DEVELOPING SOIL WATER RETENTION CURVES TO GUIDE IRRIGATION NEEDS FOR THE SOILS OF PIONEER FARM, WAIALUA, OAHU

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For my Grandpa, my cousin Ryan, and all of my family and friends.

Thank you for all of the love and support you have given me throughout my life, especially in college. Also thank you Grandpa and Ryan for always watching over me and I hope I made you guys proud.

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ABSTRACT

Improper management of water is a waste of a scarce and valuable resource as well as posing a threat to the environment. To improve irrigation scheduling in Hawai‘i, a web-based irrigation scheduling tool which incorporates real time weather data and soil moisture data will be implemented to guide farmers with their irrigation management. Soil moisture data is a key component to determine a proper irrigation recommendation, however there is little soil moisture data available for Hawai‘i's important agricultural soils. In this research, I developed soil water retention curves (SWRC) for three agricultural soils to estimate a soil moisture threshold, which is used to calculate plant available water (PAW) in cropping systems.

We collected three soils, two Mollisols (Pulehu and Ewa series) and an Oxisol (Lahaina series) with varying physical properties from the Pioneer Farm in Waialua, Oahu, and developed SWRCs for each soil. We demonstrated that soil texture and bulk density affected soil water retention where the Pulehu soil with a high sand content and the Ewa soil with a high bulk density showed less water retention and a lower amount of PAW compared to soils with a high clay content and pseudosand properties (Lahaina). The soil moisture threshold was -20 kPa for the Pulehu soil, -40 kPa for the Lahaina soil, and -70 kPa for the Ewa soil. Using the threshold, we estimated the time intervals between irrigation events using a generalized potential evapotranspiration rate that was not crop specific. We determined that the Pulehu and Ewa soils retained the least amount of PAW requiring daily irrigation applications. On the other hand, the Lahaina soil with a high clay content and high porosity retained the most PAW and a longer interval between irrigation events.

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1.0 INTRODUCTION

1.1 Water and Agriculture

Agriculture production is projected to increase over the years which will require more water resources to irrigate the crops (Sauer et al., 2010). Fresh water availability varies around the world making water scarcity a regional, local, and global issue (Rosegrant, 1997). Water used for agricultural purposes accounts for more than 70% of the total global water use making agriculture the largest user of freshwater resources (Knox et al., 2011). The efficiency of water used for agriculture globally is relatively low with over 50% of the water being lost (Bittelli, 2010). North America and Latin America have the highest amount of water available unlike other countries including Africa, Asia, and Europe where water scarcity is a growing problem (Rosegrant, 1997). By the year 2025, scientist predict that there will be 46 to 52 countries that will not have a sufficient amount of water resources available (Rosegrant, 1997). With growing demands on an increasingly scarce supply, water should be recognized as a scarce and important resource that must be regulated and managed judiciously.

Agriculture production in the United States consumes approximately 80% of the total ground and surface water and as high as 90% in the western states (USDA-ERS, 2017). US agriculture production, along with the livestock and poultry sectors, rely heavily on irrigation (USDA-ERS, 2017). According to the USDA-ERS, in 2012 approximately 56 million acres of all US croplands and pasturelands were irrigated with nearly 75% of the lands irrigated were located in the western states. Corn production in the US accounts for nearly 25% of the total US irrigated acreage harvested in 2012 (USDA-ERS, 2017).

