Designing User-Centered IoT Solutions for Small-Scale and Mid-Scale Farmers

by

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Submitted to the Integrated Design and Management Program
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Abstract

The UN predicts that by the year 2030, the global water demand will outstrip supply by 40%. In face of the global water crisis, it is crucial to increase irrigation efficiency in agriculture, which currently consumes 70% of the global freshwater supply. Studies have shown that using precision agricultural technology to control irrigation can reduce water consumption by as much as 20% and increase crop yield by up to 30% in developing countries. Such technologies, however, are inaccessible to millions of small-scale farmers who need them the most because of their prohibitive costs and design intended for large-scale farming businesses. To address this technological gap, social enterprise SoilSense delivers affordable and robust IoT soil sensor systems to small-scale farmers, empowering them to irrigate more efficiently by providing data on when and where to irrigate based on soil measurements.

This study analyzes existing literature on irrigation and soil sensor technology and applies a human-centered design approach to understand the needs of an underserved user group: small-scale and medium-scale avocado farmers. By engaging these farmers and subject matter experts in the field, key insights are drawn on the nuances of avocado cultivation, challenges in irrigation and water management, and the use of technology and data analytics in farming. This user research highlights the small-scale and medium-scale farmers' pain points and their vision for how technology could improve their operations. In addition to informing the iterative design of the SoilSense system prototype and business model, this study also endeavors to help address the global water crisis through continuous innovation and advancement in IoT agricultural technology.

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Deepest gratitude is also due to my SoilSense partners and teammates Jesper Alkestrup, Nichlas Kvist Jørgensen, and Ellie Simonson. Their camaraderie and passion to drive positive impact at the intersection of water, agriculture, and technology have inspired and helped shape this research. I would also like to express special thanks to all the avocado farmers and stakeholders who participated in this study for sharing their stories, perspectives, knowledge, and insight. Without them, we would not have a holistic understanding of the complexities and gaps in soil sensor technology and irrigation management.

I thank the MIT Priscilla King Gray Public Service Center for generously sponsoring the research study through the LEAP grant. My sincere gratitude also goes to Matt Kressy, Andy MacInnis, Anna Phan, John Stillman, the IDM staff, and my fellow classmates. Their unwavering support and inspiration fueled me through the late nights. Finally, I would like to express my deep love and gratitude to my family for their love and support throughout my life.

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Chapter 1

Introduction

1.1 The Global Water Crisis and Its Significance to Agriculture

"Water is life's matter and matrix, mother and medium. There is no life without water."

- Albert Szent-Györgyi, 1937 Nobel Prize in Physiology or Medicine

The Criticality of Water

Water, one of the most important substances on Earth, is critical to creating a hospitable climate for sustaining life and delivering oxygen and nutrients in living organisms, among other critical biological functions. UN-Water defines water as "the core of sustainable development" due to its direct impact on socio-economic development, healthy ecosystems, human survival, and global health. A universal solvent uniquely capable of existing in solid, liquid, and gaseous states in terrestrial conditions, water continuously moves through the hydrologic cycle, changing between different states through the processes of precipitation, evaporation, and condensation. Although water shifts through different states, the amount of water on Earth and in the atmosphere remains constant at 332.5 million cubic miles (Perlman 2016). A finite resource, water serves as "the crucial link between the climate system, human society and the environment," and water governance is key to managing the increasing competition for this valuable resource among the many water-dependent sectors.

<u>The Sources of Water</u>

How is water distributed on Earth? As shown in Figure 1, 96.5% of water is saline ocean water, and only 2.5% comprises freshwater.

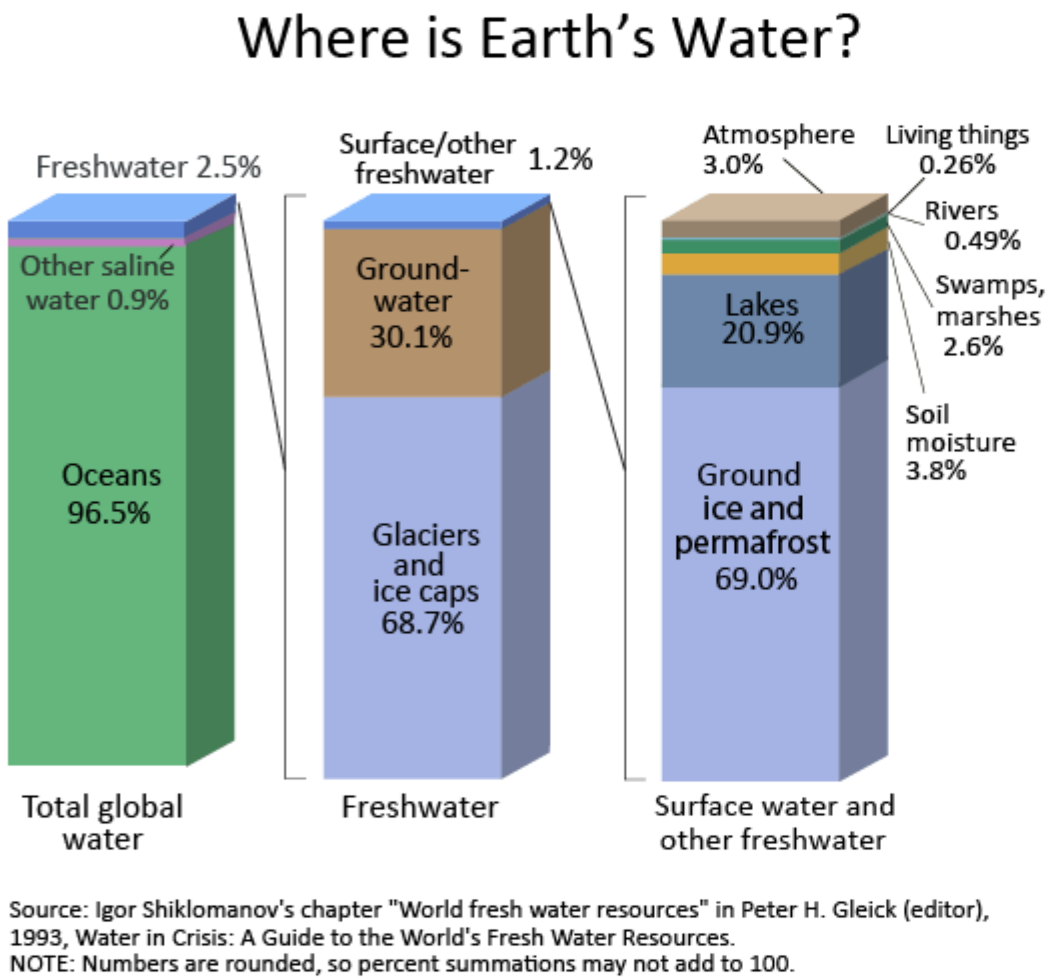


Figure 1. Where is Earth's water?

Additionally, Table 1 presents an aggregate view of the estimated global water distribution, showing the water volume, percent of freshwater, and percent of total water across 10 major water sources.

Table 1. Estimate of global water distribution

Estimate of global water distribution (Percents are rounded, so will not add to 100)				
Water source	**Water volume, in cubic miles**	**Water volume, in cubic kilometers**	**Percent of freshwater**	**Percent of total water**
Oceans, Seas, & Bays	321,000,000	1,338,000,000	--	96.54
Ice caps, Glaciers, & Permanent Snow	5,773,000	24,064,000	68.7	1.74
Groundwater	5,614,000	23,400,000	--	1.69
Fresh	2,526,000	10,530,000	30.1	0.76
Saline	3,088,000	12,870,000	--	0.93
Soil Moisture	3,959	16,500	0.05	0.001
Ground Ice & Permafrost	71,970	300,000	0.86	0.022
Lakes	42,320	176,400	--	0.013
Fresh	21,830	91,000	0.26	0.007
Saline	20,490	85,400	--	0.006
Atmosphere	3,095	12,900	0.04	0.001
Swamp Water	2,752	11,470	0.03	0.0008
Rivers	509	2,120	0.006	0.0002
Biological Water	269	1,120	0.003	0.0001
Source: Igor Shiklomanov's chapter "World fresh water resources" in Peter H. Gleick (editor), 1993, Water in Crisis: A Guide to the World's Fresh Water Resources (Oxford University Press, New York).				

A significant portion of freshwater is inaccessible since 68.7% of freshwater is stored in glaciers and ice caps, leaving only 30.1% of ground water and 1.2% of surface water. As ground water requires extraction from aquifers via wells, people most commonly use surface water from rivers and lakes, which accounts for 0.0072% of total water on Earth. Therefore, although water covers 70% of planet Earth and may appear to be inexhaustible and abundant, only a small fraction is available for use, making it a valuable and precious resource.

Water Consumption and Usage

How is water used or withdrawn from the hydrologic cycle? The United Nations Food and Agriculture Organization (UN FAO) distinguishes three types of water withdrawal: agricultural, municipal, and industrial. Agricultural water withdrawal includes using water for irrigation, livestock, and aquaculture. Municipal water withdrawal describes domestic water use, such as drinking, washing, and cooking. Industrial water withdrawal supports multiple industrial processes, such as power plant cooling, chemical treatments, product fabrication, transportation, hydroelectric generation, and precision cutting (UN FAO 2016). Among these uses, food, paper, and chemical production consumes large amounts of water (CDC 2016). Water is also withdrawn from the water cycle through evaporation into the atmosphere. UN FAO's AQUASTAT database, a tool that reports water statistics at the global and country levels, shows that after evapotranspiration, only 39% of the 110,000 cubic kilometers of annual precipitation converts to renewable freshwater.

The AQUASTAT tool also captures the water withdrawal ratios by geography. As depicted in Figure 2, at a global level, 69% of water withdrawal is attributed to agriculture, 19% to industrial use, and 11% to municipal use. The high agricultural water withdrawal is driven by economies dependent upon agriculture, primarily in Africa and Asia, where agricultural water withdrawal accounts for 82% and 81% of each respective region's water withdrawal.

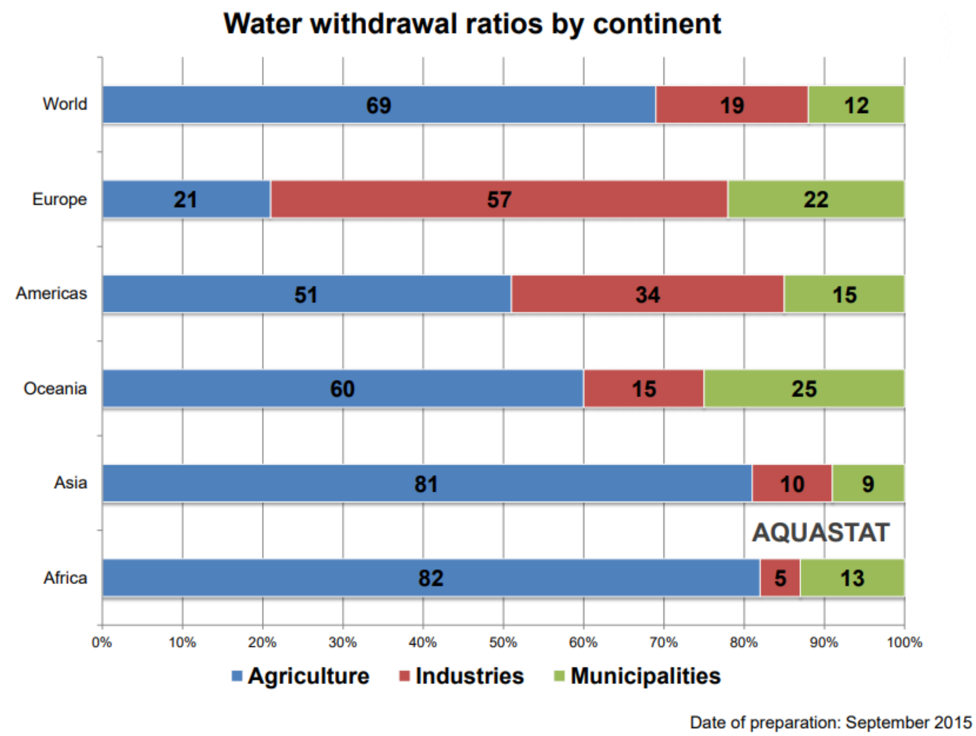


Figure 2. Water withdrawal ratios by continent

Furthermore, with world population increasing 4.4 times over the last century, the water withdrawal has grown substantially, increasing 7.3 times (UN FAO 2016). Figure 3 depicts the levels of global water withdrawal from 1900 to 2010 in the major sectors of agriculture, industries, and municipalities alongside the growth in global population over these years. Water withdrawal increased across all three sectors, with the most significant increase taking place between 1950 to 1960, and the agriculture sector consumes the largest amount of water by far.

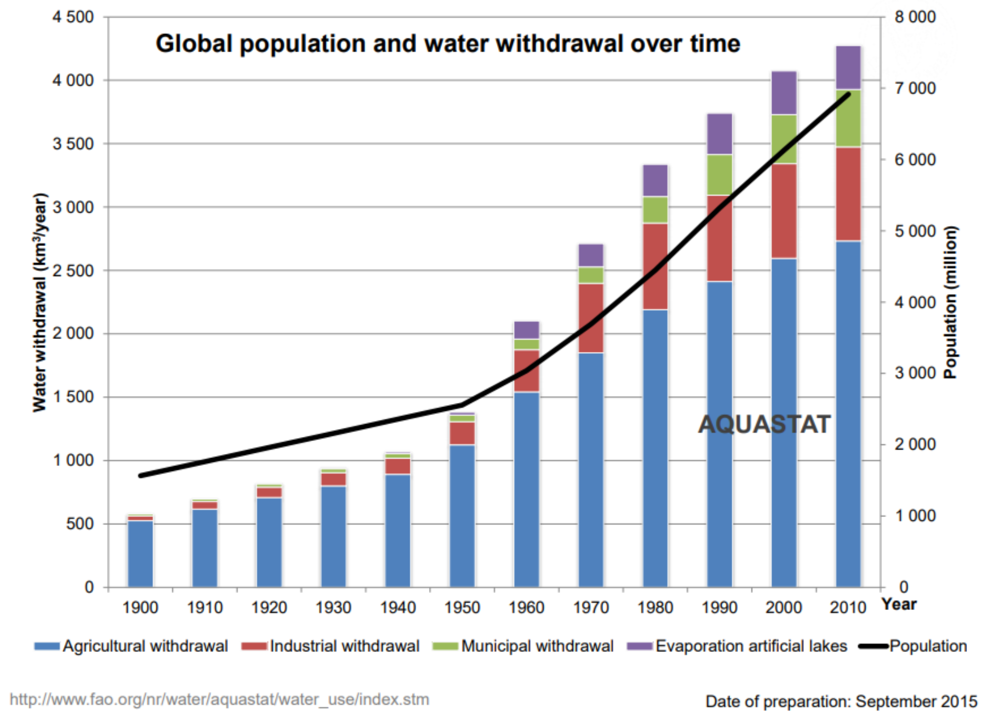


Figure 3. Global population and water withdrawal over time

<u>Present and Future Global Water Crisis</u>

Currently, 1.8 billion people drink from water sources contaminated with feces, placing them at risk of contracting diseases such as cholera, dysentery, typhoid, and polio (UN 2018). Water scarcity is derived from the annual water supply available in an area to the population. Hydrologists working together with the UN have set the threshold for water stress at 1,700 cubic meters per person and the threshold for water scarcity at 1,000 cubic meters per person. When the water supply in an area drops below 500 cubic meters, the population faces absolute scarcity. According to the UN, approximately 1.2 billion people—nearly one-fifth of the world's population—live in areas of water scarcity, and another 1.6 billion people—nearly one-fourth of the world's population—lack the necessary infrastructure to access freshwater (UNDESA 2014). Figure 4 from the World Resources Institute maps the water stress by country.

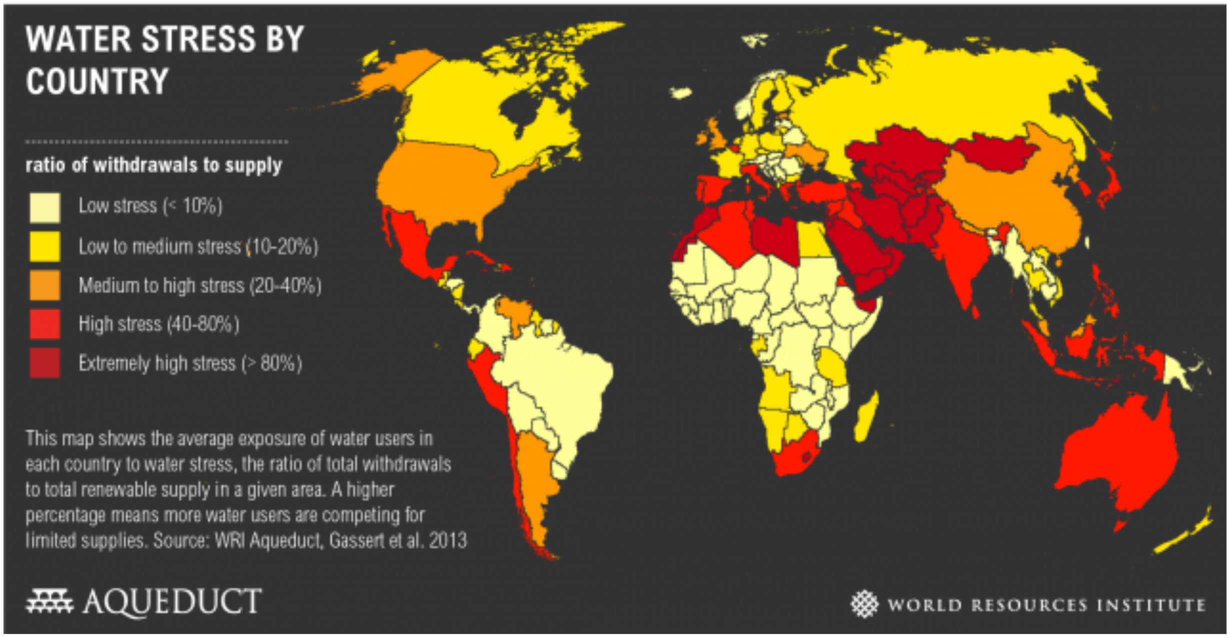


Figure 4. Water stress by country

Evidently, the majority of countries in North Africa and the Near East face acute water scarcity, as do Mexico, Pakistan, South Africa, and large parts of China and India. The World Resources Institute's study reveals that "37 countries currently face extremely high levels of water stress, meaning that more than 80 percent of the water available to agricultural, domestic, and industrial users is withdrawn annually." Water scarcity affects not only the agricultural heartlands, but also the world's most prosperous cities. The National Geographic study on global water scarcity assesses that 14 out of the 20 fastest-growing cities with the largest economies and highest populations also experience water scarcity or drought conditions. These megacities depicted in Figure 5 include Beijing, Cairo, Delhi, Istanbul, London, Los Angeles, Mexico City, Mumbai, New York, Osaka, Rio de Janeiro, Sao Paulo, Shanghai, and Tokyo.

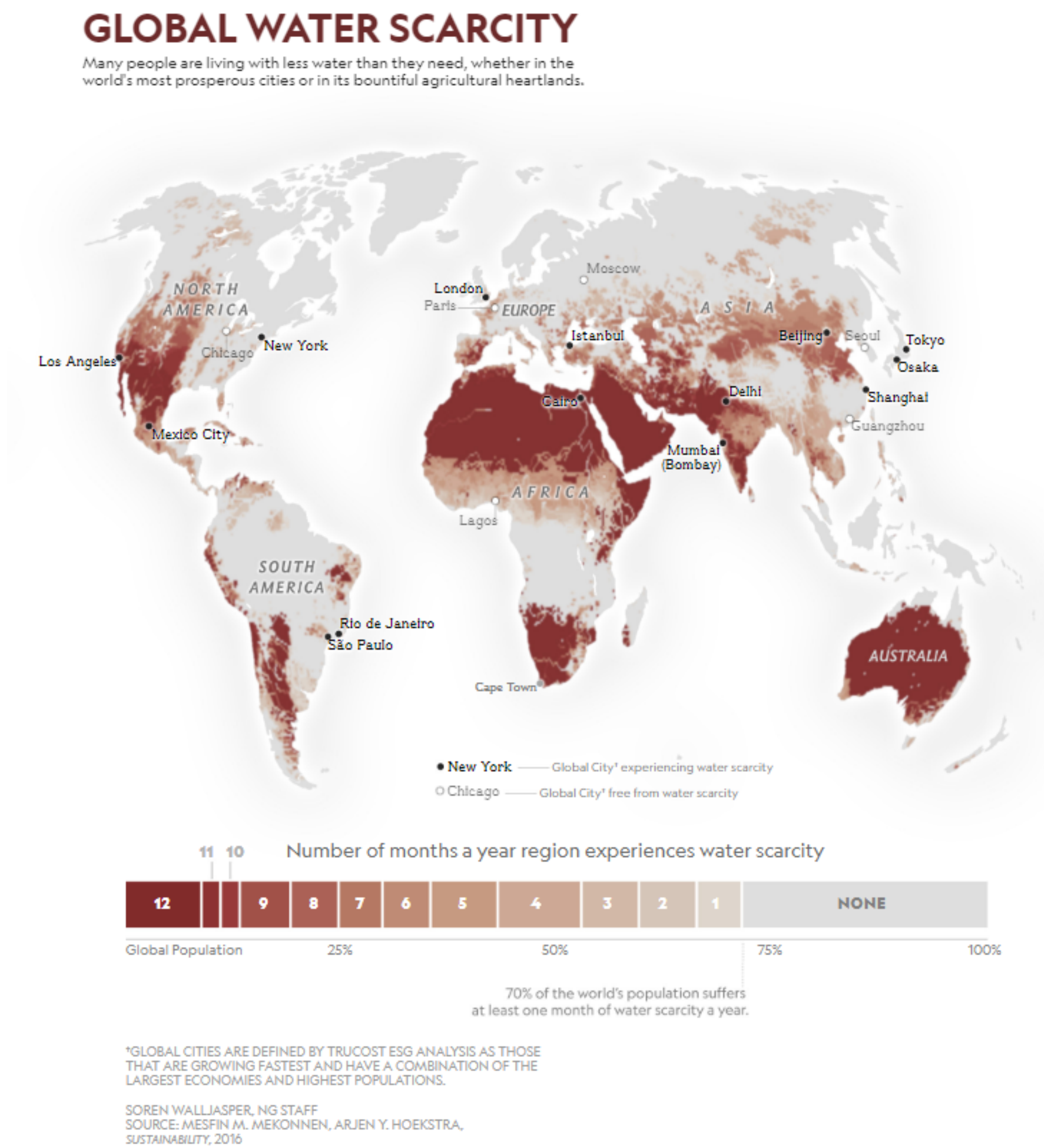


Figure 5. Global water scarcity

How will water scarcity spread in the future? Because human activity is the primary driver of water withdrawal, one must take into consideration the trajectory of the global population. The UN forecasts that the world population will grow to 8.6 billion by 2030, 9.8

billion by 2050, and 11.2 billion by 2100. Increasing amounts of water will be required to sustain human life for a burgeoning world population with longer life expectancies. Not only will more people be consuming more water for municipal use, additional water will also be required to cultivate more agricultural crops and livestock to feed the growing population unless greater water efficiencies can be achieved. In fact, continuing on the current trajectory with water use outpacing the rate of population growth in the last century and climate change impacting freshwater resources, the UN warns that the global water demand will outstrip supply by 40% in 2030 (UN 2018). Based on analysis conducted by the UN Development Program (UNDP), UN-Water, and UN FAO, "water scarcity is both a natural and a human-made phenomenon," a situation where adequate freshwater is depleted by uneven distribution, waste, pollution, and unsustainable water management.

