Porometer
    Dendrometry
    Microchip sensors

    Surface Renewal/Tule Technology
    Public Weather Station Technology (eg. CIMIS)
    Private Weather Station Technology (eg. Ranch Systems)
    Remote Sensing Technology (eg. Infrared Radiometer, LiDAR, NDVI Images)
    Other (PLEASE SPECIFY)____________
    None of these

13. As part of your water monitoring protocol in your vineyard, which of these technologies have you used in the past 12 months? (CHECK ALL THAT APPLY)

    Tensiometer technology

Dielectric Soil Moisture Sensors (eg. Capacitance and TDT, TDR sensors)
Neutron meter technology
Electrical Resistance Blocks technology (eg. Gypsum blocks)

Pressure bombs
Leaf Porometer
Dendrometry
Microchip sensors

Surface Renewal/Tule Technology
Public Weather Station Technology (eg. CIMIS)
Private Weather Station Technology (eg. Ranch Systems)
Remote Sensing Technology (eg. Infrared Radiometer, LiDAR, NDVI Images)
Other (PLEASE SPECIFY)____________
None of these

14. Thinking about other technologies that you HAVE NOT used to monitor water usage in your vineyard, with which of these are you familiar?
[SHOW LIST OF ALL TECHNOLOGIES NOT CHOSEN IN Q11/12] INCLUDE IN LIST AN OPTION TO CHOOSE NONE OF THESE

NOTE: IF NONE OF THESE WAS CHOSEN FOR Q11/12/13, SKIP TO Q20 AND Q21)

FOR Q14-19 – SHOW ALL TECHNOLOGIES SELECTED IN Q11/12/13]

15. In terms of being an effective source of information for making irrigation decisions, how would you rate these technologies?
(SCALE: EXTREMELY EFFECTIVE, VERY EFFECTIVE, SOMEWHAT EFFECTIVE, NOT VERY EFFECTIVE, NOT AT ALL EFFECTIVE)

16. In terms of reliability of correct data, how would you rate these technologies?
(SCALE: EXTREMELY RELIABLE, VERY RELIABLE, SOMEWHAT RELIABLE, NOT VERY RELIABLE, NOT AT ALL RELIABLE)

17. In terms of the cost (cost per acre), how would you rate these technologies?
(SCALE: EXTREMELY EXPENSIVE, VERY EXPENSIVE, SOMEWHAT EXPENSIVE, NOT VERY EXPENSIVE, NOT AT ALL EXPENSIVE)

18. In terms of their ease of use, how would you rate these technologies?
(SCALE: EXTREMELY EASY TO USE, VERY EASY TO USE, SOMEWHAT EASY TO USE, NOT VERY EASY TO USE, NOT AT ALL EASY TO USE)

19. In terms of their ability to help you reduce your monthly water usage, how would you rate these technologies?
(SCALE: EXTREMELY EFFECTIVE, VERY EFFECTIVE, SOMEWHAT EFFECTIVE, NOT VERY EFFECTIVE, NOT AT ALL EFFECTIVE)

20. Overall, which is your preferred technology for monitoring water usage?

ONLY ASK Q 20 IF ANSWERED NONE OF THESE TO Q11/12/13 COMBINED

21. Which of these statements best describes why you have NOT adopted new water monitoring technology in the vineyard. (Please select and rank the top 3 reasons with #1 being the Top reason).
    a. I don't know what technology options are out there
    b. The technologies are too expensive
    c. The technologies do not save me on my monthly water usage
    d. The technologies are not a reliable source of information
    e. The technologies are not an effective source of information
    f. The technologies take too much time in the vineyard to use.
    g. OTHER_______________________________

22. Do you use any of these techniques to help you monitor your water usage in your vineyard? (CHECK ALL THAT APPLY)
Shoot tip or leaf assessment
Visual inspection of vineyard
Other (PLEASE SPECIFY)
None of these

23. In the past 12 months, have you adopted any new water monitoring technologies in the vineyard[s] that you [own/manage] Yes
No (NO, Skip to 25)