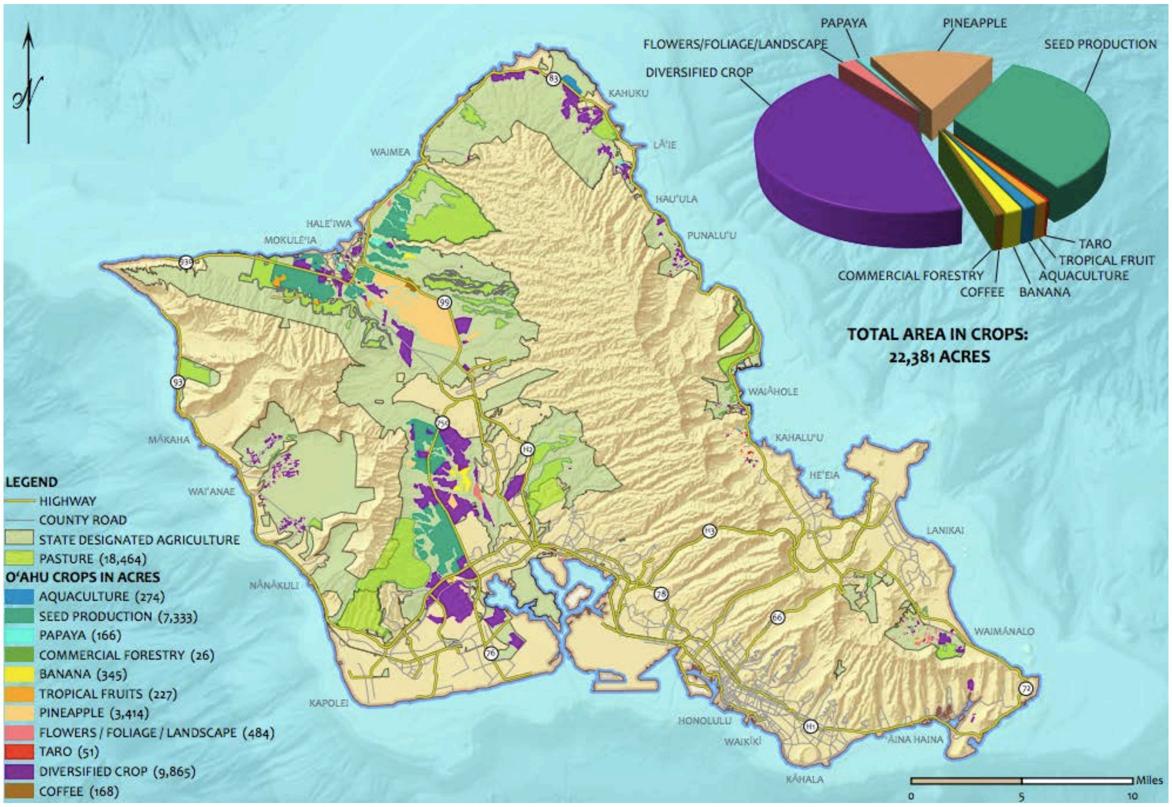

Figure 1.1 Map of Oʻahu crop production throughout the island with diversified crops covering 9,865 acres and seed production crops covering 7,333 acres. Figure taken from the State of Hawaiʻi Department of Agriculture (Melrose et al., 2016).

In the early twentieth century in Hawaiʻi, the agriculture industry was dominated by sugarcane and pineapple (Water Resource Associates, 2004). Plantation agriculture reached its peak in 1920 with irrigation systems delivering an average of 800 million gallons per day of water to approximately of 250,000 acres of crop lands (Water Resource Associates, 2004). Due to generally porous soils in Hawaiʻi, many of the irrigation systems only had small reservoirs and water needed to be diverted to fields through ditches, funnels, siphons, and flumes (Water Resource Associates, 2004). As the sugar and pineapple industry started to decline rapidly in the 1990's, agricultural lands were abandoned and increasingly converted to housing. However, as of 2015 there still remains substantial land in agriculture production. On Oʻahu, for example, there is a total of 22,381 acres of croplands with the majority of the land in diversified crops and corn seed production (Figure 1.1) (Melrose et al., 2016).

Efficient water management is a critical factor to maintain a successful crop production system. In croplands where rainfall is limiting, the absence of adequate irrigation will cause plants to undergo water stress and result in reductions of crop yield. A low crop yield due to inadequate irrigation is unacceptable to farmers and they often address this by over irrigating crops (Knox et al., 2012). Over irrigating has negative environmental impacts including the leaching of nutrients into groundwater, loss of soil by erosion into rivers and streams and eventually finding its way to the ocean (Brady and Weil, 2010), and a waste of precious fresh water resources. These issues make it important to find ways to better manage the amount of irrigation being added to crops to prevent reductions in crop yield and associated environmental impacts.

1.2 Information Needed to Efficiently Deliver Irrigation Water

Efficient delivery of irrigation water to meet specific crop water demands is complex and includes many components (Cahn and Johnson, 2017). Crop water use is affected by climatic conditions, soil conditions, and crop physiology. A simplified irrigation equation provides a framework to determine irrigation requirements in relation to crop water demand. Here we present a simplified water balance equation (EQN 1) consisting of three different aspects of soil-plant and atmospheric relationships, where gross irrigation requirement F_g, is expressed as:

$$F_g = ET_c - P - \Delta SW \qquad \text{EQN 1}$$

Where ET_c represents crop water use, which is the potential evapotranspiration (PET) multiplied by the crop coefficient (K_c) obtained in real-time by a weather station and a canopy growth model for the crop coefficient. P is the amount of precipitation and ΔSW represents the change in soil water storage, which is obtained by soil moisture sensors in the field. Soil moisture data obtained in the field must be interpreted using a soil water retention curve (SWRC) which characterizes soil water availability (Bittelli, 2010).