The Impact of Agriculture on Water Scarcity

As discussed above, agriculture accounts for 70% of global water withdrawal. Based on the FAO's review, "only about 17% of the world's cropland is irrigated, but this irrigated land produces 40% of the world's food." With irrigated agriculture responsible for sustaining the world's population yet also consuming vast quantities of freshwater, it is important to assess the irrigation water requirement against actual irrigation water withdrawal. The water withdrawn for irrigation "largely exceeds" the irrigation water requirement "due to significant losses in distribution and application" (UN FAO 2016). These losses can be attributed to evaporative losses from the soil surface, transpiration from the plant surface, and inefficiencies in irrigation management (UN FAO 2016). Based on studies conducted by the United States Geological Survey (USGS), 40% of freshwater withdrawal in the U.S. can be attributed to irrigated agricultural production. In California alone, agriculture accounts for only 3% of the state's economy, but it consumes 85% of the water withdrawn (Myers & Kent 2001). To create a sustainable and water-secure future for the world, there is a clear need and opportunity to build solutions that drive water efficiency, particularly in the sector that requires the most water—irrigated agriculture.

1.2 Overview of SoilSense

SoilSense—a social enterprise originating from the MIT D-Lab, which focuses on developing practical solutions for global poverty challenges through collaborative approaches—aims to address the global water crisis through technological innovation. The vision of SoilSense is to democratize precision agriculture technologies for the millions of small-scale and medium-scale farmers impacted by the global water crisis. In developing an affordable and robust Internet of Things (IoT) soil sensor system, SoilSense endeavors to enable farmers to irrigate more efficiently by matching the irrigation water withdrawal with the irrigation water requirement.

How does SoilSense's technology work? SoilSense's sensor system combines traditional and proven gypsum sensor technology with modern IoT communication tools, such as LoRa wireless communications, to notify farmers when the soil moisture is below set thresholds in different parts of their field. The notifications help farmers understand precisely when and where to irrigate. Figure 6 outlines the four-step process.

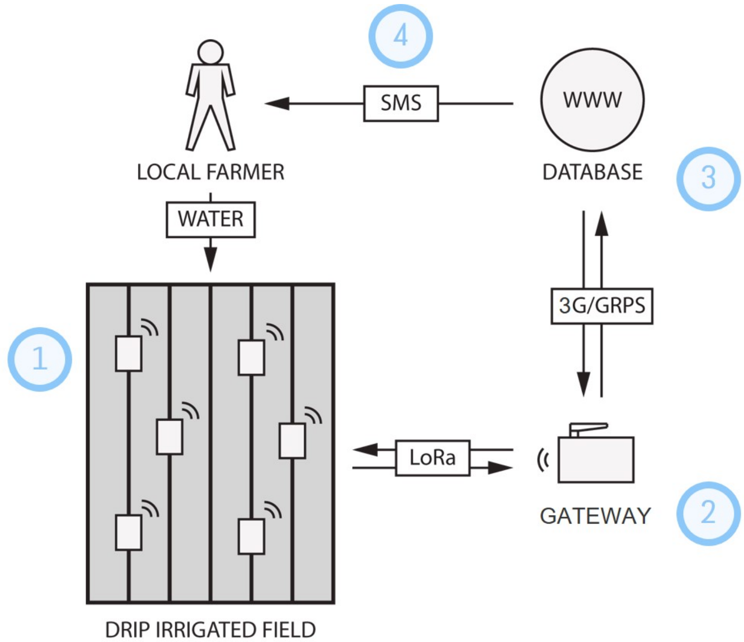


Figure 6. SoilSense sensor system

First, sensor nodes positioned around the field measure the soil moisture tension or soil water potential, which describes how much force or negative pressure the plant roots need to apply in order to extract water from the soil. Soil moisture tension is measured in kilopascals (kPa) or bars. The drier the soil, the harder it is for the plant to extract water, and the larger the numerical measure.

Second, the gateway receives the data from the sensor nodes via the LoRa wireless communication and sends the data to the cloud server via the 3G network. LoRa technology is ideal because of its long range and low power wireless platform that securely transmits data. This setup also provides added flexibility from the ability to partner with different local 3G providers.

Third, the data from the field are automatically processed in the cloud server. Depending on the farmer's needs, the sensor readings can be analyzed in multiple ways in the cloud, and only the most relevant data for the farmer are shared so as not to overload them with extraneous information.

In the fourth and final step, the farmer receives a text message notifying them when the soil moisture is low. The notification saves the farmer a significant amount of time from having to frequently check the soil moisture throughout the day. The simple four-step process is driven by a human-centered design approach, which places the small-scale and medium-scale farmers at the forefront of the design process.

1.3 Applying a Human-Centered Approach to Product Design

What is human-centered design, and why is it important to addressing the global water shortage? One could trace the roots of human-centered design back to Plato and the origins of grassroots democracy, where citizens have the ability to exercise power and express their needs through their elected representatives. The democratic method of engaging citizens—the stakeholders of a nation-state—and building governing institutions and regulations based on the needs of these stakeholders echo the fundamental principles of human-centered design.

Fast-forwarding to the 1960s, participatory design—also known as the Scandinavian approach—began to gain traction in the design world (Di Russo 2012). In this approach, end users are integrated into the prototyping phase of design projects. Although this approach places a strong emphasis on usability, it pays little attention to the user experience and user emotions. Conflicts between design decisions and user feedback are often resolved by abandoning user testing for the sake of efficiency. The idea of co-design, or collaborative design, emerges from this conflict to transform end users into cooperative designers.

Renowned design theorist Donald Norman redefined participatory design by coining the term "user-centered design." Unlike theorists in the participatory design school of thought, Norman focuses on the importance of understanding the user experience and user needs in the product development process. Norman defines the exemplary user experience as "meeting the exact needs of the customer, without fuss or bother." He also credits "simplicity" and "elegance" as the key elements that "produce products that are a joy to own, a joy to use" (Norman & Nielsen 2018). User-centered design and human-centered design are used interchangeably, but the latter delves deeper into driving creativity through a holistic, multidisciplinary mindset.

Global design and innovation company IDEO defines human-centered design as "a process that starts with the people you're designing for and ends with new solutions that are tailor made to suit their needs." Human-centered design is "all about building a deep empathy with the people you're designing for; generating tons of ideas; building a bunch of prototypes; sharing what you've made with the people you're designing for; and eventually putting your innovative new solution out in the world" (IDEO.org 2018). Today, human-centered design seeks to collaborate with the spectrum of users to understand not only their needs, but also their emotions and the social systems that underpin their needs. Because of its multidisciplinary and holistic approach, human-centered design is "seen to hold potential for resolving wider societal issues" by combining a people-focused perspective with a scientific approach toward creative problem solving (Di Russo 2012).

Architecture studio Kurani serves as a model and case study for how applying human-centered design and co-creating with users can generate powerful solutions. By engaging educators and students to dive deep into the learning experience and pedagogy in schools, Kurani is employing human-centered design principles to build a school and education model that prioritize happiness and positivity at the Riverbend School in India. Through Kurani's research and analysis, the team found that relationships are the primary source of happiness, and architecture formed around the social construct of villages enables the formation of strong relationships; therefore, Kurani's architectural design embodies the layout of a village with "intimate walkways, outdoor pavilions, and traditional courtyard housing" to encourage socializing. Equipping students with happiness and positivity will presumably by extension stimulate their overall development in the intellectual, physical, artistic, social, and environmental domains.

Similarly, SoilSense's soil sensor system adopts the human-centered design approach to build a solution that is tailored for small-scale and medium-scale farmers. The SoilSense team draws expertise from multiple disciplines—industrial design, electrical engineering, mechanical engineering, business, and agricultural development. A multidisciplinary skillset and mindset are not enough by themselves though. SoilSense also believes strongly in the importance of fostering robust local partnerships and engaging farmers to design the best-fit technology and user experience. Because of these design principles and the overarching goal to deliver direct social impact, SoilSense continuously engages with users throughout the design process to understand their user needs. Especially since small-scale and medium-scale farmers represent a unique segment of the population, observing their daily rituals on the farm, discussing their experience with growing and irrigating their crops, and understanding their emotional and functional pain points can generate invaluable insights from their user feedback. This user interaction and partnership are particularly critical throughout the prototyping process to inform the iterative design of the sensor system, validate the business model, and improve the overall user experience.

1.4 Research Questions

The SoilSense team has developed an initial sensor system prototype based on preliminary market and field research. Several key engineering, design, and business decisions around the functionality, user experience, and pricing model need to be validated by more in-depth user research. The user research aims to address these three research questions:

1. What is an appropriate target pilot market for the SoilSense soil sensor system?
2. What are the gaps and pain points with current soil sensor technologies in relation to the unique user needs of small-scale and medium-scale farmers?
3. What tools and features are helpful for small-scale and medium-scale farmers to increase crop yield and drive greater water efficiency?

The stakeholder selection and user research process are defined in Chapter 3 on Research Design and Methodology, and the detailed questions are available in the Appendix.

1.5 Synopsis

This thesis is organized in six chapters that provide an overview of how human-centered design is applied to help address the global water crisis by integrating user feedback into the iterative design and prototyping of SoilSense's IoT sensor solution. Chapter One introduces the significance of effective water management in the irrigated agriculture domain, social enterprise SoilSense's mission and human-centered design approach, and the key research questions arising in the early prototyping phase of the soil sensor system. Chapter Two maps out the irrigation and soil sensor technology landscape, analyzing the current gaps in soil sensor technology. Chapter Three delves into the research design and methodology by presenting an overview of the market research and describing the processes used to select and to interview stakeholders to gather their insights and feedback. Chapter Four summarizes the key findings from the user interviews, detailing the user demographics, avocado growing techniques, irrigation methods and tools, and user needs. Chapter Five analyzes the perspectives shared by avocado farmers and stakeholders to understand points of convergence and divergence in their avocado growing and irrigation practices. Finally, Chapter Six consolidates the analysis to address the original research questions, frames the user research in the broader academic context of related literature, and identifies areas of opportunity for future studies.

Chapter 2

Literature Review

2.1 Overview of Irrigation

Irrigation refers to the artificial provision of water to sustain growing plants and accounts for the majority of water withdrawal. Oftentimes, farmers supplement natural rainfall with irrigation to cultivate crops. The Center for Disease Control (CDC) defines eight common types of irrigation systems based on how the water is distributed through the field: surface irrigation, localized irrigation, drip irrigation, sprinkler irrigation, central pivot irrigation, lateral move irrigation, sub-irrigation, and manual irrigation. These different irrigation methods are depicted in the Figure 7.

Figure 7. Irrigation methods

Irrigation Systems: Average Application Efficiency

Among these different types of irrigation methods, drip irrigation achieves the highest average application efficiency (90%) due to its high water storage to water application ratio (Smith et al. 2014). The localization of drip irrigation delivers water droplets directly at or near the root of plants, therefore minimizing evaporation and runoff. By comparison, surface irrigation achieves 60% average application efficiency, and sprinkler application achieves 75% application efficiency (Smith et al. 2014). Surface irrigation fills the land with water by gravity without any mechanical pumps, while sprinkler irrigation disperses water like natural rainfall from a central location in the field or via sprinklers on moving platforms.

Irrigation Systems for Small-Scale and Medium-Scale Farmers

Taking into account the specific stakeholders for SoilSense, small-scale and medium-scale farmers, additional irrigation selection factors need to be considered. The FAO's guide on *Irrigation Techniques for Small-Scale Farmers: Key Practices for Disaster Risk Reduction Implementers* highlights several micro-irrigation techniques promoted by international agencies and specialized non-governmental organizations (NGOs).

It is important to note for the purposes of user experience design that the majority of small-scale farmers in developing countries continue to rely on manual irrigation today. These farming households irrigate 50 to 100 m^2 using tools such as watering cans locally produced from galvanized iron, plastic, or natural materials (e.g., bottle gourds). It only costs $5 USD or less for a watering can to irrigate an area of 100 m^2 or $500 USD per hectare (ha) (Smith et al. 2014). This method, however, is the most labor intensive, with labor costs ranging from $1,200 USD to $1,500 USD per ha per season based on the distance to the water source, assuming $1

USD per workday and a crop with a water requirement of 3,000 m^3 / ha. Therefore, the combined labor and technology costs can amount to $2,000 USD / ha.

International agencies and NGOs have introduced these micro-irrigation techniques to make groundwater sources available to small-scale farmers: treadle pumps, motorized pumps, and solar pumps (Smith et al. 2014). The treadle pump lifts water from up to a maximum depth of 7 m and irrigates 2,000 to 3,000 m^2 at a rate of 1 L per second, requiring at least 4 hours of pumping per day. Operating via a pressure or gravity outlet, the treadle pump works most effectively in areas with shallow groundwater at less than 3 m deep. Labor costs amount to $150 USD for a set of intake and output hoses, or $600 USD / ha, and the technology requires an investment of $120 USD per treadle to irrigate 2,500 m^2, which equates to $500 USD / ha. Therefore, the combined labor and technology costs can amount to $1,100 USD / ha. Motorized pumps support areas of 5 to 200 ha in village irrigation schemes; however, they can also support areas of 1 to 5 ha for more established small-scale farmers who can afford the $200 to $500 USD technology and $500 / ha per season operational costs. Solar pumps, on the other hand, have limited energy outputs and irrigate smaller areas of 0.3 to 1 ha. Although operational and maintenance costs are relatively low, ranging from $50 to $100 USD / ha, solar pumps require a high initial investment ranging from $10,000 USD / ha to $15,000 USD / ha. Treadle, motorized, and solar pumps can save farmers tremendous amounts of time transporting water across distances, and they can be connected with low-pressure pipe distribution systems or drip systems to irrigate fields. These three systems are depicted in Figure 8.

Treadle Pump | **Motorized Pump** | **Solar Pump**

Figure 8. Irrigation systems

Beyond pumps, shallow wells, canals, and pipe conveyance systems are additional methods to tap into groundwater resources. These systems require technical support for proper design, construction, and installation. Irrigation systems can also be implemented at the community level. The FAO delineates three basic types of small-scale or community irrigation schemes: river or spring diversion, small earth dams, and pump scheme. These systems can support from 5 to 200 ha and require community involvement in the planning, operation, and maintenance phases to ensure a successful deployment. High operational costs and ongoing maintenance may pose a burden to small-scale farmers. Their respective technical conditions, requirements, and constraints are defined in Table 2.

Table 2. Technical conditions, requirements, and constraints for various irrigation systems

Table 10: Irrigation schemes conditions, requirements and constraints

Irrigation system	Technical conditions	Requirements	Constraints
River or spring diversion	• Adequate water supply for two seasons • Reasonable distance (<2 km) from intake • Existing WUA	• Motivated WUA, prepared to substantially contribute in rehabilitation works and carry out O&M • Adequate funds available for diversion • Adequate technical assistance for design and technical advisory services • Intensive participatory training and extension (PT&E)	• Rehabilitation costs • Motivation of WUA members to pay fee for O&M • Tendering construction works • Support services to be provided for at least two years
Small earth dams	• Small streams • Favourable land formation (rolling) suitable for dam site • Suitable area (2–5 ha) to be irrigated near the dam site • Suitable soils for dam construction in vicinity	• Motivated water users group, prepared to substantially contribute in construction works • Adequate funds available for dam construction • Adequate technical assistance for design and technical advisory services to farmers • Specialised contractors for proper design and contractors with earth moving equipment experience	• High investment costs • Limited duration of water availability • Siltation • Flood damage risks • High maintenance • Motivation and capacity of WUA members to pay fee O&M • Support services to be provided for at least several years
Pump scheme	• Adequate water supply • Functioning main structural works • Existing WUA	• Motivated WUA, prepared to substantially contribute in construction works and carry out O&M • Adequate available funds for rehabilitation works • Adequate technical assistance from technical advisory services • Intensive farmers training (PT&E)	• Rehabilitation costs • Motivation of WUA members to pay fuel costs and O&M • Support services to be provided for at least two years

What factors do small-scale farmers need to consider when selecting the best-fit irrigation system? First, the farmers need to evaluate how far away the freshwater sources are from their field and how much water is available for irrigation during the different seasons. Then, the farmers need to determine which areas of their field are suitable for irrigation based on the fertility of the soil, landscape of the terrain, and crop type. Before deciding upon an irrigation technique, the farmer needs to conduct an assessment of the total costs, complexity of the installation, ease of operations and maintenance, and learning requirements. Government agencies and NGOs operating in the area may be able to provide consultative, financial, and training support to ensure that farmers have the adequate provisions for water sourcing, conveyance, and distribution across their fields (Smith et al. 2014).

Table 3 illustrates the main elements for consideration in an irrigation water supply system, summarizing the technical conditions, requirements, and constraints related to the different irrigation techniques.

Table 3. Technical conditions, requirements, and constraints for various irrigation techniques

Table 13: Overview of technical conditions, requirements and constraints to be considered for the various irrigation techniques

Irrigation techniques	Technical conditions	Requirements	Constraints
Watering can	Which water source (river, open shallow wells) is in walking distance	Minimal investments Watering cans commercially available	High labour input
Treadle pump	Water source not deeper than 7 metres	Capacity building for local manufacturing Development market	Labour costs
Motor pump	Available surface and groundwater sources Financing of fuel costs	Motor pump commercially available Access to markets for produce	Investment costs Operational costs
Low-cost well development	Favourable hydro-geological conditions	Training of local drilling teams Development market	Well development costs
Solar pumps	Water source not too deep Construction of water reservoir	Commercially available and local services	Low discharge, small areas High investment
Low-pressure pipe distribution system	Motor pump or treadle pump available Small reservoir	Assistance for installation by local technicians	Installation costs
Drip irrigation	Limited water resources available Reservoir and pressure height	Trained staff for installation and management advice Availability of spare parts in the local market	Installation costs Efficient operation
Sprinkler irrigation	Pumping from nearby water source (surface or groundwater)	Commercially operated farm Supplemental irrigation	High installation and operational costs

Furthermore, Table 4 outlines the investment costs and operational costs for the different irrigation technologies.

Table 4. Investment and operational costs for various irrigation technology

Table 14: Indicative investment costs of equipment

	Irrigation technology	Indicative investment costs in US$/ha	Life span in years
1	Watering can	500	2
2	Treadle pump	600–750	4–5
3	Motorized pump	200–400	5–8
4	Solar pump	10 000–15 000	8–12
5	Gravity canal system	600–800	10–15
6	Pipe distribution system	1 000–1 500	8–12
7	Open well lining	500–1 500	10–15
8	Shallow tube well	300–500	8–12
9	Sprinkler irrigation	3 000–5 000	5–8
10	Family drip irrigation	10 000–12 000	4–6
11	Small-scale irrigation schemes	3 000–8 000	10–12

Table 15: Indicative operational costs

	Irrigation technology	Indicative operational costs in US$/ha
1	Watering can	1 200–1 500 (labour)
2	Treadle pump	600–800 (labour)
3	Motorized pump	500–700 (energy)
4	Solar pump	50–100 (labour)
5	Open canal system	120–160 (maintenance)
6	Pipe distribution system	20–40 (maintenance)
8	Sprinkler irrigation	800–1 000 (energy)
9	Family drip irrigation	500–600 (labour)
10	Small-scale irrigation schemes	400–1 000

2.2 Overview of Soil Moisture Sensing

While irrigation technology is important for ensuring that crops receive the necessary water to thrive when there is inadequate rainfall, soil sensor technology supports irrigation decision-making by providing farmers with information on when, how much, and where to irrigate. First, one needs to understand the different states of soil moisture and the associated terms used to quantify the moisture content. Key measurements of moisture include: 1) soil water content, 2) soil water potential, and 3) plant available water.

Soil water content refers to the amount of water in a given amount of soil and is expressed either as a percentage of water by weight or volume of soil or as inches of water per foot of soil. Based on the type of soil, there are higher and lower water storage capacities. It is important to note that a higher water holding capacity does not equate to more water available for plants to use. Figure 9 showcases the storage capacities of different soil types.

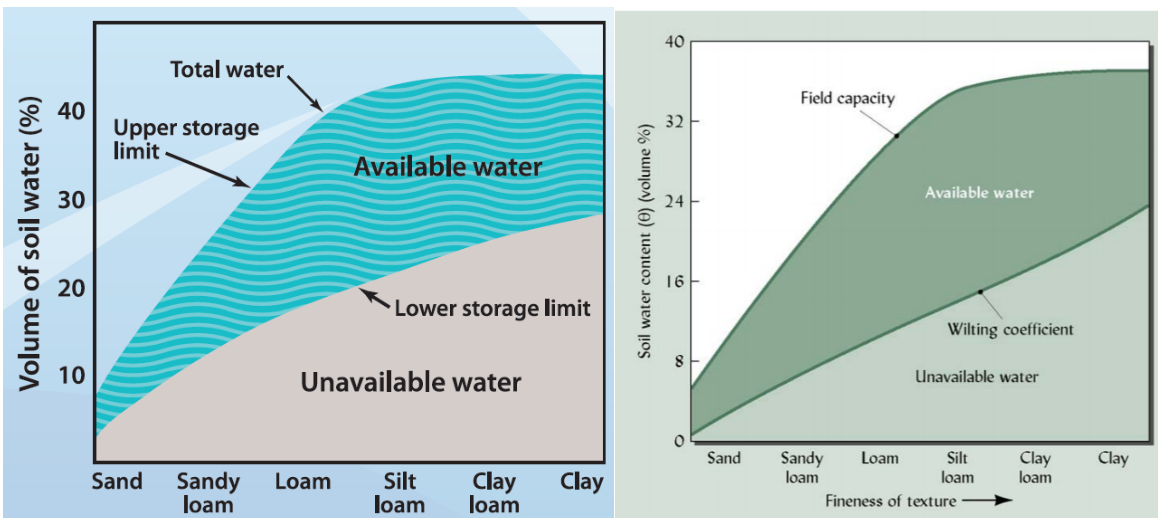


Figure 9. Amount of water available and unavailable for plant growth in various soil types

The interaction between soil type, water holding capacity, and water availability is illustrated in Figure 10.