23. Which of these statements best describes why you have adopted new water monitoring technology in the vineyard? (Please select and rank the top 3 reasons with #1 being the Top reason)

    h. To help me conserve water because of the drought
    i. To meet or prepare for new water regulations
    j. As part of a sustainability program
    k. To help me responsibly manage my land
    l. To save money on water costs
    m. To help me produce better quality grapes
    n. To try something new
    o. To save time in the vineyard
    p. To save money on labor costs
    q. To remain competitive in the market
    r. New water management technologies are easier to use compared to older ones
    s. New water management technologies are more efficient compared to older ones
    t. OTHER_______________________________

24. In terms of a percentage of your costs per acre, how much money have you saved through using a new technology for monitoring water usage in the vineyard?
    a. less than 10%,
    b. 10-29%,
    c. 30-49%,
    d. 50% or more

24. Where do you get your water from?

25. What percentage of your water do you get from?
    a. own well/groundwater
    b. municipal source
    c. Surface water: Rivers/Lakes/Streams
    d. Rainwater
    e. Other____________

(IF SOURCE WATER VIA OWN WELL-GROUND WATER (25a) AND ANSWERED SAN LUIS OBISPO OR SANTA BARBARA TO QUESTION 3, ASK:).

26. Do you source your water via a well (groundwater) in Santa Barbara or San Luis Obispo?
    Yes
    No

27. Is it over a critically impacted basin?
    Yes
    No
    Don't know

28. In 2016, how much do you pay per acre foot for your water usage?
    a. less than $1,000 per acre foot
    b. $1,000 to $1,499 per acre foot
    c. $1500 or more per acre foot
    d. I don't know
    e. Prefer not to answer

29. Which water sustainability certifications do you have (or are in the process of getting?)
    a. SWEEP Grants- California Department of Food and Ag
    b. EQIP Grants-USDA
    c. CCSW-California Sustainable Winegrowing Alliance
    d. OTHER_________________________
    e. NONE

Thank you for your time. If you would like to be entered into a drawing to win a $250 gift card towards a restaurant of your choice, please enter in a valid email address and phone number.

Email: __________________________________
Phone Number:___________________________

Thank you very much for your time.

11.4. Advantages and disadvantages to technology categories

Comparison of WMT by Category		
	Advantages	Disadvantages
Soil-based	* Data can indicate when and how much to irrigate - serving as a primary source for irrigation scheduling. * Once installed, automated data collection is easily retrieved.	*Sensors have limited “zone of influence” requiring multiple sensors to characterize vineyard water status. *Sensitive to soil variations and equipment malfunctions. *Sensor placement is critical to accurately assess water status. *Information gathered does not directly inform about the actual vine’s water status.
Plant-based	*Accurately and directly measures a vine’s water status and response to irrigation – informing when to irrigate.	*Requires manual time and labor consuming data collection (not automated) *Single point-based measurements necessitate frequent and numerous data collection points to accurately characterize a vineyard. *Equipment can be awkward and heavy to carry. *Data interpretation can be difficult and prone to user error.
Weather-Based/ Precision Viticulture (PV)	*Not point based: systems can provide automated data characterizing an entire block (surface renewal), portion of a vineyard or multiple vineyards (private weather stations, remote sensing). * Surface renewal accurately provides E data directly from a grower’s vineyard – to inform them when and how much to irrigate. *Provides convenient continuous readings and temperature alerts via telemetry to a cell phone or computer. *Can measure water loss from both the soil and the plant as one source of information for grower.	*CIMIS Reference ETo is hypothetical and not based on the actual vineyard conditions– data not reliable. *CIMIS data requires complex equations. *High land variability necessitates multiple weather or surface renewal stations for accuracy. *Remote sensing data cannot inform when or how much to irrigate it can only reliably estimate where.
Data sourced from: Peters, 2013; “Irrigation Scheduling,” 2016; Grant 2014; Burt 2012; Westover & Beal 2014; Pritchard et al 2004; Pregler 2007; Acevedo-Opazo et al 2008; McGourty 2015.		