1.3 The Soil Water Retention Curve

A SWRC shows the relationship between the volumetric water content (θ_v) and soil matric potential (Ψ) and is difficult to accurately obtain due to the nonlinear structure but plays a crucial role in water management (Tuller and Or, 2003). Volumetric water content is the amount of water that is retained in the soil pores and the matric potential describes the energy state of the water associated with the water film (Liu et al., 2012). The energy state of the water is typically measured in kilopascals (kPa) or bars and represents the amount of attractive energy between the water molecules and the soil surface. A wet soil has a high matric potential (less negative number) with a thick water film, and as the soil dries down the matric potential becomes lower (more negative number) and has a thin water film (Brady and Weil, 2010). A general SWRC shown in Figure 1.2 explains how water content changes as a function of decreasing matric potential. On the x-axis is the tension associated with the attractive energy of water to surfaces and the volumetric water content is on the y-axis. The volumetric water content at 0 kPa is when the soil is approximately at saturation. This means that all of the pore spaces within the soil are filled with water (Brady and Weil, 2010).

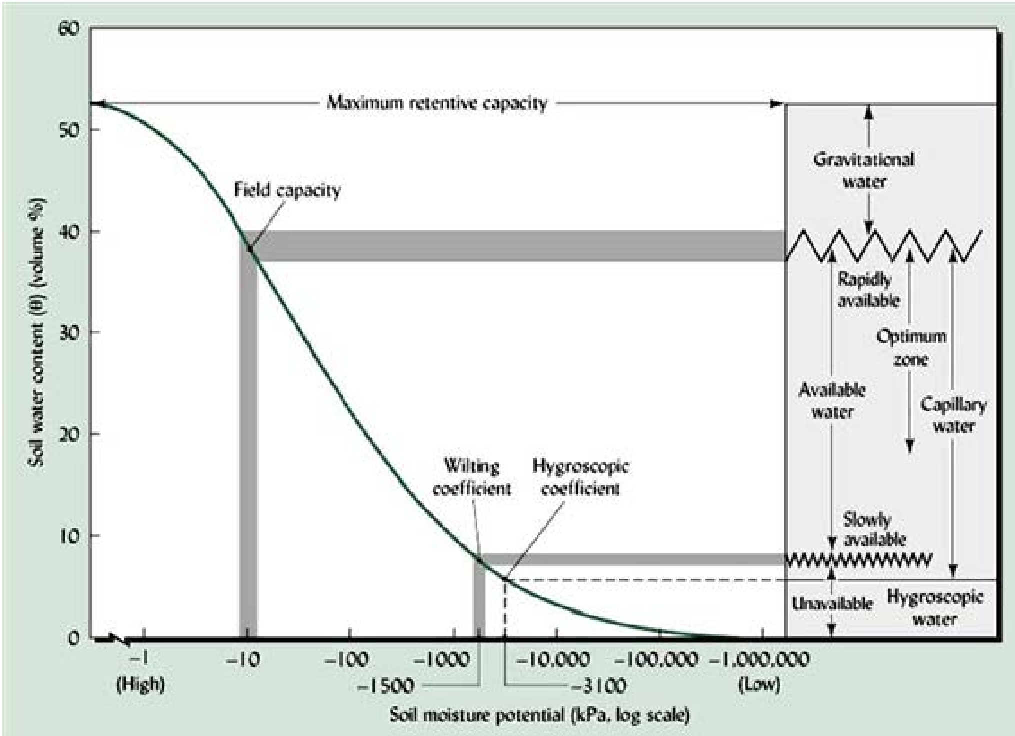

Figure 1.2 A generalized soil water retention curve showing the relationship between the matric potential (x-axis) and the volumetric water content (y-axis). Figure taken from Brady and Weil, 2010.

There are two critical water constants related to plant water availability- field capacity and permanent wilting point. Field capacity, which is between -10 to -33 kPa depending on the physical properties of the soil, is the matric potential where water can no longer be moved by the force of gravity. The water content at field capacity is the most water that will be available for a plant to use and it represents optimum soil water status for plant growth (Hillel, 2004). By convention, for sandy soils, field capacity is generally at -10 kPa and for all other soil textural classes field capacity is generally at -33 kPa. Oxisols, the weathered soils of the humid tropics rich in iron oxide clay minerals and Andisols (volcanic ash soils) are typically clay rich but field capacity is assigned at -10 kPa due to the aggregating effects of oxide clays. These soils are characterized by strong aggregation, which imparts pseudosand properties. In other words, these soils have sand-like properties meaning that soil water will move readily through the larger inter-aggregate pores much like the macropores in a sandy soil (Brady and Weil, 2010). On the drier end of the curve, is the permanent wilting point (PWP) with a low energy status of -1500 kPa. The PWP is the point at which plants can no longer extract water from a soil. However, most plants undergo water stress, with negative effects on crop growth much before the soil dries to the PWP.