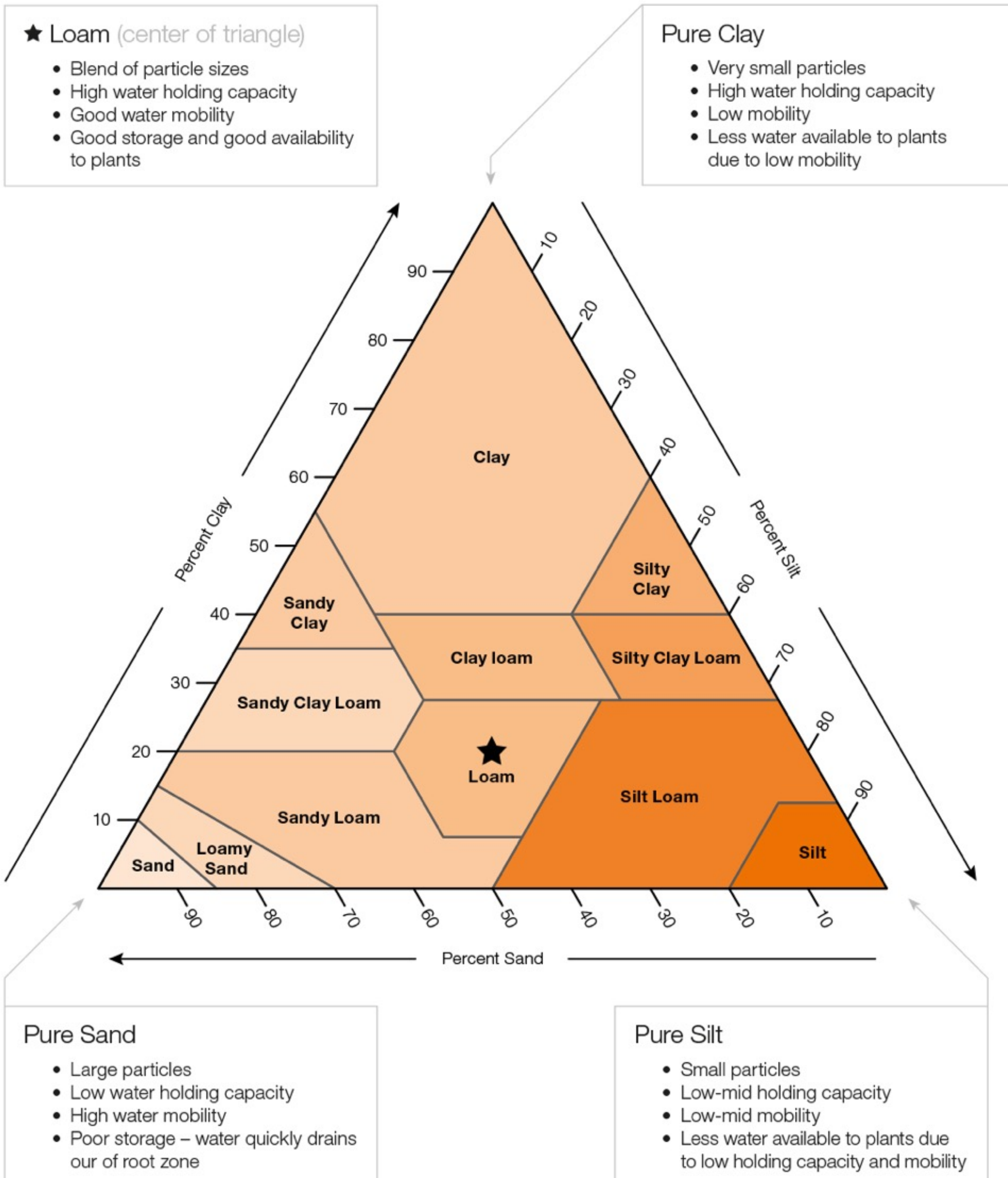


Figure 10. Soil texture triangle

Typically, sandy soils have lower water storage capacity while clay soils have higher water storage capacity. In other words, sandy soils are moist or saturated at 20% volumetric water content, but clay soils are nearly dry at the same measurement (ICT International 2014). Interpreting soil water content, therefore, requires an understanding of different soil physical properties such as its texture, structure, and porosity. On the other hand, the soil water potential measures moisture independently of these variables and works irrespective of the soil type; therefore, soil water potential is considered the "universal technique" for soil measurement (ICT International 2014).

Soil water potential is also referred to as soil moisture tension or matric potential. The soil water potential measures how much water clings to the soil, which translates into how much pressure the plant must exert to draw water from the soil. The drier the soil, the more energy the plant expends to draw water, which means the greater the soil water potential, or the more negative the number is in kilopascals (kPa) or centibars (cb). The units of kPa and cb correspond in a 1-to-1 ratio. Per ICT International, the field capacity or optimal moisture potential for agricultural plants is set at -33 kPa, while the permanent wilting point or point of plant mortality is set at -1,500 kPa. Field capacity and permanent wilting point vary from plant to plant based on the species. The plant available water, or the amount of water that is readily available to the plant, is derived from the difference between the field capacity—the upper limit of water that the soil can hold after excess water is drained by gravity—and the permanent wilting point—the lower limit of water beyond which the plant can no longer extract water from the soil. Table 5 provides Watermark's guidelines for interpreting soil matric potential readings.

Table 5. Watermark's guidelines for soil matric potential readings

Soil Matric Potential (in cb or kPa)	Implication for Irrigation
0-10	Saturated soil
10-30	Soil is adequately wet (except coarse sands, which are beginning to lose water)
30-60	Usual range for irrigation (most soils)
60-100	Usual range for irrigation in heavy clay
100-200	Soil is becoming dangerously dry for maximum production

Multiple elements contribute to the magnitude of the soil matric potential, including the soil water content, the soil pores' size, surface properties of the soil particles, and surface tension of the soil water (Whalley et al. 2013). Combined adsorption forces at the soil-water interfaces and surface tension forces at the air-water interfaces result in hydrophobic or hydrophilic soils (Soil Management 2018). Although clay soils tend to have a higher water storage capacity, the clay structure is composed of smaller pores that hold water at higher suction pressures, which require more plant energy to extract. Whalley et al. describe these forces and interactions in mathematical terms. In clay soils, the matric potential (ψ_m) is a combination of the effects of hydrostatic pressure (P) and osmotic pressure (π_D) as defined in the equation $P=\psi_m-\pi_D$. In sandy soils where there is negligible surface charge, the matric potential equals the hydrostatic pressure, or $P=\psi_m$.

According to Whalley et al., "both water content and matric potential need to be measured if soil water status is to be fully described." The van Genuchten function maps the relationship between the soil water content and the matric potential for agricultural soils. Referred to as the water release characteristic, this relationship assumes the form of a sigmoidal and highly non-linear water release curve with three distinct regions as shown in Figure 11 (Whalley et al. 2013).

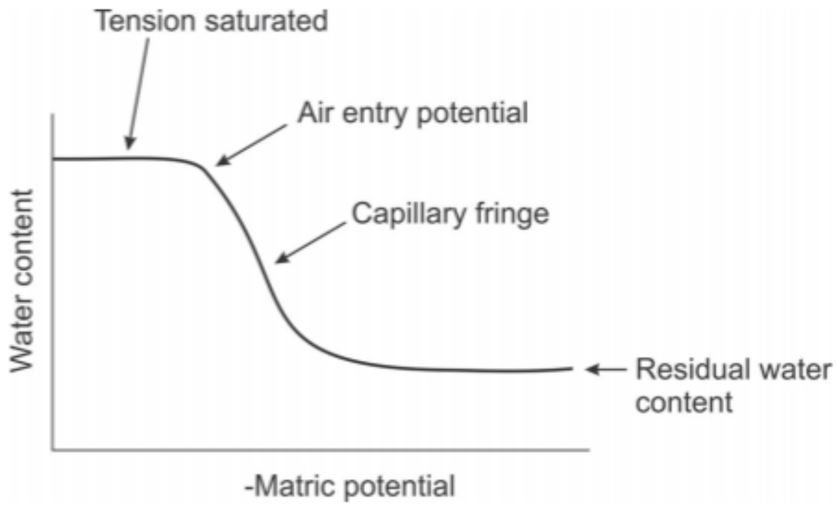


Figure 11. Water release characteristic

When the water content is saturated, the soil is “tension saturated” because no water will drain. Air gains entry into the soil matrix at the “air entry potential” and continues to invade the soil matrix through the “capillary fringe” as the matric potential becomes more negative and the soil dries. At low levels of water content, there is a corresponding low matric potential represented through a very negative matric potential, and the soil is characterized to have “residual water content” when the meniscus at the air-water interface becomes disconnected. Figure 12 illustrates the varying water release characteristics for sand, loam, and clay soil types.

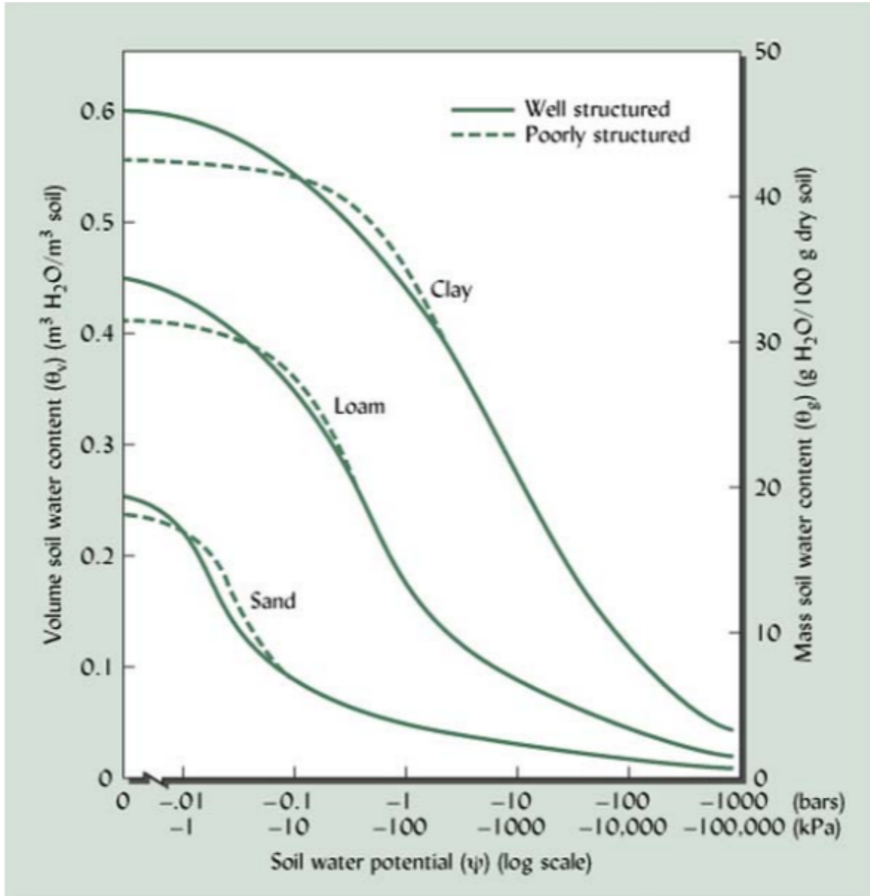


Figure 12. Water release characteristics for sand, loam, and clay soil types

Variables such as the soil type, soil damage, and soil structure can all affect the water release characteristic. Due to these variables and the non-linear relationship between the soil water content and matric potential, estimating the matric potential from the soil water content can be inaccurate. Instead, the use of soil sensors provides a more reliable reading of the soil matric potential.

2.3 Overview of Soil Sensor Technology

The majority of farmers use the hand feel method to determine the amount of water content in the soil. The farmer simply scoops up a mound of soil near the plant root zone and feels the soil moisture using their hands. Some farmers ribbon out a strip of soil between their thumb and index finger to observe how far the ribbon extends, as depicted in Figure 13; the longer the soil ribbon, the more moisture it contains.

Figure 13. Soil moisture feel test

To produce a more precise reading on soil moisture, different tools and technologies are available in the marketplace. The most commonly used tools include: 1) electrical resistance blocks known as gypsum blocks, 2) tensiometers, 3) time domain reflectometry, and 4) frequency domain reflectometry.

Electrical resistance blocks are made up of two electrodes embedded in a gypsum block, which is a soft sulfate mineral. In her research on *Measurement of Soil Moisture Using Gypsum Blocks*, Birgitte Friis Dela notes that gypsum blocks have been used in soil science for the past fifty years. Gypsum blocks are installed in the soil typically near the top third and bottom third of the active root zones to facilitate the start and end points of the irrigation cycle (Irrometer 2018). When an electric current is sent through the gypsum block, it generates a reading of the electrical resistance between the two electrodes, which correlates directly with the soil water content. When the soil is saturated, the gypsum block holds more water, which creates a lower electrical resistance. As the soil dries, the gypsum block loses water, which increases the electrical resistance. Gypsum sensors operate best at soil matrix potentials ranging from -100 kPa to -1,500 kPa and do not measure moisture content as well between 0 to -100 kPa. Figure 14 depicts Watermark's gypsum sensor on the left and Delmhorst's gypsum block on the right.

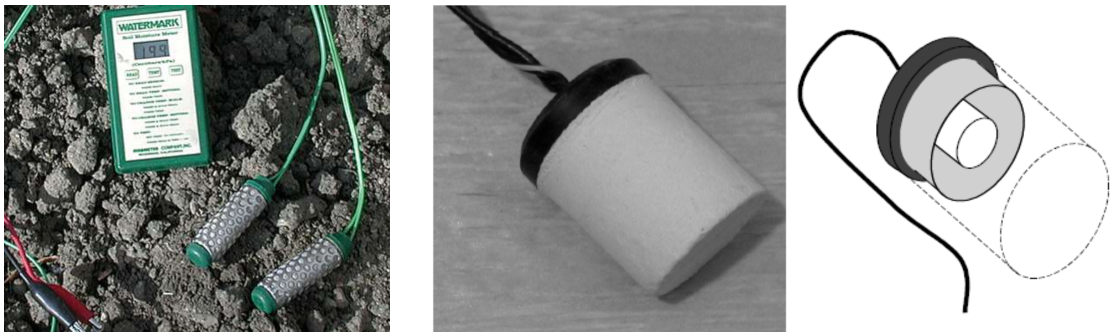


Figure 14. Watermark and Delmhorst gypsum sensors

While electrical resistance blocks can provide fairly accurate measurements, the accuracy is impacted by the installation of the blocks, the block temperature, and blocked pores (ICT International 2018). The blocks must first be soaked prior to installation, and the blocks should be placed in undisturbed soil that reflects the soil profile in the active root zone.

Tensiometers comprise a pressure gauge attached to the top of a column of water in a plastic or glass tube resting on a porous ceramic cup that is embedded in soil. When the soil is at capacity, the ceramic cup will hold the column of water in place. When the soil begins to dry and is no longer at field capacity, water seeps through the ceramic cup. The movement of water through the tensiometer creates a vacuum that is reflected in the pressure gauge. The higher the reading on the gauge, the drier the soil. Because tensiometers provide a direct measurement of matric potential, they tend to be the preferred type of sensor (Whalley et al. 2013). While tensiometers typically provide reliable and accurate readings, particularly in higher soil moisture ranges up to around -85 kPa, the water in the column needs to be refilled when the vacuum is low, and a hand pump needs to be used to remove air from the tube (Texas A&M 2018). Typically, tensiometers are installed at the base and the center of the root zone to indicate when irrigation should stop and start respectively, as shown in Figure 15.

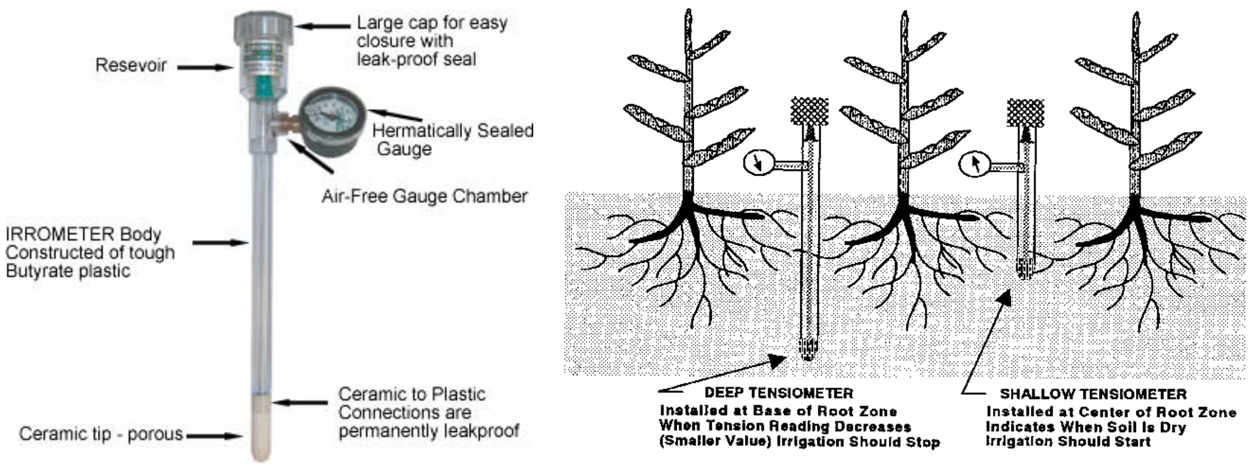


Figure 15. Tensiometer design and installation

The Irrometer tensiometer uses the graph in Figure 16 to chart the upper and lower thresholds of water depletion, which correspond to the reference dry value and the reference wet value. Watermark recommends irrigating when 50% of the available water is depleted (the vertical yellow line) and stopping irrigation around 10% available water depletion (the vertical aqua line), factoring in the soil type.

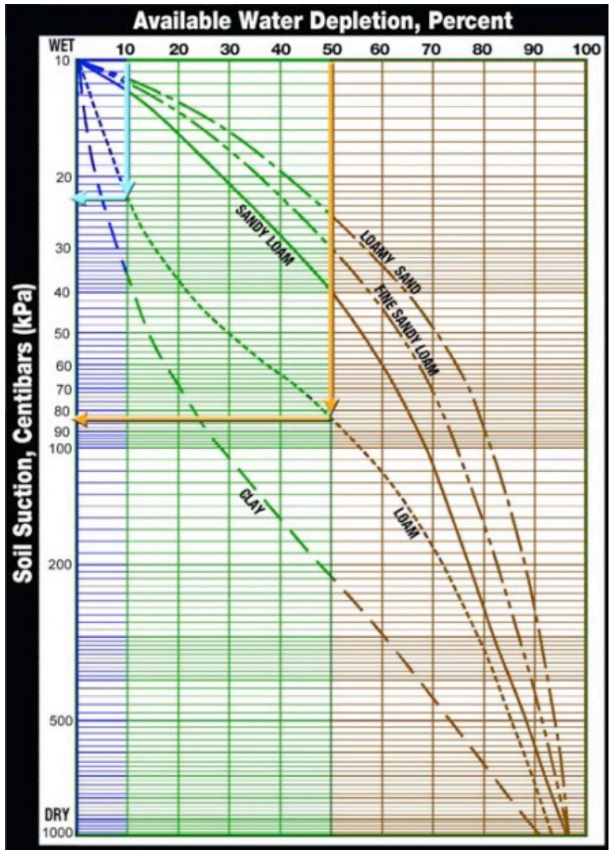


Figure 16. Soil suction and available water depletion

Time domain reflectometry, like gypsum blocks, determines soil water content through electrical measurements. In 1980, Clarke G. Topp introduced a time domain reflectometry method to determine soil water content in his article titled *Electromagnetic Determination of Soil Water Content: Measurements in Coaxial Transmission Lines*, which represents one of the foremost publications on the calibration of time domain reflectometers (Antle 1997). An electromagnetic pulse is sent through metal probes placed in the soil, which generates an electrical capacitance measurement recorded on an oscilloscope when the pulse reaches the end of the probe and is reflected. How quickly the pulse is reflected, or the travel time of the electromagnetic wave, indicates the soil water content; the shorter the wave travel time, the drier the soil because lower water content decreases the soil's dielectric (U.C. Davis 2018). Figure 17 depicts a time domain reflectometry sensor.

Figure 17. Time domain reflectometry sensor

Given the complex electrical field around the probes used in both time domain reflectometry and frequency domain reflectometry, the sensor needs to be calibrated for different soil types. Frequency domain reflectometry uses sensors that are less expensive and produce a faster response time compared to time domain reflectometers; however, the latter is known to produce more accurate measurements. British researcher R. L. Smith-Rose first documented the use of frequency domain technology to relate soil moisture in 1933 in his paper *The Electrical Properties of Soil for Alternating Currents at Radio Frequencies* (Antle 1997). The frequency domain system consists of two electrodes embedded in the soil through which an oscillating current is driven. Figure 18 depicts a capacitance probe connected to a solar power system used in frequency domain reflectometry. The voltage equals the current multiplied by the soil capacitance. As the soil water content increases, the soil capacitance increases. In other words, soil with more moisture has a greater ability to transmit electrical current (Martin 2018).

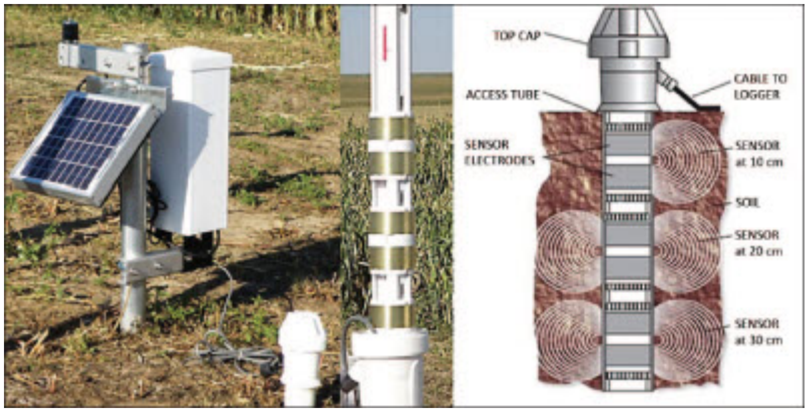


Figure 18. Frequency domain reflectometry sensor

2.4 Analysis of the Gap in Soil Sensor Technology

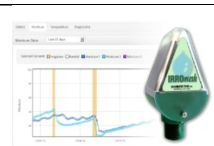
Due to limitations in the operating range of tensiometers, the academic research-oriented design of time domain reflectometers and frequency domain reflectometers, and the average higher price points for these three sensor technologies, SoilSense's market research into the competitive sensor landscape did not focus on these areas. Instead, SoilSense evaluated what is currently available in the market for electrical resistance sensors and capacitive sensors to understand where there may be opportunities for product innovation. SoilSense also reviewed smart sensors solutions that incorporated IoT, cloud-based analytics, and artificial intelligence (AI) systems.

To facilitate comparisons across sensor systems, one needs to apply a common baseline for the number of sensors that are required within a given area. The Meter Group states that the number of sensors depends on the heterogeneity of the soil and topography. The more heterogeneous the environment (e.g., existence of hills and valleys, seasonal precipitation, diverse canopy cover), the more sensors are required in areas that represent the major sources of heterogeneity. Irrometer advises installing two sensor stations per 40 acres (~16 hectares) at a minimum, with additional stations being added in problem areas or in areas with different soil conditions. Also, there should be at least two sensors in each area to capture the moisture measurement at two depths—the central and lower root zones. To factor in the heterogeneity of the land, irrigation specialists recommend using 6 to 8 sensors are per hectare (3 to 4 sensor nodes with sensors installed at 2 depths).