11.5 Cross-tabulations between relevant technologies and effectiveness

		Effectiveness of technology			
Relevant technologies	Adopter (n=45) Non-adopter (n=56)	Not effective *n*	Somewhat effective *n*	Effective *n*	Total *n*
Soil moisture sensor	Adopter	0	7 (23%)	24 (77%)	31
	Non-Adopter	4 (15.3%)	12 (46%)	10 (38%)	26
Pressure bombs	Adopter	1 (7%)	4 (29%)	9 (64%)	14
	Non-Adopter	1 (4%)	15 (56%)	11 (41%)	27
Leaf porometer	Adopter	0	4 (44%)	5 (56%)	9
	Non-Adopter	1 (5%)	10 (50%)	9 (45%)	20
Private weather station	Adopter	2 (6%)	9 (29%)	20 (65%)	31
	Non-Adopter	2 18%)	2 (18%)	7 (64%)	11
Public weather station	Adopter	4 (22%)	8 (44%)	6 (33%)	18
	Non-adopter	11 (37%)	15 (50%)	4 (13%)	30
Surface renewal/Tule	Adopted	0	2 (18%)	9 (82%)	11
	Non-adopter	0	4 (67%)	2 (33%)	6
Remote sensing	Adopted	1 (90%)	2 (20%)	7 (70%)	10
	Non-adopter	3 (21%)	7 (50%)	4 (29%)	14

11.6 Cross tabulation between relevant technologies and reliability

Relevant technologies	Adoption of technology	Reliability of technology			
		Not reliable *n*	Somewhat reliable *n*	Reliable *n*	Total *n*
Soil moisture sensors	Adopted	5	6	20	31
	Did not adopt	4	8	9	21
Pressure bombs	Adopted	2	5	7	14
	Did not adopt	4	9	14	27
Leaf porometer	Adopted	0	4	5	9
	Did not adopt	1	6	8	15
Private weather station technology	Adopted	1	8	21	30
	Did not adopt	1	2	7	10
Public weather station technology	Adopted	3	3	11	17
	Did not adopt	6	11	6	23
Surface renewal/tule technology	Adopted	0	3	8	11
	Did not adopt	0	4	2	6
Remote sensing	Adopted	1	3	6	10
	Did not adopt	1	11	2	14

11.7 Cross tabulation between relevant technologies and ease of use

		Ease of use			
Relevant technologies	Adoption of technology	Not easy to use *n*	Somewhat easy to use *n*	Easy to use *n*	Total *n*
Soil moisture sensors	Adopted	1	8	22	31
	Did not adopt	5	7	7	19
Pressure bombs	Adopted	4	5	5	14
	Did not adopt	14	9	6	29
Leaf porometer	Adopted	2	4	3	9
	Did not adopt	2	3	7	12
Private weather station technology	Adopted	0	3	28	31
	Did not adopt	0	3	7	10
Public weather station technology	Adopted	1	2	15	18
	Did not adopt	0	8	16	24
Surface renewal/tule technology	Adopted	0	0	11	11
	Did not adopt	3	2	2	7
Remote sensing	Adopted	0	1	9	10
	Did not adopt	2	5	7	14

11.8 Cross tabulation between relevant technologies and cost per acre

		Cost of technology			
Relevant technologies	Adoption of technology	Not expensive *n*	Somewhat expensive *n*	Expensive *n*	Total *n*
Soil moisture sensors	Adopted	6	17	7	30
	Did not adopt	2	14	3	19
Pressure bombs	Adopted	6	5	3	14
	Did not adopt	1	11	13	25
Leaf porometer	Adopted	3	4	2	9
	Did not adopt	5	5	4	14
Private weather station technology	Adopted	7	9	13	29
	Did not adopt	3	2	3	8
Public weather station technology	Adopted	15	1	0	16
	Did not adopt	20	0	20	0
Surface renewal/tule technology	Adopted	2	4	5	11
	Did not adopt	2	2	3	7
Remote sensing	Adopted	3	5	2	10
	Did not adopt	4	5	5	24