<u>Electrical Resistance Sensors and Meters</u>

Table 6 provides the company, photo, description, price, warranty policy, and power requirement for prevalent electrical resistance sensors and meters. Generally, electrical resistance sensors are considered to be the most affordable sensor solution due to the low cost of gypsum blocks. Per irrigation specialist Hal Werner's assessment, irrigating a field using electrical resistance blocks costs from $1.50 to $5 per acre factoring in the cost of resistance blocks ($5-$30) and meters ($150-$300). Werner's cost assessment is on par with Watermark Irrometer's estimates of $6-$35 resistance blocks and $250 meters. Prices provided on company websites lean toward the upper range of these estimates though, with industry leader Watermark pricing their sensor at $44.20 and their IRROmesh data logging system at $1,595. It is important to note that gypsum blocks can decompose or be damaged through exposure to the elements; therefore, they need to be replaced after 2 years (Werner 2002). Both analog and digital meters can be connected to gypsum sensors to generate readings. A common setup involves the farmers manually connecting the meter to the sensor, viewing the measurement, writing down the measurement, connecting the meter to the next sensor, and repeating the process. More advanced meters, referred to as data loggers, automatically record soil moisture readings from different sensors across the field, and the data is available for review and analysis through the company website and / or mobile application. These data loggers are available at a higher price point and can even be integrated with the irrigation management system to automatically turn on and turn off the irrigation when specified matric potential thresholds are met.

Table 6. Comparison of electrical resistance sensors

Company	Model	Photo	Description	Price	Warranty	Power
Delmhorst	KS-D1 Digital Soil Moisture Tester with GB-1 Gypsum Sensor Blocks		Soil moisture tester and gypsum sensor blocks; moisture range 10-1,500 kPa	- $350 (KS-D1 meter) - $120 (GB-1 pack of 10)	1-year	9V
Watermark	200SS Sensor		Sensor consists of a pair of highly corrosion resistant electrodes that are imbedded within a granular matrix; moisture range 0-239 kPa	- $44.20 (5-ft cable)	1-year	N/A
Watermark	30-KTCD-NL Meter		Handheld device designed for reading sensors in the field; moisture range 0-199 kPa; minimum 2 stations per 40 acres	- $240	1-year	9V
Watermark	900M Monitor		Data logger that automatically records soil moisture readings	- $575 (monitor only)	1-year	9V
Watermark	975 IRROmesh Node		Wireless solar powered data logging system; up to 20 sensing locations; max 3 sensors per node	- $495 (base) - $330 (relay node) - $745 (logger) - $1,595 (cellular gateway, battery pack & solar panel)	1-year	Solar panels on 2 sides

<u>Capacitive Sensors</u>

Table 7 showcases a range of capacitive sensors available in the market, including the company, photo, description, price, warranty policy, and power requirement. Unlike electric resistance blocks, capacitive sensors are made of probes that measure the volumetric water content and dielectric permittivity of the soil. Some capacitive sensors, like Alotpower's sensor, are designed for both indoor and outdoor plant use and do not require a separate meter. Depending on the performance and functionality of the sensor, the depths at which it can measure, and the length of the cable, the prices for capacitive sensors featured in the table below range from $9.68 to $279.99. Similar to electric resistance blocks, capacitive sensors can be connected to a meter or data logger to display measurements and help manage the irrigation schedule. Sentek, Decagon, and Vegetronix are "the best of the high-frequency capacitance probes"; however, the most affordable sensor among these three, Vegetronix, "has a small volume of measurement" (Robinson 2018).

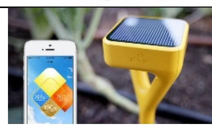
Table 7. Comparison of various capacitive sensors

Company	Model	Photo	Description	Price	Warranty	Power
Alotpower	Soil Moisture Sensor Meter		Soil moisture sensor meter for garden, farm & indoor / outdoor plants	- $9.68	N/A	No batteries
Decagon	10HS Moisture		Soil moisture sensor that measures volumetric water content (0-57%), dielectric permittivity	- $139	1-year	3VDC at 12mA to 15 VDC @ 15mA
Extech	MO750 Soil Moisture Meter		Soil moisture meter with 8-in. probe; measures 0-50% volumetric water content	- $279.99	N/A	4 AAA batteries
Sentek	Diviner 2000 Sentek Soil Moisture Sensor		Probe and hand-held data logging display unit; capacitance sensor; stores data from up to 99 sites	- N/A	30 days from date of purchase	13.8V DC 800 mA regulated power pack or a 15V universal (100-250V) AC Adaptor
Toro	Precision Soil Sensor		Soil moisture & temperature sensor; Up to 152 m wireless communication	- $109.99-$195 (probe & receiver) - $56.98-$59.82 (sensor only)	2-year	3 AA batteries
Vegetronix	VH400 Soil Moisture Sensor		Soil moisture sensor probes; capacitive sensor ; measures % volumetric water content	- $39.95 (2-m cable) - $45.95 5-m cable) - $55.95 (10-m cable)	N/A	DC supply or 3.5-20V batteries
Vegetronix	VG-METER-200		Hand held soil moisture meter with digital display	- $88.95 - $109.95 (with USB & VH400 sensor)	N/A	2 AA batteries
Vegetronix	Universal Sensor Display		Back-lit graphical LCD and touch button interface to display sensor data	- $79.95 (2-m cable) - $85.95 (5-m cable) - $95.95 (10-m cable)	N/A	N/A

Smart Soil Sensors

Table 8 showcases a range of smart soil sensors available in the market, including the company, photo, description, price, warranty policy, and power requirement. Geared toward data enthusiasts who need real-time measurements of soil moisture, temperature, humidity, nutrition, and other influencing elements, smart soil sensors provide farmers with the greatest accessibility to the data in their field. Several of these smart soil sensor companies are gaining traction through Kickstarter campaigns, which points towards a sales strategy targeted toward millennial farmers and growers who are more likely to be early agricultural technology adopters. On Kickstarter, 2,336 backers pledge $384,201 to Edyn, and 877 backers pledged $96,690 to Plant Link. These farmers stay abreast of agricultural innovation and appreciate the convenience of managing their farms with the assistance of their smart devices. Strong wireless connectivity is critical to supporting the system, and often times the data and cloud analytics come at a steep price point due to subscription-based services with high annual reoccurring fees. Furthermore, complex user interfaces can inundate farmers with data in a way such that the data overwhelms instead of supports the critical irrigation decision-making process.

Table 8. Comparison of various smart soil sensors

Company	Model	Photo	Description	Price	Warranty	Power
CropX	Basic Sensor		Soil moisture & temperature monitoring on the cloud; measures at 8″ & 18″; 1 sensor per 40 acres	- $600 - $275 (1-year subscription)	1-year	Batteries included
CropX	Pro Sensor		Soil moisture & temperature monitoring on the cloud; measures at 8″ & 18″; 1 sensor per 40 acres	- $699 - $275 (1-year subscription)	1-year	Rechargeable unit
CropX	Deep Sensor		Soil moisture & temperature monitoring on the cloud; measures at 8″, 18″ & 36″; 1 sensor per 40 acres	- $899 - $275 (1-year subscription)	1-year	Rechargeable unit
Edyn	Garden Sensor		Solar-powered sensor connected to Wi-Fi; tracks light, humidity, temperature, soil nutrition & moisture	- $79 (Kickstarter earlybird) - $99.97 (retail)	1-year	Solar-powered; rechargeable lithium polymer battery
PlantLink	Wireless Plant Sensor		System that monitors water needs of lawn, garden, or house plants; sends alerts & can auto-water; sensors reach 100-300 ft.	- $79 (Kickstarter early bird – base station & 3 links) - $99 (base station & 3 links) - $149 (base station & 5 links)	1-year	2 AAAA batteries
Pycno	Sensor Kit		Master sensor / gateway & node sensor to detect capacitive soil moisture, humidity & temperature; Wi-Fi connection via SIM card; sensor range of 500 m	Kits with master sensor, 3 node sensors, installation kit & global SIM: - $1,799 (30-cm length) - $1,999 (60-cm length) - $2,199 (90-cm length)	N/A	2W solar panel & internal battery
Zenvus	Smart-farm		Intelligent electronics sensor; collects & wirelessly transmits data on humidity, temperature, pH, moisture & nutrients to cloud server; advanced computational models	- $200 (node) - $300 (master Wi-Fi) - $300 (master GSM) - $450 (master satellite) - $650 (master combo)	N/A	Solar-powered with backup batteries

How do existing sensor technologies compare? The three categories of sensor types each possess a mix of advantages and disadvantages. Although existing electrical resistance sensors have relatively low equipment costs, the analog design used in many cases requires a more labor intensive approach to view, track, and manage the data and a manual approach to derive insights from the data. Capacitance sensors generate measurements at a high frequency; however, affordable capacitance sensors only measure small volumes. Finally, smart soil sensors provide farmers with a plethora of information. While this data may be useful, it can be challenging to understand how to apply the data due to the large volume of data that is captured. Furthermore, smart soil sensors have very high price points in comparison to electrical resistance sensors and capacitance sensors. Through this review of existing sensor solutions coupled with findings from user research conducted with farmers detailed in Chapter Five, it is evident that there is an opportunity to design an affordable electrical resistance sensor that minimizes the labor cost by reducing the manual labor required, helps the farmer quickly determine when, where, and how much he or she needs to irrigate, and better integrates into the farmer's farming processes.

Chapter 3

Research Design and Methodology

3.1 Market Research

In order to understand the global water crisis, identify a target pilot market, and comprehend the irrigation and soil sensor technology landscape, I draw upon both quantitative and qualitative data from multiple sources. Comprehensive reports prepared by UN agencies including the FAO, UN-Water, and UNDP and studies conducted by U.S. governmental organizations including the USGS and CDC present a picture of how the global water crisis came to be and the factors that lead to the forecast of growing scarcity and stress. Agricultural studies and market reports prepared by various agricultural academic institutions are used to analyze which geographies and crops are the most suitable for deploying soil sensor technologies based on the criteria established in Chapter 2. Finally, academic research involving soil science and irrigation specialists is supplemented by commercial studies conducted by sensor companies such as Watermark to analyze the current soil sensor technologies, irrigation practices, and avocado growing techniques.

3.2 Stakeholder Selection

Building further upon the market research, I designed a targeted user research study to answer the three research questions identified in Chapter One. First, I pinpointed the target user group through assessing different geographic markets and crop markets based on the following seven market criteria:

- Geographic markets that are susceptible to water scarcity or water stress
- Geographic markets with economies that depend upon agriculture
- Crops with high moisture and drought sensitivity
- Crops that produce large volumes and yield high returns
- Crops where farmers are already using a form of soil moisture sensor
- Crops experiencing a growing market demand
- Crops that require irrigation

The assessment covered the following geographic markets and crop markets, which met different aspects of the aforementioned market criteria:

- Geographic markets: Brazil, Chile, China, India, Mexico, Peru, South Africa, and the United States
- Crop markets: avocados, cauliflower, coffee, collards, cotton, cucumbers, eggplants, okra, peppers, tomatoes, watermelon, and wine grapes

From the above two lists, I honed in on avocados grown in Southern California, factoring in the seven market criteria and my ability to access and communicate with key users in the market.

After identifying the target market, I first reached out to professors and researchers in Southern California from the University of California (U.C.) Riverside, U.C. Cooperative Extension, CalPoly San Luis Obispo, and Fresno State Center for Irrigation Technology. Speaking with avocado and irrigation experts helped me develop a baseline understanding of the local challenges and also led to connections with four avocado growers who were open to setting up in-person interviews. Then, I widened my search by researching avocado growers and representatives with contact information publicized on the California Avocado Commission website. Each potential lead received an introductory e-mail followed by a phone call. Surprisingly, the cold outreach yielded positive responses as the majority of avocado growers were eager to contribute toward research that could improve their water use efficiency and crop yield. Only a handful turned down the request for an interview and visit, citing time conflicts during the period. The overall high willingness to contribute and share their challenges served as a preliminary validation of the market opportunity and clear need for a solution. As more avocado growers agreed to interviews, they also recommended neighboring growers and expanded my list of contacts.

It is important to note that this user selection process lends itself to creating a self-selected group of voluntary avocado growers who share some of the following attributes:

- Have an affiliation with avocado academic research and / or the California Avocado Commission
- Demonstrate an interest in or are open to exploring technological tools to improve avocado growing practices
- Stay abreast of avocado growing best practices and can be considered early adopters

Due to these user attributes, findings from the user research may skew toward representing the subset of avocado growers who are the most motivated and likely to implement technologies such as SoilSense's soil sensor system.

Table 9 provides an overview of the demographic range of avocado stakeholders interviewed in person.

Table 9. List of interviewees

Interviewee Role	Age Range	Gender	Location	Years of Experience	Avocado Acreage
Agriculture	41-65	Male	Fallbrook, CA	22	N/A
Manager	41-65	Male	Temecula, CA	15	2,000
Owner	40 and	Male	Bonsall, CA	4	38
Owner	40 and	Male	Bonsall, CA	5	60
Owner	40 and	Male	Pauma Valley,	16	1157
Owner	40 and	Male	Valley Center,	11	17
Owner	41-65	Male	Bonsall, CA	2	16
Owner	41-65	Male	Escondido, CA	40	100
Owner	41-65	Male	Fallbrook, CA	7	12
Owner	Over 65	Male	Escondido, CA	45	29.5
Owner	Over 65	Male	Fallbrook, CA	47	1030
Owner / manager	40 and	Male	Valley Center,	4	181
Owner / manager	Over 65	Male	Temecula, CA	10	12
Packing house	40 and	Female	Escondido, CA	13	N/A
Packing house	41-65	Male	Escondido, CA	34	62
Packing house	41-65	Male	Fallbrook, CA	32	175
University	40 and	Female	Riverside, CA	11	N/A
University	41-65	Female	Fallbrook, CA	33	N/A
University	41-65	Female	Riverside, CA	28	30
University	41-65	Male	Irvine, CA	26	20

The selected users comprise avocado farmers, packing house representatives, farm consultants, and university researchers based in the San Diego county area spanning the areas of Bonsall, Escondido, Fallbrook, Pauma Valley, Riverside, Temecula, and Valley Center. The interviewees average 20 years of experience, and their avocado farms range from 12 to 2,000 acres. While both their years of experience and age range across wide spectrums, the majority of the selected users assume responsibilities related to observing, collecting, and/or analyzing the data from their avocado field.

3.3 User Research Process

Data from users is collected via in-person interviews and farm visits. The duration of the interviews and farm visits range from 1 to 3 hours. The primary objectives of speaking to farmers and subject matter experts are to understand the nuances of growing specific crops, challenges in irrigation and other areas, and how technology and data analytics are currently used on farms. The interviews follow these procedures and protocols stipulated by the Committee on the Use of Humans as Experimental Subjects (COUHES):

- Before the interview begins, the interview participant is informed that they may choose to answer or not answer any questions and to stop the interview at any time or for any reason.
- The interview participant is then asked for their verbal consent to participate and for their consent to record the interview (notes and / or audio), to photograph their farm, and to publish results from the research with the understanding that all interview recordings would be stored in a secure work space until the completion of the research project, after which the recordings would be destroyed.
- The interview will include questions on their farming experience, pain points in growing crops, their vision for how technology could improve their operations, and their feedback on the SoilSense prototype. During the interview, notes are taken to document their responses and observations of their reactions and interactions on the farm.
- If any photographs of the interviewee are taken during the interview, the interviewee is asked to sign a MIT Media Release Form to grant MIT the license to use and display the photograph publicly.

- Following the interview, the interview participant is thanked and asked if they would be willing to respond to follow-up questions, should any arise. They are also provided with the investigators' contact information so that they may reach out and share any additional information.

Although a comprehensive list of questions has been developed, a more conversational approach is purposely used to facilitate the discussion with the farmers and to encourage open and honest dialogue. This approach invites farmers to freely share their perspectives on general farm operations, avocado growing and technology, SoilSense technology, and the business model for agricultural tools. The free-flowing discussion also presents farmers with the opportunity to hone in on pain points and topics that they are passionate about. The comprehensive list of questions can be found in the Appendix along with a visual aid to gather user feedback on which type of message farmers would prefer to receive regarding their field's soil moisture levels and irrigation readiness.

Chapter 4

Research Results

4.1 Stakeholder Analysis

As described in Chapter Three, a total of 15 avocado farm visits involving 20 avocado stakeholders were conducted in San Diego county, California, to understand different avocado growing methods, irrigation methods and tools, and key user needs for this group. Distinctive attributes that characterize this group are summarized below.

4.1.1 Role

The diverse group of stakeholders involved in this user study include the following number of people in different roles:

- 9 avocado farm owners
- 1 manager for avocado farms owned by others
- 2 people who are both owners and managers
- 3 university researchers from U.C. Riverside and the South Coast Research and Extension Center
- 3 representatives from two major avocado packing houses
- 1 specialist in implementing agricultural data solutions.

There are several categories of farmers among the avocado farm owners. First, there are the full-time farmers. This group can be sub-divided into those who are retired and those who are not yet retired. Then, there are the part-time farmers who work another full-time job and dedicate the majority of their off-work hours to cultivating their farm. For example, one of the interviewees described his schedule as follows, “My office is actually on the East Coast, so I start the day at 6 a.m. anyway. I’m usually out here every Saturday and Sunday, and then I get out here maybe two times a week.”

In general, farm managers take care of the entire operations for absentee owners. Their responsibilities include planting, irrigating, managing the technology, fertilizing, harvesting, implementing different strategies to secure a robust crop yield and reduce operational costs, and keeping the owner abreast of farm activities. Per one of the managers, “owners are not really hands-on.” Some owners request to meet their grower every week, some call quarterly, and some only interact with their farm manager when there is an issue.

Packing house representatives manage both the avocado groves owned by the packing house as well as relationships with growers. They tend to have close working relationships with the growers that supply their avocados and not only understand their growers’ crop yield, but also their soil topography and irrigation schedule. One of the packing houses participating in this study mentioned that they represent 400 growers, of which over 50% are small-scale farmers with less than 5 acres, approximately 50 are large-scale farmers with 20 to 100 acres, and the remaining approximately 37.5% are medium-scale farmers with 5 to 20 acres.

4.1.2 Gender

Overall, the majority of avocado stakeholders interviewed were of the male gender at a male to female ratio of 4:1. This reflects the gender disparity in the wider California agricultural community, which is predominantly male. Per the USDA NASS 2012 Census of Agriculture, 70% of all U.S. farm operators are male, and 85% of principal farm operators are male. Looking at the male to female ratio of the interviewees based on their role, there is the highest representation of females in academia; 75% of university researchers interviewed were female. Also, a third of the stakeholders interviewed from avocado packing houses are female. All 12 farm managers and owners interviewed are male.

4.1.3 Age Range

The average age of the principal operator role in the overall U.S. farming community has increased over the past 30 years from 50.5 to 57.1 (USDA 2014). Similarly, the California avocado community is also witnessing a growing population of farmers with a higher average age. A 50-year-old avocado farm owner exclaimed, "I'm 50 and I feel like I'm the young kid doing this, which is really kind of scary." As the "owner" and "manager" roles are parallel to the "principal operator" role as defined by the USDA, the analysis on age focuses solely on these roles and does not include the packing house representatives, university researchers, and agriculture technologist. Of the 12 farm managers and owners interviewed, 41.67% are aged 40 and under, 33.33% are between the ages of 41 to 65, and the remaining 25% are over 65 years old.

4.1.4 Location

This user study focused in the San Diego county area of California. The majority of interviews take place in Fallbrook and Escondido. Table 10 shows the specific locations of the interviewed avocado stakeholders based on their role.

Table 10. Interviewee roles and locations

Location in California	Owner / Manager	Packing House	University Researcher	Agriculture Technologist
Bonsall	25%	-	-	-
Escondido	16.7%	66.7%	-	-
Fallbrook	16.7%	33.3%	25%	100%
Irvine	-	-	25%	-
Pauma Valley	8.3%	-	-	-
Riverside	-	-	50%	-
Temecula	16.7%	-	-	-
Valley Center	16.7%	-	-	-
Total	100.00%	100.00%	100.00%	100.00%

4.1.5 Background

The avocado stakeholders come from different backgrounds. Of the 12 avocado farm owners and managers, 5 have grown up in an agrarian setting and are continuing their family's work in agriculture. Due to their extended exposure to and experience in farming from an early age, their growing methods may be influenced by practices learned from their family's farms. Several avocado owners and growers transitioned from construction-related roles to farming. There may be a correlation between the skills obtained from construction work and the farmers' proclivity and ability to handle the technological installation and maintenance on their farms. There is also a subset of avocado farm owners and managers who transitioned from other career paths, including a former pathologist, an entrepreneur, professional in the biotech industry, and a solutions architect working in wireless communications.

4.1.6 Years of Experience

The group of farm owners and managers who were interviewed have a range of years in experience in relation to avocado farming. Relatively novice farmers have between 2 to 5 years of experience. These farmers have yet to see the results of their farming methods since it can take more than two years to see the impact of the irrigation approach, fertilization method, and other inputs on the crop yield. The more experienced farmers have between 7 to 18 years of experience. The farmers with the most experience have between 40 to 50 years of experience. This body of research reflects a sum of over 150 years of combined knowledge from these avocado farm owners and managers as well as insights from packing house representatives and university researchers.

4.1.7 Size of Farm

The avocado farms visited ranged from 12 acres to 1,030 acres. While most growers involved in this study had one farm, some growers—especially the ones with family farms—had two to four farms within the vicinity of each other on different plots of land. For the most part, the avocado farm owners interviewed work on the farms themselves occasionally with the help of a spouse or child, hiring one to two people to help pick bins of avocados during harvest season. The avocado farm managers work with an irrigation and picking crew, and the size of the crew depends on the acreage of farms belonging to their client.

4.1.8 Crops Grown

All avocado farm owners and managers interviewed grow the Haas avocado for commercial purposes because this species generates the highest return. Fuerte and Zutano avocados are also grown by some of these farmers, although on a much smaller scale. Several of the stakeholders interviewed expressed interest in cultivating gem and reed avocados, which are "stronger" varietals that are more resistant to root rot, produce larger fruit, bear fruit consistently (unlike the Haas, which bears fruit in alternating years), and grow vertically (as opposed to horizontally) to facilitate pruning. Beyond established species of avocados, some farmers find new species of "volunteer trees," which spring up from the ground where an avocado has fallen. Because it can be difficult to turn a profit on avocados especially during the first years a new grove is planted and during periods of climatic change, some avocado farmers supplement their income and sustain their farm by growing citruses such as lemons, mandarins, oranges, grapefruits, and kumquats.

4.1.9 Attitude toward Technology

This study recognizes that it involves a self-selected group of individuals who agreed to share their avocado growing knowledge to facilitate the development of a soil sensor solution. This means that the stakeholders may already have a tendency to use technology or may have an interest in agricultural technological developments. Given the various backgrounds and attributes of these farmers, however, there is a clear spectrum that defines their attitude toward the adoption of technology on their farm. It is important to note that although the majority of growers are well-informed of avocado growing practices and can cite research results from studies conducted in different countries, they often use phrases such as "I feel…" and "my feeling is that…" when describing why they use or do not use certain approaches or technologies.

On one end of the technology adoption spectrum, farmers say, "Instinct always presides [for irrigation]." These farmers rely on their instinct, which is backed by their experience and observations in the field (e.g., feeling the soil with their hand and looking for telltale signs on the tree). A farmer who does not use any sensors quoted this old saying, "Farmer's feet are the best fertilizer and data collector." To them, walking the fields and using their trees as indicators are the most effective ways to understand the soil and tree condition. In other words, "trees are the best sensor." One farmer explains, "when trees are little, they may wilt on a hot day. In ten minutes though, the tree will wake up after I apply a bucket of water." In the eyes of other farmers who are more receptive to technology adoption on the farm, these farmers seem to be rooted in traditional ways of farming. One farmer expressed, "I don't want to call them old guys because they don't seem that old, they use the technology, they get it, and they're on Instagram. But when you tell them to apply it to farming, they say, 'I don't know--we've been doing it this way for a long time.'"

On the other end of the spectrum, there are farmers who invest in significant numbers of soil sensors—up to four sensors per half acre—to develop a comprehensive mapping of their soil condition at different depths across their field. To these farmers, especially those who are singlehandedly managing their farm, technology could greatly help them plug the many different parameters in irrigation into an equation and better schedule their irrigation cycle. This user group sees data as an assistant that can paint a clearer picture of their avocado trees' growth conditions to increase water efficiency and crop yield and even help with forecasting. As one farmer states, "If you can do predictive analytics on this sensor, that would be awesome. I would be the first one to be a customer and sign up for that."

Although these farmers appreciate having technologies to facilitate soil sensing and irrigation, the majority of farmers interviewed share a nuanced perspective in the middle ground. While they are interested in technology to drive operational efficiency, they indicate that they "like the human aspect of this" and want to "be in the decision-making position." Even when the sensor integrates with the irrigation system and can automatically turn on and off the irrigation system, some farmers prefer receiving an alert and being able to press a button on the controller (e.g., a panel, their phone, or computer) to turn on and off the irrigation system. The system should be able to suggest actions, and the human should be able to override the suggestions. These farmers express, "I like going out, seeing the block, feeling the leaves, and being hands-on while getting readings on my phone."

4.1.10 Interest in New Growing Methods

In addition to exploration of and investment in technologies to support their avocado farms, the interviewed farmers showcase their experimentation in new growing methods. One type of growing method experiment involves rootstock trials, where the farmers dedicate a portion of their farm to propagate and test the performance of new avocado rootstocks. Avocado trees are grown when scions of desirable cultivars are grafted onto various rootstocks (Bender et al.). These clonals then adopt the desirable qualities of high-performing trees, such as resistance to salinity, Phytophthora root rot, various fungi, and drought, among other forms of disease resistance. Four of the interviewed farmers share the different rootstock trials being carried out on their farms; these include tests with the following rootstock varieties: PP35 (Duke 7), PP40 (Evestro-UC 2036), PP80 (Lexa), VC801 (Mico-UC 2076), VC207 (Kidd-UC 2032), and PP37 (Dusa). In the trials, farmers plant a row of different rootstocks, irrigate the seedlings with the same amounts of water, and evaluate which rootstocks grow faster and produce more fruit. More than one farmer has cited the strong performance of the Dusa and the Lexa rootstocks. Often times, these trials are conducted in partnership with researchers like Peggy Mauk, Mary Lu Arpaia, and David Crowley from institutions such as the University of California Riverside who develop new rootstocks. Avocado nurseries also work on developing rootstocks with that resist root rot.

While rootstock trials are one of the more common forms of experimentation on the farm, these farms also feature other new growing methods, such as high density farming, which is gaining traction on many of the farms due to its ability to drive water efficiency. Two of the family farms that were interviewed set up pilots to test new soil sensor technology from startups. Both farms respond favorably to the sensor technology and user interface and express a desire to continue using the technology if only the startups had stayed afloat. One of these farms even exclaims, “I don't know why growers don't try more things. If somebody says, ‘Try it’, I'm game. If you develop your system, call me, and I would be more than happy to try it.”

Unconventional strategies also surface on these farms. On one farm, the grower applies a seaweed spray to his avocado trees to help them grow fruit. According to this farmer, “seaweed has a natural plant growth regulator, which tells trees to grow fruit and not leaves and helps control thrips,” an avocado pest that scars fruit. He proclaims, “every year, my trees get a lot of fruit” and credits the seaweed spray for being super helpful. Clearly, this user group involves stakeholders who, despite being cost conscious, are willing to invest time and money in piloting new growing methods to develop stronger and healthier avocado trees that yield more fruit.

4.1.11 Relationships with Avocado Community

The California avocado community is a tightknit group of growers, packing house representatives, researchers, and stakeholders involved with the California Avocado Commission. Many of the growers know fellow growers in the same locale and recognize the established family farms in the area. Novice growers may not be as well connected in comparison. Generally, the avocado growers are open to sharing best practices and express an interest in learning from one another. During one of the farm visits, the farm owner received a call from one of the leading avocado researchers in California and immediately set up a meeting for the next morning to connect our research team with the avocado researcher, two other growers, and an agricultural data solution expert. A multitude of growers partner with university researchers to implement test trials on their farms. These growers also have strong relationships with their the packing houses, their business partners who introduce their fruit to retail stores and customers. Growers, researchers, and packing houses all engage with the California Avocado Commission, a trade association that promotes and brands California avocados. Some stakeholders serve on the board of the California Avocado Commission, whereas others join as members. The shared passion for producing high quality fruits and finding solutions to challenges related to growing avocados brings the group of diverse avocado stakeholders together.

4.2 Avocado Growing Methods

This section describes the various avocado growing methods and practices recounted by the interviewees. The farm managers and owners conducted a detailed walkthrough on their farms and demonstrated key activities and processes related to cultivating their avocado trees, analyzing the soil, and irrigating the farm. Similarly, the packing house representatives and university researchers also led tours of their facilities and groves. Understanding the avocado growing process and methods is key to understanding the avocado growers' needs. Their insights are organized by topic in the following sub-sections: avocado species, avocado flowering, pollination, and growth cycles, soil attributes, water attributes, avocado growing strategies, avocado growing challenges, operational costs for avocado farms, expected yields, and the market demand.

4.2.1 Avocado Species, Flowering, and Pollination

The avocado originates in southern Mexico, Central America, and the West Indies and was consumed by Native Americans and Aztecs in those regions. Spanish historian Gonzalo Fernandez de Oviedo wrote about the fruit in 1526 in *the Summario de la Natural Historia de las Indias*, and Spanish conquistador Pedro de Cieza de Leon later coined the Spanish name "aguacate" in 1550 (Shepherd & Bender 2012). At the time, the avocado was noted to be growing in Panama, Ecuador, Colombia, and Peru. As more explorers ventured into Central America, they continued to encounter avocados; even George Washington wrote in 1751 about tasting "agovago pears" in Barbados (Shepherd & Bender 2012). Seedling avocado trees were eventually brought into California, and the first plantings occurred around 1850.

Although the green-skinned Fuerte avocado was the preferred fruit in the early days, the black-skinned Hass avocado, produced by chance by mailman Rudolph Hass in 1926, gained commercial success and recognition over the years, and by 2011, "Hass avocados comprised 94.5% of the avocados grown commercially in California" (Shepherd & Bender 2012). The Hass avocado gained its current position in the marketplace in part due to major branding and marketing campaigns led by packing houses, growers, and the California Avocado Commission. As stated by one of the farm owners, "For the most part, I only grow Hass. For commercial use, that's all I grow." The prevalence of this varietal is supported by this university researcher's remark as well, "Some mailman produced the original Hass avocado. Now that's what everybody grows." The farmers' inclination to grow Hass avocados is driven primarily by the market demand for this fruit, which is generally harvested and sold when it grows to be 5 to 8 ounces.

Due to root rot in avocado trees caused by the fungus *Phytophthora cinnamomi* and other challenges highlighted in section 4.2.5 below, researchers and growers are experimenting with different rootstocks to produce stronger, disease-tolerant avocado trees. Two species that are gaining traction are the Reed avocados and the Gem avocados. The Reed avocado can grow to be 10-20 ounces, which is more than twice the size of the Hass avocado. The Reed avocado also yields fruit more consistently unlike the Hass avocado, which bears fruit in alternating years. Because the Reed avocado tree grows straight vertically, it is easier to manage when it is planted in a high density arrangement, and it requires less water to grow. The Hass avocado tree, if left unpruned, continues to grow both horizontally and vertically. One can expect to find the Reed avocado in certain Whole Foods Market stores this year, per one of the farmers. The Gem avocado is similar in quality and flavor to the Hass avocado, and it grows to be 7 to 11 ounces. Unlike the Hass species, the avocado fruit for Gems grows in clusters hidden within the canopy of the tree. This structure protects the fruit from sunburn, strong winds, and heat. The Gem avocado also shares desirable traits of the Reed. For example, the Gem tree grows vertically, is conducive to high density planting, and produces more fruit because it does not tend to follow the alternate bearing cycle of the Hass. A farmer shared his plans to plant 1,000 Gem avocado trees.

To secure year-round fruit coverage, some farmers plant different species of avocados that ripen at different times. On one grove, the farmer planted Fuertes which ripen between November to March, Hass which ripen between January to July, and Lamb Hass which ripen between August to November.

4.2.2 Avocado Flowering, Pollination, and Growth Cycles

Avocado trees are subtropical or tropical fruit trees that perpetually grow and develop without going dormant. This means that they grow throughout the year, with a slower growth during the winter timeframe. Avocados grown from seed do not produce fruit that is true to the parent variety. To produce the desired fruit, growers graft the desirable variety onto the rootstock. Typically, new avocado trees begin to flower and bear fruit in the third year and produce full crops by the fourth or fifth year. Given the long investment period, farmers starting with young avocado trees do not break even until 5 to 7 years later.

Typically, avocado trees blossom from the late winter through the early summer (e.g., late February to the first week of June, as shared by a grower), and the harvesting season varies based on the type of avocado tree. Healthy avocado trees in California are known to produce up to a million flowers each year, but "fewer than 200 flowers per tree will set fruit that will hold and develop to maturity and harvest" (Bender 2012). This is partly due to the avocado's unique flowering behavior. The avocado flower is bisexual and has both female and male organs. When the flower first opens, it functions as a female for 2 to 3 hours receiving pollen at the stigma from other avocado flowers (Bender 2012). The flower closes for the rest of the day and night, and the flower functions as a male the next day shedding pollen for several hours before the flower closes permanently (Bender 2012). Given the limited timeframe for cross-pollination and the dependency on good weather—defined at 80% to 90% humidity and 60 degrees Fahrenheit by one of the growers—farmers invite beekeepers to bring their hives to the avocado farm to facilitate the cross-pollination process. Per avocado specialist Dr. Gary Bender, "the length of the flowering season is variable according to race, cultivar and temperature" (Bender 2012).

The flowering season is further complicated by the "on" and "off" years. Farmers struggle with producing consistent avocado crop sizes year after year because avocado trees tend to adopt an alternate bearing cycle where there is a large crop of small avocados in one year followed by a small crop of large avocados the next year. In the "on" year, the large crop inhibits fruit set and flowering. During the "off" year, the small crop induces fruit set and flowering, creating a self-perpetuating alternate bearing cycle. Multiple factors contribute to this alternate bearing cycle. The California Avocado Commission cites climatic events, water-deficit stress during bloom or fruit set, under fertilization, and over pruning as potential causes for "off" crop and excessive fruit set or retention as potential causes for "on" crops. Due to the alternate bearing cycle and the repercussions one growth cycle can have on the next, "the timing of pruning or removing excess young fruit affects next year's productivity of new shoots and the third-year harvest" (California Avocado Commission 2018).

Different varieties of avocados mature at different times throughout the year (e.g., the Hass in April and the Reed in July), and trees within the same variety generally mature at approximately the same time. Once the fruit is mature, they can be stored on the tree and harvested over the ensuing months. Different varieties can hold on the tree for varying lengths of time. Generally, the popular Hass avocado is harvested between April to October. Reeds can be harvested between July and October. Fuertes are harvested from November to June. Table 11 shared by the University of California Cooperative Extension details the maturity season of common Ventura varieties of avocados. Once the avocados are picked, they soften and become ready to eat over a few days to a week.

Table 11. Maturity season of common avocado varieties in Ventura County

Maturity season of common Ventura varieties		
Variety	**Season**	**Color**
Anaheim	June - September	Green
Bacon	November - March	Green
Bonita	September - November	Green
Corona	June - August	Green
Daily	September - November	Green
Duke	September - November	Green
Dickinson	May - October	Dark purple
Edranol	April - July	Green
Fuerte	November - June	Green
Hass	April - October	Black
Hellen	June - September	Green
Jim	October - January	Green
Mac Arthur	July - October	Green
Mesa	May - July	Green
Nabal	June - September	Green
Pinkerton	December - April	Green
Reed	July - October	Green
Rincon	April - June	Green
Ryan	May - June	Green
Santana	September - February	Green
Zutano	October - March	Green

4.2.3 Soil Attributes

In discussions with the growers, they shared the soil composition in their groves. The majority of growers—around 83%--indicated that the soil in their field is heterogeneous and made of multiple soil types. One farmer indicated that he has "8 to 10 different types of soil." It is important to note the heterogeneity of the soil composition because soil type factors into soil sensing and irrigation. Some farmers have a more consistent soil topology. For example, one farmer stated, "especially at 8 inches, my soil topology is completely uniform."

Hearkening back to Observant's Soil Texture Triangle discussed in Chapter 2.2, the different soil types are characterized by the composition of clay, sand, and silt in the soil. Sandy soils contain large particles and have a low water holding capacity because the water quickly drains through the root zone of plants. Clay soils have very small particles and a high water holding capacity; however, less water is available to plants due to the low mobility of water. Silt soils have small particles with a low to mid-range water holding capacity.

At least 42% of the farmers mentioned having decomposed granite soil, and at least 58% mentioned having sandy loam soil. Decomposed granite is a gravely soil with some particles that are even larger than sand particles. Sandy loam and loamy sands are comprised of 10% to 20% clay and 50% to 85% sand. Decomposed granite creates a good environment for avocados because the soil drains well and holds nutrients well. When decomposed granite is dry, however, "it's like digging into a rock," per a farmer whose soil is predominantly made up of decomposed granite. Both decomposed granite and sandy loams can be found in higher elevations compared to clay soils. Per one farmer with 60 acres of avocado trees, "the lower the land is the deeper the soils are, and the more clay the soil is going to be. Towards the top, it is going to be a little more sandy and more granitic." The same farmer expressed, "Soil types around here change pretty often, so we are just kind of guessing a little bit." To manage the heterogeneity and the soil composition and the uncertainty due to changing soils, farmers install sensor sets at different elevations where there are different soil types.

Effectively managing the acidity in the soil improves the health of avocado trees. The ideal pH for optimal avocado tree growth is around 6.5. Within the 6 to 6.5 pH range, the avocado tree absorbs less chlorides, reducing the chloride damage to the trees. Because the pH of the Colorado River water can be as high as 8.5, some farmers apply humic acid, sulfuric acid, or elemental sulfur around the base of the tree to lower the pH. One farmer quoted a report that stated that California soil only has 2% organic matter, but avocado trees thrive in soils with 4%

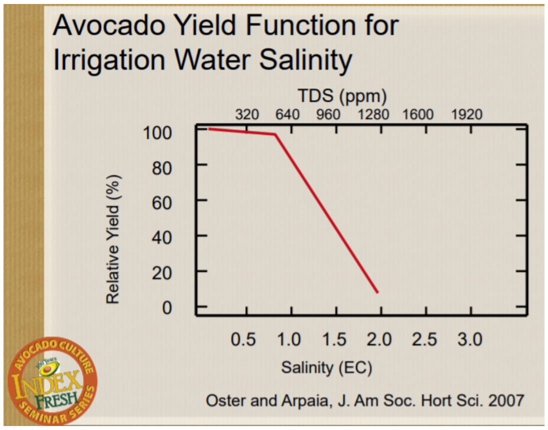
organic matter. Humic acid appears to be the preferred type of acid because it not only reduces the uptake of chlorides, but it also increases the organic matter in soil.

To prevent stunted tree growth, farmers take care to fertilize their avocado farms with the appropriate nutrients. A university research remarked that major elements nitrogen, potassium, and phosphorus (NPK) are the most important nutrients for avocados, adding that minor elements like zinc and manganese are also important. Farmers usually submit leaf samples to a lab once or twice per year, soil samples once per year, and water samples once per year. Nutritional levels in the leaves fluctuate over time, stabilizing in September for avocados; therefore, farmers usually conduct the leaf analysis during that month. Some farmers check the NPK levels on a monthly or quarterly basis. Having the results at least three months before fertilization occurs is helpful so that the farmer can plan ahead. The results from the lab help the farmers determine if there are any nutrient deficiencies and validate their chloride levels. The application of nitrogen depends on the type of avocado being grown and whether the farmer wants larger or smaller fruits and thicker or thinner rinds. Fertilizer can be added in the irrigation water or directly on the plant leaves. Minor elements like zinc and manganese are typically sprayed on the leaves in the spring. Although nutrients are important for avocado tree growth, some farmers have expressed that the use of fertilizer has increased two-fold in the past ten years, and some growers may be over fertilizing. Excessive fertilizer not only increases costs significantly, but it also increases the amount of chlorides in the soil, which has the potential to damage the tree.

4.2.4 Water Attributes

In San Diego county, avocado growers primarily derive their water from the district, which is sourced from the Colorado River. Due to water shortage in the region, growers have resorted to digging their own wells. A farmer with 38 acres of avocados mentioned sourcing water from 4 wells, and a farmer from a family farm with 60 acres of avocados sources water from 25 wells.

The water from the district is known for high chloride and salt content, which severely impacts avocado growth. District water is recycled or reclaimed water that is treated with chlorine to treat the pathogens, which results in the high salinity. As one farmer laments, "Chlorides are one of the biggest problems that we fight, especially during a drought because we are getting the majority of our water from the Colorado River." High salinity is referred to as a high "EC," which stands for electrical conductivity. EC is quantified in total dissolved solids (TDS) or parts per million (ppm), with 1 EC equating to about 640 ppm of salt. Farmers reported a range of 70 to 300 ppm in water sourced from the district. Water from their wells "can be a hit or miss," with EC ranging from 125 to 250 ppm. For context, applying water with 100 ppm of salts at 4-acre feet per season means adding 2,200 pounds of sodium chloride to the soil (California Avocado Commission 2018). As evidenced by Figure 19 from a report on *Managing Avocado Fertilization and Irrigation Practices for Improved Yields and Fruit Quality*, avocado yield declines as water salinity increases, and the decline sharpens severely around 525 ppm chlorides. Avocado experts recommend maintaining the total salt in irrigation water at 175 ppm.



Suitability of Water for Irrigation

Quality	Electrical Conductivity (millimhos/cm)	Total Salts (ppm)	Sodium (% of total salts)	SAR	pH
Excellent	0.25	175	20	3	6.5
Good	0.25-0.75	175-525	20-40	3-5	6.5-6.8
Permissible	0.74-2.0	525-1400	40-60	5-10	6.8-7.0
Doubtful	2.0-3.0	1400-2100	60-80	10-15	7.0-8.0
Unsuitable	>3.0	>2100	>80	>15	>8.0

Figure 19. Avocado yield and water salinity

While the farmers interviewed mostly fall within the range of permissible water salinity, growers focus extensively on minimizing the EC to maximize production and crop yield in order to sustain their avocado farm. Many farmers adjust their irrigation schedule for leaching, applying excess water in order to flush salt out from the root zone. University researchers recommended adding a 15% leaching fraction. Leaching, however, also adds salt to the soil from the salty water. Packing houses with more resources invest in reverse osmosis (RO) machinery to desalinize the water before applying the water to their fields. Water management for avocado growers is a careful balancing act to adequately irrigate and fertilize the field, activities which increase the EC, while reducing the EC through leaching and making sure not to over irrigate and cause root rot.

4.2.5 Avocado Growing Challenges

High chloride content in the soil is the most common challenge that all farmers brought up. It is also the challenge that they elaborated the most extensively on, with many citing it as "the biggest problem that we fight." When there is high salinity, the trees start showing tip burn—the green leaves turn brown around the edges and furl up. This reduces the amount of surface area available for photosynthesis, thus stunting growth. Per one farmer, "50% tip turn on leaves causes fruit drop." Almost every grove in the farm visits contained trees with some degree of tip burn, but some groves had a higher volume of tip burn compared to others. As one farm owner explained, "You'll see some groves and say, 'Wow, there are a lot of brown leaves!' And then you will see [a larger farm] who drills wells and has big reverse osmosis machines, and then you'll say, 'Wow, what a beautiful grove!'" High soil salinity also makes it more difficult for avocado trees to absorb moisture due to inhibited root growth, which reduces avocado yields. Both water and fertilizer contribute to the chlorides in the soil. To manage this issue, some farmers refrain from using herbicides, which helps to mitigate the EC level but results in the growth of weeds, which require frequent and intensive manual labor to remove. As discussed in the previous section, leaching is also applied. One farm manager indicated, "I always irrigate 5% below the roots so that there is not tip burn from the salt. There is a lot of salt right at or below the 5% line." Another mitigation strategy, which is more cost effective than installing expensive reverse osmosis machinery, involves blending multiple water sources to balance the EC. One grower stated, "I blend state water at 85 ppm with Colorado River water at 100 ppm."

Phytophthora cinnamomi root rot is another commonly cited challenge. When too much irrigation is applied to the avocado tree, the water inundates the shallow roots of the tree. Symptoms of root rot are mirror symptoms of high EC. Trees develop small, pale green, or yellowish leaves with tip burn, and leaves drop from the tree. Small branches at the tree top die, thus removing the protective canopy and exposing other branches and the fruit to sunburn. Root rot leads to the death of roots, which eventually leads to the death of the tree. Well-drained soil is key to preventing root rot, and using resistant rootstocks also protects the trees. Per one farmer, maintaining the appropriate pH levels in the soil can also help alleviate root rot. The scale of impact is clear from this veteran grower's account; "Vista was the avocado capital of the world. Phytophthora killed Vista, and Fallbrook became the capital."

Pests are also an issue that avocado farmers face. The polyphagous shot hole borer is a small beetle that infests trees with a fungus that destroys the delivery of food and water to the tree, eventually killing the tree. Avocado thrips are another pest. They damage the leaves of the avocado tree and scar young fruit, producing "brown mummified fruit." This is detrimental to growers because it reduces the quality, and hence the price, that growers can obtain from their fruit. The persea mites feed on the underside of avocado leaves and cause premature leaf drop and defoliation, which lead to sunburnt fruit and bark, fruit dropping, and reduced yields.