11.9 Cross tabulation among relevant technologies and most positively perceived attributes.

	Most positively perceived technologies				
Relevant technologies	Usage *n*	Effective *n*	Reliable *n*	Easy to use	Not expensive *n*
Soil moisture sensor	31(69%)	24(77%)	20(65%)	22(71%)	6(19%)
Private weather station	31(69%)	20(65%)	22(71%)	28(90%)	7(23%)
Public weather station	18(40%)	6(33%)	11(65%)	15(83%)	15(83%)
Pressure bombs	14(31%)	9(64%)	7(50%)	5(36%)	5(36%)
Surface renewal/Tule	11(24%)	9(82%)	8(73%)	11(100%)	2(18%)
Remote sensing	10(22%)	7(70%)	6(60%)	9(90%)	3(30%)
Leaf porometer	9(20%)	5(56%)	5(56%)	3(33%)	2(2%)

11.9 Approved Research Paper Proposal

IMW Research Paper Proposal Submission Form			
Student ID	**23290**	**Date of submission**	**April 30, 2018**
RPP Version No	**2**	**Name of Advisor**	**Mary Gorman-McAdams MW**

Note: RPPs must be submitted via your Advisor to the IMW

Proposed Title

A Study of Water Monitoring Technology in the Drought Affected Counties of San Luis Obispo, Santa Barbara and San Diego: Current Usage, Attitudes Towards Technologies, and Factors that Influence Adoption.

Research Questions: Define the subject of your Research Paper and specify the specific research questions you plan to pursue. (No more than 200 words)

Water management in California viticulture is a high priority. In 2016 alone, drought resulted in an economic loss of $603 Million, a loss of 4700 jobs, and a net surface water shortage of 2.6 million acre-feet in California (UC Davis Center for Watershed Sciences). According to the US Drought Monitor, San Luis Obispo, Santa Barbara, and San Diego Counties are in the most impacted 'D4 Exceptional Drought' and 'D3 Extreme Drought' zones. Hence, water-monitoring technology, including irrigation and vine water status monitoring, is important to study, as water use continues to remain at the forefront of California public policy.

Currently, water monitoring is done by measuring moisture through the soil (tensiometers or neutron moisture meters), the vine (remote sensing infrared radiometers or sap flow sensors) and the weather (California Irrigation Management Information System or CIMIS weather stations).

This study will analyze the adoption of different available technologies, establish different technology perceptions, and to identify factors that influence adoption among wine grape growers.

An initial analysis of existing technology will present the technologies available in the market. A survey will establish grower adoption levels, rank grower perceptions of the different technologies regarding cost, ease of use, usability and reliability of water monitoring in Santa Barbara, San Luis Obispo, and San Diego/Ramona counties. Factors that influence wine grape grower water-monitoring technology adoption will be explored, especially whether worsening drought conditions and/or increased water usage regulation has influenced adoption. Results from within San Luis Obispo, San Diego and Santa Barbara Counties will be compared. This research paper will address three questions:

1. **Which technologies are available in the market?**

2. Who (i.e. which growers) has and who has not adopted technologies and what are grower perceptions of these technologies?

3. **What factors influence the adoption of water monitoring technology in these counties? And is there a correlation between water regulation and the adoption of technologies?**

Background and Context: Explain what is currently known about the topic and address why this topic requires/offers opportunities for further research. (No more than 200 words)
The economic and water losses resulting from 5 years of drought have spurred California legislators into action as evidenced by the passing of the Sustainable Groundwater Management Act (SGMA) in 2014 restricting growth of agriculture in areas over "critically overdrafted" ground water basins like the Paso Robles groundwater basin (California Department of Water). This has put water conservation research at the forefront of public policy ensuring that government agencies (California Department of Water) and Universities (University of California Cooperative Extension: UCCE) make water conservation methods, irrigation and monitoring tools available to agriculturalists. Studies like 'Technology in Precision Viticulture: A State of the Art Review' from the *International Journal of Wine Research* have also been published detailing available WMT and their effectiveness. Based on initial interviews with wine grape growers in Santa Barbara, San Luis Obispo and San Diego and Ramona Counties the overall water monitoring technology adoption rate was found to be less than 50%. Combined with sustained drought conditions and water regulations that limit water use, clearly there is a need for further research on this topic.
Sources: Identify the nature of your source materials (official documents, books, articles, other studies, etc.) and give principle sources if appropriate. (No more than 150 words)
Sources will include a combination of published research material, scholarly articles, magazine and periodical publication such as: • Matese A, Di Gennaro SF. (2015). Technology in precision viticulture: a state of the art review. *International Journal of Wine Research*, *2015:7* 69-81. doi: https://dx.doi.org/10.2147/IJWR.S69405 • C Acevedo-Opazo, B Tisseyre, H Ojeda. (2008). Is it Possible to Assess the Spatial Variability of Vine Water Status? *Journal International des Sciences de la Vigne et du Vine, 42 (4): 203-219*. Doi: 10.20870/oeno-one.2008.42.4.811 • Lasky, M. (2015, June). Water Use and Monitoring. *Wine Business Monthly*, *XXII (6),* 54-61. Interviews will also be conducted with subject- matter experts, including: • Dr. Mark Battany- UCCE Chief Viticulturist for San Luis Obispo and Santa Barbara • Dr. Lowell Zelinski- Viticulturist at Precision Ag Paso Robles and President of the Independent Grape Growers Association of the Paso Robles Area • Dr. Carmen Gispert- UCCE Chief viticulturist for Riverside and San Diego • Producers of WMT • Large scale viticulture management companies (Jeff Newton at Coastal Care, Jim Stollberg at Maverick Farming)
Research Methodology: Please detail how you will identify and gather the material or information necessary to answer the research question(s) and discuss what techniques you will use to analyze this information. (No more than 500 words)
Review of secondary sources and primary research interviews: Review published research material, scholarly articles, magazine and periodical publications and interview subject matter experts in order to identify: • Review and summary analysis of the most relevant WMT available and in use today. **Survey growers:** Survey vineyard managers/growers to uncover: • Who has and who has not adopted water-monitoring technologies?

- Which technologies are being used?
- What factors influence adoption of these technologies?
- Grower attitudes towards the cost, effectiveness, reliability and usability of available technologies
- Whether drought or new regulations have impacted adoption.

Survey Methodology:
The population size of 493 includes:

- Vineyard managers and grape growers in San Luis Obispo, San Diego and Santa Barbara Counties (size will be sourced from Department of Agriculture).

And is sourced from:

- San Luis Obispo/Paso Robles Counties: Independent Grape Growers of Paso Robles, San Luis Obispo Vintners Association, Paso Robles Wine Country Alliance
- Santa Barbara County: Santa Ynez Wine Country Association, Santa Rita Hills Winegrowers Alliance, Santa Barbara Vintners Association
- San Diego County: Ramona Valley Vintners Association, San Diego County Vintners Association, Ramona Valley Winery Association
- Department of Agriculture/Measurement Standards public records request for growers who use pesticides (organic and otherwise) in San Luis Obispo, Santa Barbara and San Diego Counties. This information will be used to determine the size of vineyards.
- University of California Cooperative Extension: Dr. Carmen Gispert Viticulture Farm Advisor for San Diego County.

With a confidence level of 95%, a confidence interval of 10%, the anticipated completed survey count would be 90. Using a list of producers built from the sources above, surveys will be sent via email.

Potential to Contribute to the Body of Knowledge on Wine: Explain how this Research Paper will add to the current body of knowledge on this subject. (No more than 150 words)

This study seeks to examine wine grape grower and vineyard manager adoption and perceptions of WMT. The results should serve to illuminate the most user-friendly, affordable, effective and reliable technologies currently in use, better understand wine grape grower preferences and develop recommendations for other wine grape growers considering investing in WMT. Understanding wine grape grower preferences can also help technology developers and university researchers improve technology design. Uncovering factors that promote or hinder adoption among wine growers can identify policy and communication areas for improvement. Understanding the influence of regulation on adoption will assist government agencies to better assess necessary further actions needed to promote a more widespread adoption.

Proposed Time Schedule/Programme: This section should layout the time schedule for the research, analysis and write-up of the Research Paper and should indicate approximate dates with key deliverables. *Dates of submission to both Advisors and the IMW must be those specified by the IMW.*

May: Complete final draft. Revisions.

June: Submit to advisor.