Larger pests also cause trouble for avocado growers in the form of gophers and coyotes. Gophers eat the roots of avocado trees. To contain gophers, some farmers use wire fences, and some even go to the extent of gassing the gophers. As for coyotes, almost all farmers expressed frustration with coyotes for chewing on the water hoses and breaking sprinkler tops. One researcher explained, "Coyote pups are essentially like puppies—they play with the pipes like a toy, but it is very expensive to the farmers." The expense comes from having to replace the pipes and sprinklers and also from the time and labor spent. Growers use different approaches to manage coyotes annihilating their pipes and sprinklers. They share compassion for the animals, understanding that the coyotes, squirrels, and rabbits look for water; therefore, one farmer showed how he leaves water around for them, which also benefits the bees, who need a lot of water. Some growers use different equipment to deter coyotes. A grower replaced his half-inch PVC pipes with three-quarters inch poly pipes and found that "for some reason, [the coyotes] did not like it."

In addition to challenges related to water and pest management, farmers also face challenges associated with the natural elements, particularly drought, the Santa Ana winds, and frost. Due to the California drought, farmers were forced to cut back on water in 2015. San Diego county had 25,000 acres of avocado farms before the drought, and the acreage has been reduced to 15,000 acres. Faced with drought, farmers expressed that "sensors would be really helpful in getting creative" with irrigating efficiently. Farmers in California cannot depend on rain. A packing house representative cited that there is only 6 inches of rain this year, while there was 22 inches of rain last year. "A quarter inch of rain will not change irrigation practices, but one inch of rain would mean that you do not need to irrigate for a week," according to one grower. This signifies that precise irrigation is vital to maintaining avocado farms. "Crazy Santa Ana winds," which come between the months of October to February, severely stress the trees. These hot winds hit the trees at 45 to 90 miles an hour, drying out the trees and causing fruit to drop from the tree. The winds prevent proper irrigation application and also increases evapotranspiration. To demonstrate the impact, one farmer exclaimed, "I lost thousands of pounds of fruit, but I've got guys who lost half their crop." When faced with the Santa Ana winds, constant irrigation helps to alleviate the situation. This brings up the water cost though and is not sustainable for small-scale farmers. Frost is yet another challenge as farmers struggle to keep the trees at a temperature between 40 to 90 degrees Fahrenheit. Some farmers plant their avocado trees higher up on hills to combat frost.

Theft is also a concern for avocado growers although the groves are on private property in rural areas. Several growers had walls built around their grove and electrical gates. Only one grower brought this issue up, and he described the issue in these terms, "Agricultural theft is huge. It's organized crime, and people can strip out a grove overnight."

Finally, a challenge that farmers reported involves the long growth cycles of avocado trees. “What you do today, you will not see [the results] for two years.” Since new groves can take more than three years to produce fruit and the activities applied to growing avocados do not show the full results until two years later when the fruit goes through the alternate bearing cycle, it is difficult for farmers to assess if what they are doing is advantageous for their trees.

4.2.6 Avocado Growing Strategies

Several key avocado growing strategies were mentioned by the farmers. High density farming is one of the most commonly seen trends. Although it is not a new method in agriculture, its application to avocado growing is relatively current. Interestingly, different farmers defined high density farming in different quantitative terms, ranging from 5-ft by 5-ft planting to 10-ft by 10-ft planting. While some farmers planted the vast majority of their trees in this structure, others dedicated only a portion of their farm to high density planting. For farmers transitioning an existing grove to high density, they need to remove trees in the appropriate pattern. The owner of one of the larger groves expressed that high density farming works well on a small scale. The key benefit associated with high density farming relates to higher yield while using the same amount of water.

Pruning is also key to proper avocado tree management because cultivars like the Hass grow considerably in both vertical and horizontal directions. Pruning not only gives the avocados a balanced look, but it ensures that nutrients and enough sunlight gets to the branches and leaves, which helps to create healthier and more fruit. Multiple methods exist for pruning, such as the “vase method, Christmas tree method, and Israeli method.” Farmers are well-read, citing papers related to pruning. One farmer showcased his trees which have been pruned using the Israeli method, which works well with trees that have five easily identifiable main branches sprouting from the trunk. Another farm manager described that "the goal is to have three to four main branches so that sunlight gets into the middle. We want new shoots and to control horizontal growth." Limiting the height of the tree is another major part of pruning. One farmer prunes his trees down to a height of 6-feet, and the farmers generally allow their pruned trees to grow up to 7 or 10-feet tall. Controlling the height of the avocado trees helps create a more uniform water demand across the grove, also reducing the overall water requirement. Furthermore, pruned trees facilitate the harvest process by removing the need for laborers to climb onto extended ladders to pick fruit, thus saving time and labor cost. The majority of visited farms prune their trees; however, there are also farms with behemoth avocado trees grown from the latter half of the 1900s.

Multiple farms had boxes of bee hives stacked near their avocado trees. These farmers maintain a symbiotic relationship with beekeepers, each benefiting from the other. Typically, the avocado growers do not need to pay for bees which help cross-pollinate the avocado trees. Similarly, beekeepers do not need to pay for the avocado trees which help their bees cultivate honey. The beekeepers bring their bees to the avocado farms in time for flowering and remove their bees after the flowering period. To showcase the significance of bees in the growth of avocados, the farm owner for the largest farm from the visits built a bee building, which also helped to protect his staff from bee stings.

As another good practice followed by all farmers interviewed, the farmers leave the leaves that have fallen from the avocado trees on the ground. These leaves serve as a good natural mulch for the trees.

To try to improve production by eliminating the biennial bearing and increasing the fruit size, some farmers have tried girdling avocado trees. This involves cutting through the avocado bark to stop or reduce the flow of sap below the girdle line, which causes the carbohydrates and starch to accumulate above the girdle line where the leaves and fruit are (Davie et al. 1). One farm manager recommended making the girdle line high up. The few farmers who have tried girdling described it as a method to achieve one final good yield from the avocado tree before it is cut down and removed. Most of the interviewed farmers, however, expressed concerns that girdling could make the tree vulnerable to pests such as the shot hole borer.

Two farm managers discussed the merits of stumping avocado trees that have grown too tall and unwieldy to irrigate properly. This is a last ditch attempt to save an ailing tree by cutting the tree right above the graft, which gives the tree the opportunity to form new buds and essentially start a new life, bearing fruit again in 3 to 4 years. The farm manager recommended stumping trees in May or June and giving the trees a deep soak, then waiting to water the trees only after shoots develop. The cost of stumping a tree is quoted to be $35 per tree, which is considered a low cost.

4.2.7 Operational Costs for Avocado Farms

Operational costs for avocado farms entail the following components: water, fertilizer, weed and pest control, ground maintenance, equipment such as sensors, irrigation tools, tractors, and fruit picking cost. One of the farm owners with 12 acres of avocados quoted $50,000 to run his farm. Another farm owner with 16 acres of avocados also quoted $50,000 to run his farm per year and provided the following breakdown: $20,000 to $30,000 for water, $3,000 for fertilizer, $20 to $25 per hour for labor to harvest the fruit, and the remainder goes toward miscellaneous costs such as stumping.

Whether the farm has high or low acreage, water accounts for the majority of operational costs. A farm owner of a more established family farm with 2 groves, one with 457 acres and the other with 700 acres, quoted a total annual cost of $7,000 to $8,000 per acre to run his farms. Assuming an average of $7,500 per acre per year in costs, this amounts to $8,677,500 to grow avocados on the 1,157 acres. According to this farmer, water costs make up 80% of his total operational cost. This means an annual water cost of $6,942,000. Farms with more acreage also have pruning costs and a greater labor cost. On a smaller scale farm with 16 acres, a farm manager mentioned that water accounts for 60% to 75% of the total operational cost on the farms that he manages, and he shared a water bill of $100,000. Trees that are younger require less water and only account for about 20% of total operational costs though. Water is a significant expense because it is both costly in California and required in large volumes to produce maximum avocado yields. As quoted by several farmers, the cost of district water in San Diego ranges from $1,300 to $1,800 per acre-foot, which refers to the feet of water applied over one acre. On average, 4 acre-feet of water are applied per year. This means that per annum, water costs range from $5,200 to $7,200 per acre.

Generally, labor costs account for the second largest cost to avocado farmers. One farm manager contracts out for labor at $20 an hour. Of the $20, the worker receives $12 to $15, the contractor receives $1, and the remaining $4 to $7 is used to cover worker's compensation, insurance, and tax. Finding good workers can be challenging for farmers who are singlehandedly growing avocados on their farm and do not have enough funding to hire a full labor workforce. These small-scale farmers resort to using workers from local landscaping businesses or people sourced from hiring centers for one day a week and paying them $10 to $20 an hour. During harvest season, the farmer may have the worker come more often. $12 to $15 per hour is standard for an entry level worker. One farmer indicated, "I know guys who will work for 10 hours at $10 an hour, but they do really shoddy work. I'd rather pay $15 an hour and get 6 hours of really good work done without exhausting the guy." Once farmers find good help, they are usually willing to provide pay raises to encourage the workers to return. Because a large labor force is required to pick avocados once they have matured, the 1,030-acre organic farm included in this study, built a low-cost dormitory to house the avocado pickers, which are made of immigrants mostly from Mexico. Avocado pickers are paid by the number of filled bins and then by pound if the bins are not filled to the brim. Laborers are paid $0.10 to $0.18 per pound of picked avocados. These large-scale farms also invest in irrigators who walk through the fields to check the pipes, sprinklers, and sensors and manage the irrigation. On a hilly 457-acre grove, one farm owner hires seven irrigators; he estimates that he would only need one irrigator for every 100 acres if his grove were on flat land. The total labor cost shared by a farm manager overseeing a 16-acre farm adds up to $50,000.

Fertilizing the trees and maintaining the grounds (e.g., pruning, weed abatement, pest control, etc.) make up the third largest portion of operational costs. Fertilizing and pruning are important for preventing stunted tree growth. A fertilizer enthusiast with 12 acres, one farmer spends $5,000 on fertilizers and $2,000 on weed control. He quotes ground maintenance costs of $2,000 per acre.

4.2.8 Expected Yields

"I feel like I farm super efficiently, but if I went and did the math, and I used two times the water, even at 50,000 to 60,000 pounds of fruit over my 12 acres, I still wouldn't be profitable," explained one farm owner. In order to break even, farmers need to achieve around 8,000 pounds of avocados per acre per year, and it can take 5 to 7 years of investment before profits are realized. Usually, avocado trees produce 50 to 300 pounds of fruit per tree per year. On average, avocado farmers produce between 6,000 to 8,000 pounds of fruit. A crop yield of

10,000 pounds per acre per year is generally positively viewed upon, and farmers mentioned knowing of other hyper productive farms that produce up to 20,000 pounds per acre per year.

Among the interviewed farmers, some aim to grow 8,000 to 10,000 pounds per acre per year, and others aim for 12,000 to 15,000 pounds per acre per year. Overall, their goal is to achieve the full potential of their grove. Due to the diverse challenges—including irrigation difficulties—mentioned in Chapter 4.2.5, coupled with the relatively young age of their groves, several of the interviewed farmers are producing only 5,000 to 7,000 pounds per acre per year. Several other interviewed farmers are on target with their goals, achieving 12,000 to 15,000 pounds per acre per year. All farmers, however, are still evaluating ways to increase their crop yield through methods such as improving their irrigation efficiency.

4.2.9 Market Demand for Avocados

The interviewed farmers recognize the growing demand for avocados by consumers, with U.S. consumption reaching 2.3 billion pounds of avocados this year and European demand for avocados growing 25% per year according to one farmer. Even countries in Asia are developing a taste for avocados. CNBC reports that "avocado sales to China are expected to more than double this year as demand continues to grow for the fruit from the country's expanding middle-class population (Daniels 2018). The Economist predicts that avocados will quickly become "America's favorite fruit" due to estimates that the average annual consumption of avocados has grown from one pound in 1989 to more than seven pounds in 2016. Per one farm owner, the largest single day of avocado consumption in the U.S. is the Super Bowl. The demand is so high that "imports from Mexico quadruple during the Super Bowl." This can be a source of frustration for Californian avocado growers who only grow avocados for domestic consumption. As one farmer expressed, "I don't have an export crop, and we get hit really hard with Mexican fruit," so he suggests applying tariffs on imported avocados. Taking a step back, he recognized that with both American and Mexican avocados in the market, "it has done a good thing for us because people can expect to have avocados year round, which creates market sustainability." Then, he recommended implementing improved checks and balances on the quantity of imports. From the perspective of the packing houses, their priority is to procure a high volume of large and high quality fruit to consistently meet the growing demand. Sourcing from different countries helps to balance the drop in avocado availability during alternate bearing avocado years in California. A packing house representative shared that 50% of the crop they pack is from California, and the other 50% is from Mexico. Table 12 shows the volume of Hass avocados in pounds that was produced in 2017 in the key avocado-producing regions of California, Mexico, Chile, the Dominican Republic, and Peru (Hass Avocado Board 2018).

Table 12. Avocado production in pounds by region in 2017

California	Mexico	Chile	Dominican Republic	Peru	Total Volume
202,077,261	1,734,117,320	80,895,572	33,390,000	141,663,747	2,192,143,900

In face of competition from avocado imports, the interviewed farmers remarked that Californian avocados are of a higher quality due to the higher standards set by the U.S. Department of Agriculture, better cultivation methods and cultivars, and significantly reduced time that the avocados spend in transit to get to U.S.-based customers. In the U.S., avocados are classified into three grades. The U.S. No. 1 includes the best avocado fruit—the ones of the highest quality which are sold at grocery stores. These avocados receive premium prices based on their size. The "golden standard' for Hass avocados is a size 60, which refers to the target of fitting 60 avocados in a 25-pound box. On average, a size 60 Hass avocado weighs around 6.8 ounces. U.S. No. 1 Hass avocados that are 8-ounces or more can earn a premium price. U.S. No.

2 avocados suffer from aesthetic damages due to wind scarring or sunburn. These avocados are sold at a reduced price to restaurants and guacamole producers. Low quality avocados classified as U.S. No. 3 avocados are usually trashed. One farmer trashed 300 to 400 pounds of U.S. No. 3 avocados. Any avocado that has fallen from the tree cannot be sold, per U.S. regulations.

4.3 Irrigation Methods and Tools

4.3.1 Soil Sensors on the Avocado Farms

Across the sampling of avocado farms and university research farms, the majority of growers used the Irrometer tensiometer produced by Watermark. Some farms supplemented the tensiometer with more advanced sensor systems developed by the following companies: SenTech, Aquacheck, CROP.SENSe, Hortau, Decagon, Netafim, or AquaSpy. Two farms piloted smart sensor systems from startups on their farms for a brief period with positive results; however, neither startup continued on and removed the sensors from the farms. Only one farm owner did not use any sensors. The growers shared a mixture of positive and negative user feedback on the various systems. A university researcher gave a mixed review of Decagon's sensor probes, referencing a colleague who "did not have a lot of success" estimating and logging the water content with the caveat that another professor uses Decagon's probes "all the time" and "has not had any problems." For small-scale farmers though, the high cost of the Decagon system makes it difficult to justify the purchase. One of the more tech savvy farm owners commented, "I have one Decagon, but I do not use it too much because it costs $250 for one sensor." The one farmer who used Sentek sensors credited their reliability but expressed that "going to the field to download the data was a pain." Overall, farmers testified in alignment that the Irrometer tensiometer, despite its simplicity, meets their needs. One of the most established family farm owners stated, "I have used [Irrometer] tensiometers for 40 years, and it works well." A few farmers expressed interest in exploring drone technology to identify water shortages.

While all growers placed sensors at two or more depths at each sensor station or node, the growers had divergent opinions on the number of sensors that are required. The sensor density varies based on the homogeneity or heterogeneity of the growers' soil profile and the number of irrigation blocks on the farm. It also varies based on the size of the trees, with some farmers installing three to four tensiometers per block in blocks with bigger trees, as opposed to one tensiometer per irrigation block. On one end of the spectrum, there are farmers who say, "I am all about sensor density." One farmer designed and built his own IoT network application and integrated it with his irrigation sprinklers. He demonstrated his 22 stations across the 22 irrigation blocks on his 12-acre farm. There are two sensors per station installed at different depths. He plans to double the number of stations using less expensive sensors to arrive at one station per half acre of land, which will take him to 88 sensors. He credits his existing sensors and the replacement of older, mature trees with younger ones, which consume less water, for helping him reduce water consumption by 75%. According to him, "the more data points you have, the better the analysis, and the better you can watch the micro-trends occur." This perspective contrasts with the guidelines set by the U.S. Department of Agriculture, which recommends installing a soil moisture sensing station for each area with different soil types. On the other end of the spectrum, there are farmers that use just one sensor per crop type or no sensors at all. The farmer that did not use any sensors explained, "I would need 20 sensors for my 16 acres due to the different soil types, conditions, altitudes, and directions that the trees are facing in." To a newer grower like him, the financial investment and labor required to maintain the sensors on his hill-side grove could not be justified.

As sensor costs varied widely based on the number of sensors, field size, and sensor brand, it is challenging to conduct a standardized comparison of the sensor costs. A few farmers provided reference points for sensor costs. At one family farm, the owner expressed a willingness to pay $300 per sensor, citing the value as “a very reasonable cost” for the Hortau sensors; however, this farmer pointed out that recurring costs associated with sensor data is not sustainable at his scale given the high number of sensors needed across his two farms spanning 1,157 acres. “Cellular would be $5 per month, but a $10 monthly subscription fee for each sensor is expensive for the farm and not practical.” On the other hand, a farm owner with only 30 acres quoted $1,400 to set up sensors for each block and commented that the $10 monthly subscription fee with $300 in software costs is reasonable. Several different brands of sensors are used at this farm, including Irrometer, AquaSpy, and Decagon. One of Decagon’s most expensive soil sensors also senses salinity and can cost $4,000 per station, which is too expensive for these farmers. At the high end on these farms, the cost per Irrometer station ranges from $2,000 to $3,000 with monthly cellular and subscription fees. One family farmer installed the IRROmesh system with a cellular gateway and 15 stations for his 40-acre grove. He paid $20,000 in total for the system, and additional stations would cost $250 each. In his 13-acre grove, he installed 10 sensor stations and expressed that “the precision helps.” At the low end, the popular Watermark soil sensors cost $40 each with about a 4-year life span. That amounts to $10 per year per sensor, and the farmers are comfortable replacing the sensors as needed.

The growers are meticulous in how they installed their sensors because the installation method impacts the accuracy of the sensor readings. Several growers demonstrated using a ¾-inch soil probe or an auger to remove soil where the station is going to be installed and preparing a wet slurry of soil to insert the station into. The wet slurry helps to remove any air pockets and is key to minimizing the soil disturbance. Newer growers expressed, “I am still trying to find the ultimate way to dig into the soil.” Farm managers with experience can complete this process within six minutes. Growers that use tensiometers need to perform this process every two to three weeks when the water in the tensiometer needs to be refilled.

Typically, growers analyze each irrigation block to assess where there are different soil types and determine which tree within the block is the best representation of the field. Farmers try to pick a medium-height tree growing. Picking a representative tree is key because on bigger trees, soil sensors may provide different readings depending on how closely they are placed to the larger roots or the small feeder roots. To demonstrate this point, a farm owner shared the experience of a fellow farmer who had bought 100 sensors and placed them under every other tree. 80% of the sensors read within 1 to 2 cB, while the other 20% read 10 to 15 cB because 80% of the sensors were closer to the feeder roots and 20% were closer to the big roots. In general, sensor placement is determined based on multiple considerations related to the number of irrigation blocks, different soil types, where there are different avocado cultivars, and which trees are the most representative of the grove.

As mentioned earlier, avocado farmers usually install 2 to 3 sensors at each station to capture readings at different depths, with some farmers installing up to 5 sensors at different depths. Table 13 captures the different sensor depths in inches indicated by 9 of the growers, and the asterisks represent the depths that respective farmers focus on to make irrigation decisions. Because the roots of the avocado tree are relatively shallow with 90% of the roots existing in the top 12 inches of soil, most of the soil sensor users focused within that root range. Measuring moisture at deeper depths such as 24 inches is useful for leaching purposes.

Table 13. Sensor depths

Depth	User A	User B	User C	User D	User E	User F		User G	User H	User I
1st	12"	8"	6" *	6"	8"	8"	6"	6" *	6" *	8"
2nd	18"	24"	12" *	12"	16"		12"	8"	18" *	22"
3rd	36"		24"		24"		16"		24"	36"
4th					32"		24"			
5th					40"					
Notes						Small trees	Large trees			

How do the farmers receive the readings from their soil sensors? The majority of farmers walk their fields every day to feel the leaves, check for broken irrigation pipes and sprinklers, and check the analog readings at each sensor station. This approach allows the farmer to be more "hands-on," and identify if there are any issues on their farm. This is also important because they "like to get out of the office as soon as possible." Daily monitoring is more critical over the summer, whereas weekly monitoring is permissible over the winter. Growers using this manual approach of monitoring tend to also manually write down the sensor readings at different depths at each station, especially in the first year after installing the sensors. The sensor readings are scribbled onto scrap paper that fits in the farmers' pockets, and some farmers transfer the readings over into an Excel spreadsheet afterward. One farmer noted that he records the tensiometer readings and "puts them on clipboard in his house." After the first year, farmers develop a sense of confidence in their understanding of the field, and they tend to discontinue the cumbersome and manual process of documentation. For other growers, receiving the sensor readings directly through an application on their phone simplifies the process and saves them time by helping them know the time of day when they should go out into their field. One farmer set up his own system such that it sends him a text message when the readings cross a threshold. He prefers the text message over the application alert because "if the application is asleep on the phone, you can miss it, but text messages always come through." Even with the text messages or application alerts, the farmers still make their rounds and walk through the irrigation blocks.

In addition to soil moisture data, all farmers collect data regarding the weather. One packing house representative noted that their growers log the weather on a calendar and observe the temperature, winds, and rain. If the temperature goes above 90 degrees Fahrenheit, it is marked in red. If the temperature goes below 40 degrees Fahrenheit, it is marked in blue. A variety of sources are used for gathering weather data, including the weather application on mobile devices, the local weather websites, the Weather Channel, Weather Underground, and the California Irrigation Management Information System (CIMIS). Most farmers observe not only the weather for that day, but also the weather 7, 10, 14, or 21 days out. One farmer noted, "I do not look that far because we do not get a lot of variation in weather in Southern California. Also—the local weather station and CIMIS—nobody gets it right." On the other end of the spectrum of weather importance, one farmer recommended installing a personal weather station because "weather is important," and at $4,000 to $5,000 per weather station or less than $1,000 for a HOBO weather data logger, "everyone should have one."

CIMIS not only reports air temperature data from over 145 automated weather stations in California, it also provides irrigators with measured information such as solar radiation, soil temperature, relative humidity, wind speed, and wind direction, and derived information such as vapor pressure, dew point temperature, reference, and evapotranspiration (ETo). A free resource available online, CIMIS was developed in 1982 by the California Department of Water Resources and U.C. Davis to drive water efficiency. The avocado farmers that use CIMIS focus specifically on the temperature data and ETc—water lost to the atmosphere through evaporation from soil and plant surfaces and transpiration from plants—to determine when and how much to irrigate. Using ETc requires calculations based on the crop coefficient of 0.75. While most farmers agree that "ETc has been around for a while, and understand that some people get good results," they feel that "with ETc, you still might be over or under irrigating" because it does not take into account the soil type. Others exclaim, "it is always off" and only use it as a "rough gauge" or a "safety check" to validate their soil sensor readings.

Other sources of information include the irrigation calculator on avocadosource.com, which was developed by an avocado expert that is well-respected within the avocado growing community in California. There are also "old and fast rules" that some farmers abide by. An example of these rules is to irrigate 12 hours every 4 days during part of the year and to irrigate 8 hours every 7 days during the other part of the year. To represent a larger sampling of farmers in California, Figure 20 shows the percentage of California farmers who use different types of methods to determine when to irrigate.

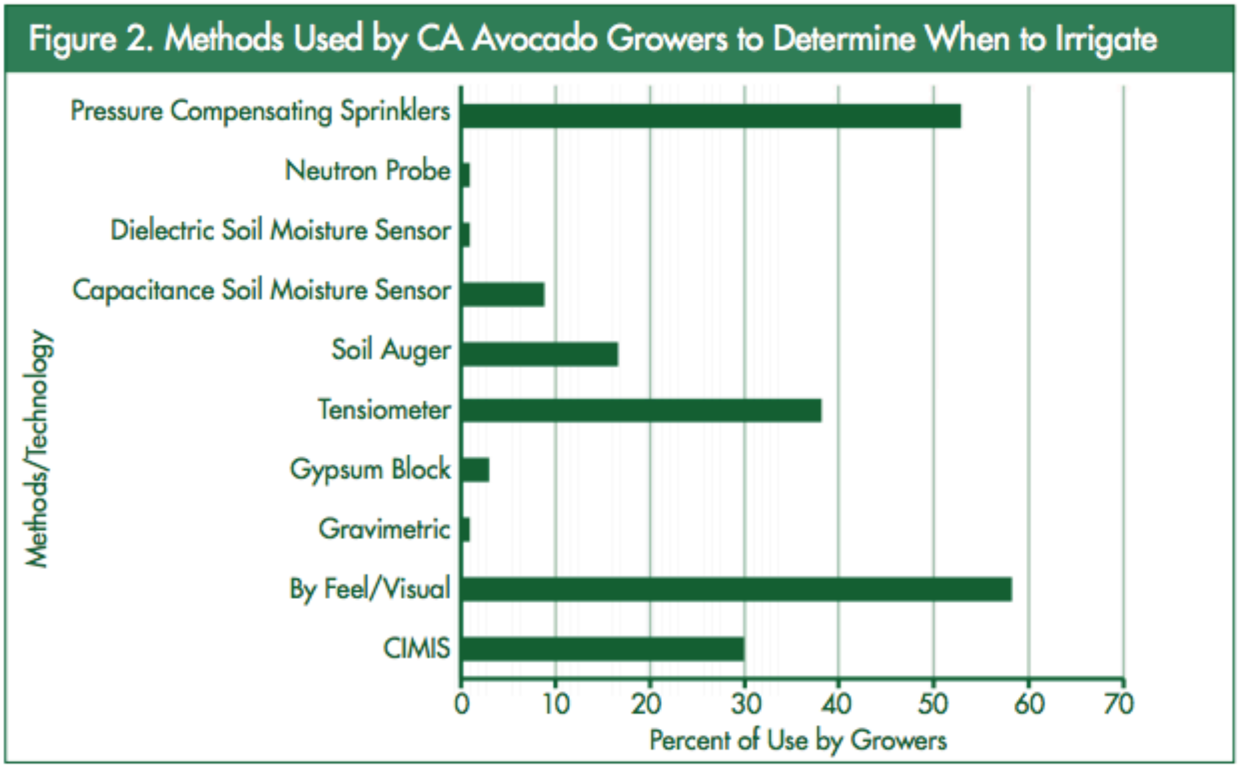


Figure 20. Methods used by California avocado growers to determine when to irrigate

4.3.2 Irrigation Practices

Soil sensor readings help farmers determine when to turn their sprinklers on and off. As discussed earlier, sensors are installed at various depths. The sensor embedded higher in the soil profile indicates when irrigation needs to begin, and the sensor embedded lower in the soil profile indicates the irrigation duration or when the soil is sufficiently moist. According to one farm manager, when his 6-inch sensor reveals 10 cb in sandy soil, he turns on his sprinklers until his 12-inch sensor reaches 0 to 10 cb. For clay soils, he turns on his sprinklers when his top sensor is at 30 cb. When it is flowering season, he turns on the sprinklers when the top sensor is at 20 cb. Another farmer with decomposed soil at the top and clay soil at the bottom of his field turns on his sprinklers when his top sensor reads 30 cb and shuts off his sprinklers when his bottom sensor reads 10 cb. One more farmer reported irrigating his decomposed granite field beginning when the top sensor reads 14 cB and ending when his bottom sensor reads 0 cb. A farmer practicing deficit irrigation begins to irrigate the avocado trees when the sensors are between 30 cb and 80 cb. Clearly, different soil types impact the measurements at which farmers determine when to start and stop irrigating their fields.

Equipped with knowledge from their soil sensors, weather reports, CIMIS, and their experience, farmers need to determine which days to irrigate which blocks, how long to irrigate each block, and the appropriate flow rate to run the sprinklers at to keep their trees in a non-stressed condition. All growers use on average one micro-sprinkler per tree, running between 12 to 25 psi. One farmer mentioned using two micro-sprinklers per tree. Sprinklers that fan out 3 to 5 feet from the sprinkler base are optimal for avocado trees to penetrate the shallow, wide roots beneath the soil. Irrigation schedules vary by season. Typically, farmers irrigate weekly or every 10 days if the weather is mild. Some farmers irrigate twice or three times a week when the temperature is high. As a general rule of thumb, "irrigate as much as possible—24/7—when it is really hot." The growers apply from 2.35 to 4.3 acre-feet of water per acre per year to their farm. Farmers that rely on sensor readings to irrigate are able to apply water more efficiently, using less than the standard 4 acre-feet per acre per year designated by U.C. Riverside. Several farmers shared their irrigation schedules. For one packing house, their groves are watered 16 hours per week with 20 gallons of water per tree over the summer. This is reduced during the winter when their groves are watered 12 hours per week. On a family grove, watering occurs 10 hours per week in the summer, whereas they irrigate only 5 hours every 2 weeks during the winter, using 12 gallons of water per hour. At yet another grove, the avocado trees are watered 6 days a week for 24 hours each day, using 18 gallons of water per sprinkler per hour.

Irrigation systems can be turned on and off either manually or automatically. Manual control entails the farmer collecting his sensor readings and manually turning on and off his valves. Automatic control involves an integrated soil sensor system and irrigation management system. In a semi-automated mode, the farmer receives a notification when the sensor crosses a threshold and can turn on and off the irrigation system directly from his phone. In a fully automated mode, the irrigation system would turn on once the sensor crosses a threshold. A handful of growers currently already use semi-automated control, but the majority still manually control their irrigation system. Because convenience, the ability to make strategic decisions, and the "hands-on" experience in the field are important to these growers, many expressed a desire to move toward semi-automated control.

4.3.3 Technology Maintenance

Across all interviews, there is a common preference among growers and owners to take care of the technology maintenance themselves. One farmer indicated, "I do 95% of the work here myself." This hands-on approach can be attributed to several factors. First, several of the farmers have past experiences that have helped them acquire skills in technology maintenance (e.g., growing up on a farm or working in construction). Second, the farmers can save money by fixing the pipes and systems themselves. Third, farmers consider maintenance responsibilities such as replacing tensiometers an easy task that requires only 5 minutes.

Chapter 5

Discussion of Results

5.1 Key User Needs Identified through California Research Results

A wide range of user needs emerged from the interviews with avocado farm owners and managers related to existing challenges on the farm. These user needs can be prioritized into high, medium, and low priority user needs based on their impact on water efficiency, crop yield, and the farmers' finances.

5.1.1 High Priority User Needs

All farmers expressed frustration with managing the high chloride content in the water supply, the difficulty in irrigating the appropriate amount to properly nurture the plant and leach the chlorides without causing root rot, and the increasing cost of water. As one farmer stated, "The more we optimize on water, the more we start paying for water. We just went through a drought where the water district could not sell us water. Now that we are out of the drought, they can sell us water, but they need to raise the rates on the water to meet their revenue targets, which means that we have to figure out ways to use less water." The Fallbrook Public Utility District raised water rates by 25%. This forces growers to find ways to offset their water cost because avocados require a significant amount of water to grow well. Some farmers build wells; however, limited water supplies still present a challenge to the farmer. One farmer explained, “We had a well that produces 10 gallons of water a minute, which is not enough. I need it to produce 40 gallons a minute.”

Affordability is a key factor in farm operations. When considering whether to invest in equipment such as sensors, affordability is one of the top considerations. Different pricing structures of existing solutions are discussed in Chapter Four and allude to the price points that farmers are willing and able to pay for sensors.

Reliable, accurate information on when the soil condition also critical, at about a 90% accuracy level. One farmer discredited Hortau’s sensor for being unreliable, inaccurate, and expensive. According to one farmer, “when you have 22 blocks that all need water, it gets a little hard to see which one is going the fastest.” This is exacerbated by pump irrigation limitations. Farmers are not able to water their whole grove at once and instead need to irrigate different blocks over the days of the week. Not only do the sensor readings need to be reliable, they also need to be representative of the soil. One farmer proposed using drones to derive a more accurate representation of the soil over the entire field and merging the two measurements by drone and by sensor together.

When asked about the most important information they would need from their sensor, these four measurements emerged: the water matrix potential, the salinity, the temperature, and the rate of water depletion. Beyond these four readings, farmers also expressed the desire to know the following from the system: measurements of nitrogen, phosphorus, and potassium, an indication of whether salt is being leached from the soil, pH, and ETc. Some farmers need as much information as available, requesting sensors at every 4 inches, suggestions from the sensor system, and even predictive analytics. “The more it can think, the better.” No matter how sophisticated the system is though, farmers still value the human touch and retain the need to make the final decision, override the system, and walk through their fields regularly.

5.1.2 Medium Priority User Needs

Farmers need to protect their avocado trees from strong Santa Ana winds and extreme sun, which can cause fruit drop and tarnish the appearance of the avocado, thus affecting its sale value.

Across the board, farmers mentioned that coyotes and animals chewing through their water pipes presents a big issue because the water is not applied to their trees, they need to spend time and money repairing the pipes, and there is potential financial loss from fruit drop if the broken pipe is not discovered early. Being informed when there is an issue with the pipes and locating the source of the problem is important to farmers, who would otherwise need to walk through their fields and manually check.

On the topic of government and politics, growers have voiced their struggles with over regulation in relation to water pricing and usage and under regulation in relation to avocado imports into the U.S.

From a design perspective, farmers discussed how having a simple user interface for the sensor system is key to increasing the usability of the system. "The simpler the better for farmers," who are not interested in high maintenance sensors. The sensor must be easy installable, and the measurements must be presented in a way that is intuitive for the farmers to understand. A university researcher commended the CropSense sensor interface for having user-friendly graphs that can be created for the day, week, month, or any desired period. This ability to look across different periods is important because farmers need to be able to look back on the most productive and least productive years to try to recreate the conditions that generate the most crop yield. This requires the ability to compare and draw correlations between different factors such as weather conditions and irrigation schedules. Farmers expressed their need to overlay different factors and to see visual graphs with numbers instead of tables. One farmer described how he visualizes his water supply as a full bucket that becomes depleted over time. The design of the sensor display needs to map to farmers' existing mental model so that the data does not confuse the irrigator. Language is another design factor as the growers and workers operate in English and Spanish.

Because farmers are constantly out in the field, they need to be able to access various information about the weather and soil condition in a portable way. Many of the farmers stated that they refer to their phones frequently, rely on phone notifications in general, and show data from their phones to others. They only view the sensor graphs from a computer screen if they want to print them from the office.

Before farmers become comfortable with investing in new technology, they must first come to trust the technology. Trust is built on viable proof that the technology works and makes financial sense. Farmers seek validation from other farmers and from researchers in the field. Seeing the technology working on another grove, be it a pilot on a farm or a plot of university land, makes a convincing case for investing in the technology. The longevity of the company—its ability to stay afloat—also impacts the farmer's trust in their technology.

5.1.3 Low Priority User Needs

For small-scale farm owners, the need to notify other irrigators of when and how much to irrigate is negligible as they often run the farm operations themselves. Larger family farms and farm managers, however, need to be able to communicate irrigation schedules clearly with their irrigators.

Having higher quality solar panels is helpful to power the soil sensor system and to reduce the time, effort, and money needed to replace poor quality solar panels.

From a technology maintenance perspective, farmers need to know when to replace gypsum blocks or refill tensiometers. Some farmers have expressed the convenience of receiving a text message. Others have expressed concern over poor cellular service.

While a full automated and integrated sensor-irrigation system that requires minimal work on the part of the irrigator is desired by some farmers, most farmers value the human touch. There is also interest in predictive analytics to help with decision-making on the field.

5.2 Implications for SoilSense Design

Based on the above user needs identified through the interviews with California avocado growers, several implications can be drawn to shape the design of SoilSense's sensor technology. It is important to note that these implications are drawn from a group of users who share some commonalities with avocado farmers in the developing world context (e.g., challenges with irrigation, weather, and water salinity); however, additional contextual factors need to be taken into consideration to adequately design for farmers in the developing world. The implications below focus on lessons learned from California.

Currently, the SoilSense solution uses gypsum blocks to measure the soil matrix potential. Taking into account the key variables that need to be factored into irrigation scheduling, there is an opportunity to augment salinity measurement given avocados' sensitivity toward salts. Because gypsum blocks degrade over time in 2 years, improving upon the gypsum material to enhance its longevity will make it more competitive compared to WATERMARK sensors, which degrade over 4 years. Since weather can be derived from multiple external sources including CIMIS, the Weather Channel, Weather Underground, and local weather stations, SoilSense would not need to supplement the sensor with weather measurement. This would help reduce sensor costs. In a future prototype when more capital is available for further product development, the sensor could integrate weather data from these external sources to give farmers targeted recommendations (e.g., Santa Ana winds are due to arrive tomorrow. Would you like to lengthen the irrigation period by 4 hours?)

The majority of farmers expressed a strong preference for simple notifications via text message, validating our initial design of using text messages to inform farmers of when and where to irrigate. Based on the user feedback that farmers prefer suggestions from their sensors, SoilSense can select words and phrasing that offer tailored suggestions to the farmer while enabling the farmers to make the final decision. Given the preference for text messages, the next SoilSense prototype does not require the buildout of a complex mobile application that uses sensor data to control the irrigation system. This feature can be saved for a future prototype that allows farmers to turn on and turn off the irrigation system after receiving a notification. Instead, there is an opportunity to build a mobile application that provides a seamless user experience, showcasing clear soil sensor measurements in color-coded graphs over customizable periods of time.

Farmers also provided valuable insight on pricing. For reliable and accurate soil moisture measurements, farmers are more willing to pay one-time fees for equipment, but they question even $10 monthly subscription fees. This can help inform the pricing model for SoilSense, which currently involves both one-time fees and recurring subscription fees. If SoilSense decides to implement a recurring subscription fee, it is important for SoilSense to clearly articulate what is included in the subscription fee and the added value to the farmer.

Chapter 6

Conclusion

6.1 Summary and Contribution to Research

Global studies conducted by the UN show the escalation of the global water crisis over the years. With agricultural irrigation consuming 70% of the global freshwater supply, there is a clear need to focus on developing innovative solutions in this sector. This user study contributes to the larger body of research related to soil sensor design and use and irrigation efficiency by delving into the current practices of small-scaled and medium-scaled avocado growers in California. Through in-depth user interviews, the user needs of these California avocado growers are brought to light and can help inform the design of soil sensor technology to increase water efficiency and crop yield.

This thesis is organized into six chapters. Chapter One introduces the global water crisis and the impact of agriculture on the crisis, and it also introduces SoilSense, the significance of human-centered design, and three key research questions. Chapter Two provides a review of literature related to irrigation methods for small-scale farmers and existing soil moisture solutions in the market and the market gap. Chapter Three defines the research approach and methodology, including the stakeholder selection and user research process. Chapter Four reveals the results from the user research, including an in-depth stakeholder analysis, overview of avocado growing methods, and discussion on irrigation methods and tools. Chapter Five synthesizes the research results into key user needs for California avocado growers and proposes ways to iterate on future SoilSense sensor prototypes. Finally, Chapter Six concludes the study by hearkening back to the three original research questions and proposing areas of opportunity for future studies.

6.2 Research Questions

To validate key engineering, design, and business decisions around the functionality, user experience, and pricing model, the user research aims to address these three research questions:

1. What is an appropriate target pilot market for the SoilSense soil sensor system?
2. What are gaps and pain points with current soil sensor technologies in relation to the unique user needs of small-scale and medium-scale farmers?
3. What tools and features are helpful for small-scale and medium-scale farmers to increase crop yield and drive greater water efficiency?

In response to the first research question, there is a clear opportunity to pilot the SoilSense soil sensor system with avocado growers. The interviews validated the extensive challenges surrounding irrigation scheduling, water efficiency, and water costs for this high value crop with a growing market demand. This farmer's remarks provide strong evidence for the potential of the California avocado growers' market, "I don't know why growers don't try more things. If somebody says try it, I'm game. If you develop your system, call me and I would be more than happy to try it."

In response to the second research question on the gaps and pain points with current soil sensor technologies, the market analysis and field research show that current solutions exist at two ends of a spectrum. On one end, solutions are too expensive and too complex for farmers with limited acreage to justify the purchase. On the other end, solutions are affordable but too simplistic, depriving farmers of critical information to improve irrigation efficiency on their farm. SoilSense has the clear opportunity to harness the combined capabilities of gypsum sensors and IoT communication solutions with simple text messages and clear visual graphs to better guide farmers in critical irrigation decision-making.

Finally, the key tools and features to help small-scale and medium-scale farmers increase crop yield and drive greater water efficiency include accurate soil moisture measurements and salinity measurements from a reliable soil sensor and good weather data from consistent local sources. This data needs to be readily accessible on the farmer's phone so that they can reference the data while they walk through their fields. Historic data must also be stored and quickly retrievable should the farmer want to do a multi-period analysis to determine trends in crop yield and irrigation patterns.

6.3 Areas of Opportunity for Future Studies

The user research for this study focused on a self-selected group of avocado growers in California with a propensity to adopt new technology. Additional user groups can be explored in future studies. One of such groups includes growers in California who are late adopters of technology. When the next prototype is ready for testing, SoilSense can set up pilots with the farmers from this study. Additional research and testing in developing countries such as Mexico, Colombia, the Dominican Republic, and Peru would generate valuable insights for designing a solution that works for small-scale and middle-scale farmers with less means and less access to resources, unlike the small-scale and middle-scale farmers in California. Planning for future markets to explore, there are opportunities to conduct user studies with farmers who grow other high value crops that require large volumes of water, such as nuts, citruses, and grapes. The value is clear; SoilSense can enable farmers to irrigate more efficiently through user-centered design and innovative technology.

Appendix

List of User Interview Questions

Demographics

First and Last Name:	
Farm Name:	
Location (City, Country):	
# of People in Farm	
Farm Size (in hectares)	
Crops Grown:	
Years of Experience Farming:	

General Farm Operations (GFO)

1. Please walk us through a day on the farm. Does this vary by season? How?
2. What are the inputs to the farm? How are seeds, fertilizer, equipment, etc. procured?
3. How much does it cost to grow avocados (upfront and annual recurring)?
4. What are the farm's outputs? How much avocado is sold (e.g., X lb is sold per month or year)? What is the price of avocado?
5. To whom are the avocados sold? How are avocados sold (e.g., by distributors)?
6. What do you see as the overall main challenge in your work on the farm?
7. What is the next improvement that you are going to invest in for the farm?

Avocado Growing and Technology (AGT)

1. Avocado Growing
    a. Tell us about how you grow your avocados.

b. What are the seasonal impacts on avocado growing?

    1. How have drought conditions / irrigation patterns changed over time?

c. How does the soil type impact avocado growing? Tell us about your soil type.

    1. How do you assess your soil composition?

d. What are the key challenges to growing avocados (e.g., water, land, salinity, pests, etc.)? What are your current solutions for addressing these challenges?

e. How many avocados do you grow per season?

2. Irrigation

    a. How do you irrigate your field?

    b. Where does the water supply come from? How much does it cost (either percentage of total farm costs or annual total cost?

    c. Who is responsible for irrigating the farm? How does that person determine when to irrigate?

    d. Do you use a technology to determine irrigation needs?

        1. If so, where did you get the technology from?

            1. How do you use the technology? Why do you do XYZ?

            2. How useful is current technology? Why? What does the technology do well vs. not so well?

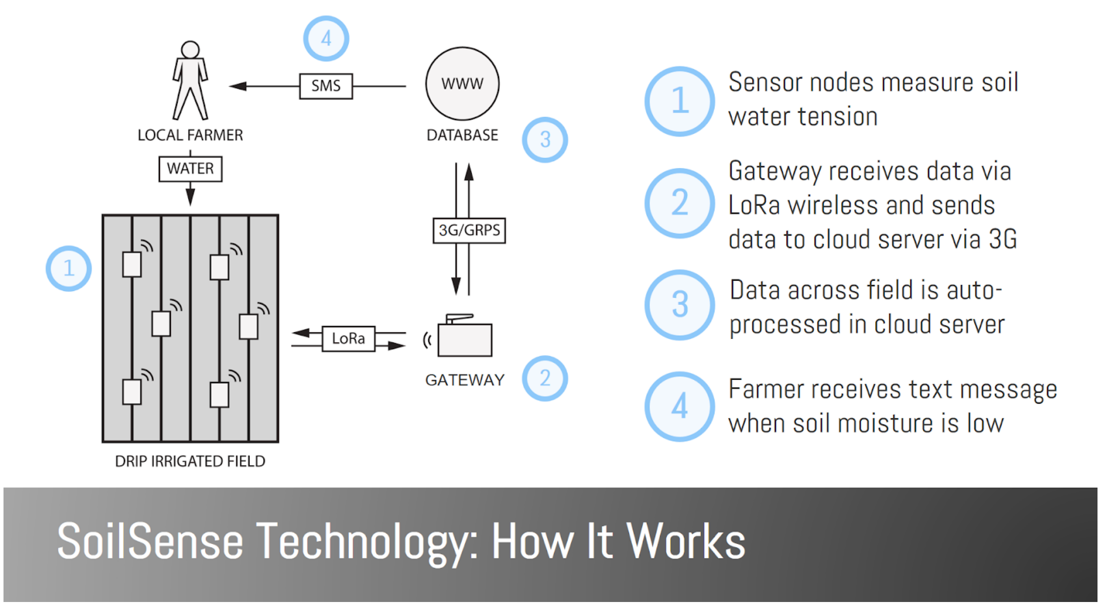
            3. How do you maintain the technology that you use today?

        2. If you do not use a technology, why don't you have something to assist with determining when and how much to irrigate?

1. Have you heard of tensiometers or watermark or gypsum sensors? What is your opinion on this technology? Which brand(s) do you use / are you familiar with? Show photo.
2. Our sensors measure soil tension, similar to tensiometers. If the farm currently uses tensiometers, how do you interpret and use the soil tension information (e.g., do you manually compare the measurements to threshold values to determine if irrigation is required)?

<u>User Feedback</u>

1. Do you currently use any devices that connect to the internet and report back to you?
2. *Explain how SoilSense technology works.* What is your initial impression of this prototype and what it does?
   a. E.g., This is a prototype of a soil sensor that detects moisture level and sends a text message to your phone when your field needs to be irrigated. Note: Can explain technology in more depth and show visual aid below



3. Installation

a. *Explain that each gypsum block measures moisture at its local position*. Where would you position these sensors in the soil? At how many depths and how deep each? Why?

b. How would you physically place and install the sensor at the locations described before? E.g., if you would dig the soil, with what tool would you dig? Can you show us? *Ask farmer to actually do it.*

c. *Explain that the measurement is wirelessly transmitted to the solar-powered gateway that has to face the sun and be within 1 km (for now) of the sensors, with mobile coverage.* Where would you position the gateway? Is there phone coverage at this spot? If so, which cellular provider do you use? *Document with photos*.

4. User Needs

   a. Does this sensor meet your farming needs? Why? In what ways does this sensor not meet your needs?

   b. What are the most important things (top 3) for the sensor to detect (e.g., moisture, soil nutrients, salinity etc.)? Why?

   c. How long would you expect an irrigation management system to last before a component should be replaced?

3. Notifications

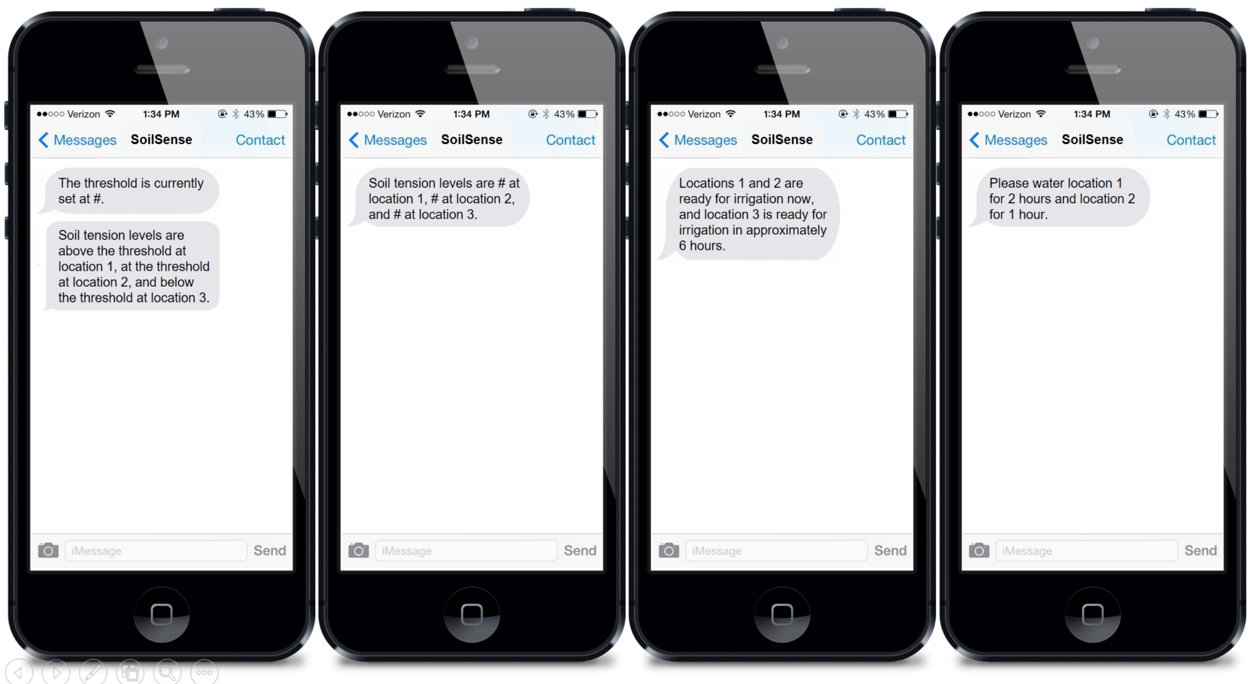
   . Who should receive the notifications regarding your field?

      i. What does the person managing the irrigation and land need to be notified of in relation to the field / crop? E.g., when to irrigate, how much to irrigate, etc.

ii. What does the person owning the land need to be notified of in relation to the field / crop?

a. Ideally, how would the system send notifications regarding the field / crop (e.g., via text message, manually check sensor, notification in an app, etc.)?

b. Which of these notifications would you prefer? How would you improve upon them?



d. How would you feel about getting a recommendation to irrigate instead of the actual data measurements (i.e., soil tension)?

e. Which would you prefer to receive:

i. Automatic notifications when the soil is ready for irrigation

ii. Scheduled notifications every hour, 2 hours, twice a day, etc.

iii. Limiting notifications to certain hours of the day (which hours?)

f. Would you act according to a message such as, “Please water the field for 2 hours.”? What if your gut feeling tells you watering is not needed? What if your gut feeling tells you to water even if the sensor claims that watering is not necessary?

4. Data
    a. What do you monitor for your farm on your phone today (e.g., check the weather)?
    b. What data trends related to your field do you need to track? What do you currently track, and how is it tracked?
    c. What forms of data visualization do you use currently? What is important for you to be able to visualize?
    d. Would you log into a website to see data trends on your field? Why or why not?
    e. Would you open an app on your phone to see data trends on your field? Why or why not?

Business Model

1. How long have you had your current irrigation management system for? Has it broken down? If so, how long after it was purchased and how did it break down? What did you do to fix it?
2. Sourcing
    a. Where do you buy farm equipment, technology, and irrigation management system? Why?
    b. How did you learn about X?
        1. X being the most recent ag-tech "investment" for this farmer, such as an irrigation system, new plow, tractor, sensor, etc.)
3. Services

a. Would you prefer installing the irrigation management system yourself or having a technician install it for you? Why?

    1. If you installed it yourself, how long did it take you? Time, money, effort required?

b. What services do you need from the irrigation management system company, if any (e.g., installation, maintenance, training, etc.)?

c. If one of the sensor nodes stops sending any data, whom would you contact to get it fixed? How long of a response time would be reasonable to you?

4. Marketing

    a. "This sensor results in a 10% yield increase and reduces water use by 15% on average." Would you trust this statement if it came from:

        1. National academic institution (e.g., MIT)
        2. Avocado growers cooperation (e.g., California Avocado Commission)
        3. Your neighbor / fellow farmer
        4. Farming publication (e.g., magazine, newsletter, etc.) - which one(s)?
        5. Other

5. Pricing

    a. How much does your current irrigation management system cost to purchase and maintain?

    b. Would you be willing to purchase this system at $500 USD per hectare up front and $500 USD / year / hectare for service fees and online data analysis?

        1. If no, what if it costs $500 USD upfront and $200 per year?
        2. What if it costs $300 USD upfront and $200 per year?

3. Would you rather have a higher annual cost and no upfront cost? Or vice versa?

c. We expect that 3 sensor nodes are needed per hectare to achieve a 10% increase in yield and 15% reduction in water use. This will cost $300 per hectare upfront and $200 per year per hectare for data fees and our online data analysis. What is your immediate reaction to this price compared to the expected benefits?

d. What qualities do you expect from a product at this cost?

e. How would you react if I tell you that the sensors have to be replaced every 2 years at a cost of $20 each? (I think that right now, not buying in bulk, they cost $15 per sensor and there are 2 sensors per "sensor node" that we have, so if we estimate at $10 market price to the farmer per sensor, it would be $20 per sensor node to replace.)

Bibliography

Amazon (2018). *Alotpower Soil Moisture Sensor Meter*. Retrieved from https://www.amazon.com/Alotpower-Moisture-Hygrometer-Outdoor-Battery/dp/B06XC6QD3B/

Antle, C. (1997). *Soil moisture determination by frequency and time domain techniques*. Retrieved from https://etd.ohiolink.edu/rws_etd/document/get/ohiou1177613443/inline

Bender, G.S. (2012). *Avocado flowering and pollination*. Retrieved from http://ucanr.edu/sites/alternativefruits/files/166371.pdf

Bender, G.S., Menge, J.A., & Arpaia, M. (2012). *Avocado rootstocks*. Retrieved from http://ucanr.edu/sites/alternativefruits/files/121265.pdf

Brouwer, C., Prins, K., & Heibloem, M. (1989). *Irrigation water management: Irrigation scheduling*. Retrieved from http://www.fao.org/tempref/agl/AGLW/fwm/Manual4.pdf

Calafrica SA (2018). *Irrometers*. Retrieved from http://www.calafricasa.co.za/soil_moisture_measurement.htm

Cale, T. (2018). *Irrigation needs and how to test for them*. Retrieved from https://www.ndsu.edu/pubweb/chiwonlee/plsc211/student%20papers/articles08/tyrelcale/Irrigation.html

California Avocado Commission (2013). *Avocado grove salinity management best practices*. Retrieved from https://www.californiaavocadogrowers.com/cultural-management-library/avocado-grove-salinity-management-best-practices

California Avocado Commission (2018). *Alternate bearing cycles*. Retrieved from https://www.californiaavocadogrowers.com/growing/how-california-avocado-tree-grows/alternate-bearing-cycles

California Avocado Commission (2018). *Growth cycles and crop size*. Retrieved from https://www.californiaavocadogrowers.com/growing/how-california-avocado-tree-grows/growth-cycles-and-crop-size

California Avocado Commission (2018). *Our growers*. Retrieved from https://www.californiaavocado.com/the-california-difference/our-growers

California Avocado Commission (2018). *Your representatives*. Retrieved from https://www.californiaavocadogrowers.com/commission/your-representatives

Centers for Disease Control and Prevention (2016). *Industrial water*. Retrieved from https://www.cdc.gov/healthywater/other/industrial/index.html

Centers for Disease Control and Prevention (2016). *Types of agricultural water use*. Retrieved from https://www.cdc.gov/healthywater/other/agricultural/types.html

Cornell University (2018). *Method of irrigation*. Retrieved from https://nrcca.cals.cornell.edu/soil/CA3/CA0324.php

CropX (2018). *Products*. Retrieved from https://www.cropx.com/products/

Crowley, D. et al. (2015). *Managing avocado fertilization and irrigation practices for improved yields and fruit quality*. Retrieved from http://indexfresh.com/wp-content/uploads/2015/10/seminar12.pdf

Daniels, J. (2018, January 10). Avocado sales could more than double this year, helped by demand from China's middle class. *CNBC*. Retrieved from https://www.cnbc.com/2018/01/10/chinas-middle-class-is-boosting-demand-for-avocados.html

Davie, S.J. et al. (1995). Girdling avocado trees for improved production. *South African Avocado Growers' Association Yearbook*, 18, 51-53. Retrieved from http://www.avocadosource.com/Journals/SAAGA/SAAGA_1995/SAAGA_1995_PG_051-053.pdf

Dela, B.F. (2001). *Measurement of soil moisture using gypsum blocks*. Retrieved from http://www.emsbrno.cz/Data/Resources/pdf/Dela2001.pdf

Delmhorst Instrument Company (2018). *KS-D1 digital soil moisture tester*. Retrieved from http://www.moisturemetersdelmhorst.com/content/delmhorst/brochure/KS-D1-Moisture-meter-Soil.pdf

Di Russo, S. (2012). *A brief history of design thinking: how design thinking came to "be."* Retrieved from https://ithinkidesign.wordpress.com/2012/06/08/a-brief-history-of-design-thinking-how-design-thinking-came-to-be/

Droughts, storms and global demand tests America's love affair with avocado. *The Economist*. Retrieved from https://www.economist.com/business/2018/01/25/droughts-storms-and-global-demand-tests-americas-love-affair-with-avocado

Enoch Media (2018). *Big garden box*. Retrieved from https://www.enoch.com/big-garden-box.html

Escalera, J., Dinar, A., & Crowley, D. (2015). *Adoption of water-related technology and management practices by the California avocado industry*. Retrieved from https://s.giannini.ucop.edu/uploads/giannini_public/14/2e/142e8e15-848b-4825-82db-af2312b5fcda/v18n3_2.pdf

Extech Instruments (2018). *Extech MO750: Soil moisture meter*. Retrieved from http://www.extech.com/display/?id=14615

Food and Agriculture Organization of the United Nations (2016). *Water uses*. Retrieved from http://www.fao.org/nr/water/aquastat/water_use/index.stm

Harrison, K. (2012). *Irrigation scheduling methods*. Retrieved from http://extension.uga.edu/publications/detail.html?number=B974&title=Irrigation%20Scheduling%20Methods

Hass Avocado Board (2018). *Avocado shipment volume data 2017*. Retrieved from http://www.hassavocadoboard.com/shipment-data/historical-shipment-volume/2017

Home Depot (2018). *Edyn garden sensor*. Retrieved from https://www.homedepot.com/p/Edyn-Garden-Sensor-EDYN-001/205833447

ICT International (2014). *Soil water potential*. Retrieved from http://ictinternational.com/content/uploads/2014/05/soilmoisture-waterpotential-02.pdf

ICT International (2018). *Soil moisture measurement instrumentation*. Retrieved from http://www.ictinternational.com/casestudies/soil-moisture-measurement-instrumentation/

IDEO.org (2018). *What is human-centered design?* Retrieved from http://www.designkit.org/human-centered-design

Irrometer (2018). *Electrical resistance blocks*. Retrieved from http://www.irrometer.com/pdf/research/DROUGHT_WEB_RESIS_BLOCKS-UC%20DAVIS_Drought_Management.pdf

Irrometer (2018). *Watermark soil moisture sensors*. Retrieved from http://www.irrometer.com/sensors.html#wm

Jen, N. (2017). *Design thinking is bullsh*t*. Retrieved from https://99u.adobe.com/videos/55967/natasha-jen-design-thinking-is-bullshit

Kickstarter (2018). *Edyn*. Retrieved from https://www.kickstarter.com/projects/edyn/edyn-welcome-to-the-connected-garden

Kickstarter (2018). *PlantLink*. Retrieved from https://www.kickstarter.com/projects/1387729422/plant-link-listen-to-your-plants/description

Kujawski, J. (2011). *Measuring soil moisture*. Retrieved from https://ag.umass.edu/fact-sheets/measuring-soil-moisture

Kurani (2018). *Riverbend School*. Retrieved from https://kurani.us/riverbend/

Leahy, S. (2018, March 22). From not enough to too much, the world's water crisis explained. *National Geographic*. Retrieved from https://news.nationalgeographic.com/2018/03/world-water-day-water-crisis-explained/

Lynch, S. (2001). *Plant available water*. Retrieved from http://planet.uwc.ac.za/nisl/Invasives/Assignments/GARP/atlas/atlas_188t.htm

Maddocks, A. (2013). *Water stress by country*. Retrieved from http://www.wri.org/resources/charts-graphs/water-stress-country

Martin, D. et al. (2018). *Measuring soil water content*. Retrieved from https://www.pioneer.com/home/site/us/agronomy/library/measuring-soil-water/

Martinez, C., & Russell-Anelli, J. (2016). *Soil water*. Retrieved from http://www.css.cornell.edu/courses/260/Soil%20Water.pdf

McGlade, J. et al. (2012). *Measuring water use in a green economy*. Retrieved from https://europa.eu/capacity4dev/unep/document/measuring-water-use-green-economy

Menge. J.A. (2018). *Master list of avocado rootstocks*. Retrieved from http://www.ucavo.ucr.edu/Rootstocks/UCRootstocks.html

METER Group (2018). *10HS soil moisture sensor*. Retrieved from https://www.metergroup.com/environment/products/ech20-10hs-soil-moisture-sensor/

METER Group (2018). *Soil moisture sensors—how many do you need?* Retrieved from https://www.metergroup.com/environment/articles/how-many-soil-moisture-sensors-needed/

Myers N., & Kent, J. (2001). *Perverse subsidies: How tax dollars can undercut the environment and the economy*. Washington, DC: Island Press.

Norman, D., & Nielsen, J. (2018). *The definition of user experience (UX)*. Retrieved from https://www.nngroup.com/articles/definition-user-experience/

Pelletier, M.G. et al. (2016). Frequency domain probe design for high frequency sensing of soil moisture. *Agriculture*, 6(4), 60-72. https://doi.org/10.3390/agriculture6040060

Perlman, H. (2016). *How much water is there on, in, and above the Earth?* Retrieved from https://water.usgs.gov/edu/earthhowmuch.html

Perlman, H. (2017). *The water cycle*. Retrieved from https://water.usgs.gov/edu/watercycle.html

Pimentel, D. et al. (2004). Water resources: Agricultural and environmental issues. *BioScience*, 54(10), 909-918. https://doi.org/10.1641/0006-3568(2004)054[0909:WRAAEI]2.0.CO;2

Pitts, L. (2016). *Monitoring soil moisture for optimal crop growth*. Retrieved from https://observant.zendesk.com/hc/en-us/articles/208067926-Monitoring-Soil-Moisture-for-Optimal-Crop-Growth

Pycno (2018). *Quick start guide*. Retrieved from https://www.pycno.co/quick-start

Reinke Manufacturing Co. (2018). *Lateral move*. Retrieved from https://www.reinke.com/lateral-move.html

Robinson, B. (2018). *Devices for measuring soil moisture: Selecting sensors for use with the SoilWaterApp*. Retrieved from http://www.soilwaterapp.net.au/Documents/Review%20of%20Soil%20water%20sensors.pdf

Sentek Technologies (2018). *Portable soil water monitoring solution*. Retrieved from http://www.sentek.com.au/products/portable.asp

Shepherd, J.S. & Bender, G.S. (2012). *History of the avocado industry in California*. Retrieved from http://ucanr.edu/sites/alternativefruits/files/166369.pdf

Sheppard, J., & Hoyle, F. (2018). *Water availability*. Retrieved from http://soilquality.org.au/factsheets/water-availability

Shiklomanov, I.A. (1993). World fresh water resources. In P.H. Gleick (Ed.), *Water in crisis: A guide to the world's fresh water resources* (pp. 13-24). New York, NY: Oxford University Press.

Skierucha, W., & Wilczek, A. (2010). A FDR sensor for measuring complex soil dielectric permittivity in the 10–500 MHz frequency range. *Sensors*, 10, 3314-3329. https://doi.org/10.3390/s100403314

Smith, M., Muñoz, G., & Sanz Alvarez, J. (2014). *Irrigation techniques for small-scale farmers: Key practices for DRR implementers*. Retrieved from http://www.fao.org/3/a-i3765e.pdf

Soil Management (2018). *Soil-water potential: Meaning and types*. Retrieved from http://www.soilmanagementindia.com/soil/soil-water-potential-meaning-and-types-soil-management/4520

Sprinkler Supply Store (2018). *Toro Precision soil sensor*. Retrieved from https://sprinklersupplystore.com/products/pss-kit-precision-soil-sensor?variant=43673680457&gclid=EAIaIQobChMIq5vYgoyb2wIVhsBkCh0RHAj0EAQYAiABEgLDX_D_BwE

T-L Irrigation Co. (2018). *Center pivots*. Retrieved from https://www.tlirr.com/products/center-pivots/

Texas A&M AgriLife Research and Extension Center at San Angelo (2018). *Tensiometer*. Retrieved from https://sanangelo.tamu.edu/extension/agronomy/agronomy-publications/grain-sorghum-production-in-west-central-texas/how-to-estimate-soil-moisture-by-feel/soil-moisture-measuring-devices/tensiometer/

The Orchard Garden (2014). *My journey through school gardens in the central region of Ghana*. Retrieved from http://theorchardgarden.blogspot.com/2014/09/my-journey-through-school-gardens-in.html

Toro (2018). *Precision soil sensor*. Retrieved from https://www.toro.com/en/professional-contractor/irrigation-sensors-remotes/precision-soil-sensor

United Nations (2007). *Coping with water scarcity: Challenge of the twenty-first century*. Retrieved from http://www.fao.org/3/a-aq444e.pdf

United Nations (2018). *Water facts*. Retrieved from http://www.unwater.org/water-facts/

United Nations Department of Economic and Social Affairs (2014). *Water scarcity*. Retrieved from http://www.un.org/waterforlifedecade/scarcity.shtml

United Nations Department of Economic and Social Affairs (2017). *World population prospects: The 2017 revision, key findings and advance tables*. Retrieved from https://esa.un.org/unpd/wpp/Publications/Files/WPP2017_KeyFindings.pdf

United States Department of Agriculture (2014). *2012 census highlights*. Retrieved from https://www.agcensus.usda.gov/Publications/2012/Online_Resources/Highlights/Farm_Demographics/

University of California at Davis (2000). *Soil-water potential: Concepts and measurement*. Retrieved from http://lawr.ucdavis.edu/classes/ssc107/SSC107Syllabus/chapter2-00.pdf

University of California Cooperative Extension (2018). *When to pick avocados*. Retrieved from http://ceventura.ucanr.edu/Com_Ag/Subtropical/Avocado_Handbook/Harvesting/When_to_pick_avocados_/

University of California Drought Management (2018). *Tensiometers*. Retrieved from http://ucmanagedrought.ucdavis.edu/PDF/DROUGHT_WEB_TENSIOMETERS.pdf

Vegetronix (2018). *Digital soil moisture meter*. Retrieved from https://www.vegetronix.com/Products/VG-METER-200/

Vegetronix (2018). *Universal sensor display*. Retrieved from https://www.vegetronix.com/Products/VG-DISPLAY/

Vegetronix (2018). *VH400 soil moisture sensor probes*. Retrieved from https://www.vegetronix.com/Products/VH400/

Virtual Soil Science Learning Resources (2018). *Time domain reflectometry*. Retrieved from http://labmodules.soilweb.ca/time-domain-reflectometry/

Water.org (2018). *The water crisis*. Retrieved from https://water.org/our-impact/water-crisis/

Werner, H. (2002). *Irrigation management: Using electrical resistance blocks to measure soil moisture*. Retrieved from http://irrigationtoolbox.com/ReferenceDocuments/Extension/SouthDakota/FS899.pdf

Whalley, W.R., Ober, E.S., & Jenkins, M. (2013). Measurement of the matric potential of soil water in the rhizosphere. *Journal of Experimental Botany*, 64(13), 3951-3963. https://doi.org/10.1093/jxb/ert044

World Wildlife Fund (2018). *Water scarcity*. Retrieved from https://www.worldwildlife.org/threats/water-scarcity

Zenvus (2018). *Store*. Retrieved from https://www.zenvus.com/store/

Zenvus (2018). *Zenvus Smartfarm*. Retrieved from https://www.zenvus.com/products/smartfarm/