1.4 Soil Properties Affecting Water Retention

Soil properties including soil texture, clay mineralogy, soil organic carbon content, and bulk density are important determinants of soil water retention behavior (Brady and Weil, 2010). Soil texture is defined as the amount, expressed as a percentage, of sand, silt, and clay sized particles in a soil volume. Texture affects surface area and the distribution of pore size, which controls water retention and availability. Sand sized particles, ranging from 2 mm to 0.05 mm, have low specific surface of approximately 11 to 227 cm^2/g and inherently low water retention capacity. Furthermore, sandy soils are dominated by macropores, which are large and promote the flow of water through the soil relatively quickly. Water in macropores (pores greater than 0.08 mm diameter) do not retained water well and is easily removed by gravity. Silt sized particles ranging from 0.05 mm to 0.002 mm have a greater amount of pores, a larger surface area of approximately 454 cm^2/g, and higher water retention than sand sized particles. Silty soils contain both macropores and micropores (smaller than 0.08 mm) which will retain more water compared to a sandy soil. Clay sized particles are characterized as particles smaller than 0.002 mm that have the largest surface area of approximately 8,000,000 cm^2/g. Clay-rich soils are dominated by micropores. Water in micropores are held tightly with a low matric potential and much of the water retained is not plant available (Brady and Weil, 2010).

The soil organic carbon content of a soil is related to the amount of organic matter that is present. The surface area of soil organic matter can range between 550 x 10^3 to 800 x 10^3 m^2/kg (Pennell et al., 1995).Organic matter acts as a glue for soil particles which makes it an aggregator and increases the water retention of the soil. Soils with good aggregation generally will have a lower bulk density, good water retention, and a mixture of macropores and micropores which promotes water movement within the soil. The amount of soil organic carbon amounts to about 50% of the total organic matter present within the soil (Brady and Weil, 2010). Soil organic matter affects the structure and adsorption properties of a soil, however previous studies on the relationship have revealed contradictory results (Rawls et al., 2003). Some scientist had found that soil organic matter has an effect on soil water retention at matric potentials of -33 kPa and -1500 kPa while other scientist have found it does not (Rawls et al., 2003).

Bulk density (D_b) is a mass measurement of a soil which includes both solids and pores. Soil texture, degree of aggregation, and amount of organic matter all effect soil bulk density. Sandy soils have a higher bulk density than clayey soils. Increasing amounts of organic matter will aggregate the soil and decrease the bulk density of the soil. Well-aggregated soils have a low bulk density due to the amount of pore space created within the soil. Bulk density is directly related to the amount of pore space where the more pore space within the soil will generally result in a lower bulk density (Brady and Weil, 2010). Thus, bulk density affects water retention through its control of pore space. However, we note a clay-rich soil dominated by micropores will have a high water retention capacity, but a larger proportion of that water is tightly held in micropores and not plant available. Bulk density is generally lower in surface soils and increases into the subsoil. Soil compaction, a common occurrence in heavily cultivated agricultural soils, increases soil bulk density by eliminating pore space with a net reduction in soil water holding capacity (Brady and Weil, 2010).

1.5 Plant Available Soil Water

Not all water present within the soil is available for plants to absorb and use for growth. The water potential of the plant root must have a greater negative value (lower energy status) than the soil in order for the plant to absorb and use the water available (Hillel, 2004). The total plant available water (PAW) is calculated by the difference between the amount of water at field capacity and water at the PWP. However, using the PWP as the bottom end of PAW is not practical because plants have already suffered irreparable damage if soil moisture drops to this level. The soil moisture threshold is the matric potential where the plants begin to show water stress because they have a difficult time pulling the water from the soil. This threshold can be estimated by examining behavior of the SWRC and identify the point where the curve starts to level off on a SWRC. In soil that has a lower matric potential than the threshold, the plants may start to express signs of water stress and indicates to the farmer that water needs to be added. The threshold can be interpreted with a SWRC and measured in the field by using a tensiometer. The threshold varies depending on the type of crop, soil type, and their interaction with climatic conditions. Table 1.1 provides an example of how the threshold varies by crop type. Crops that experience water stress quickly have a threshold at the wet end of the curve (-20 to -60 kPa) such as celery, cantaloupes, and potatoes whereas crops such as sweet corn, tomatoes, and cotton have a threshold in drier soils with a lower water potential (-50 to -120 kPa) (Datta et al., 2017). Typically in irrigation management the plant available water is the water at field capacity minus the soil moisture threshold.

Table 1.1 Examples of recommended soil moisture thresholds for different types of crops (taken from Datta et al., 2017).

Type of Crop	Soil Moisture Threshold (kPa or cb)
Celery	20-30
Potato	30-50
Cantaloupe	35-40
Lettuce	40-60
Sweet Corn	50-80
Tomato	60-150
Cotton	100-120

1.6 Irrigation Management Tools

There are different types of irrigation management tools to guide farmers on the amounts of irrigation they add to their crops and when to apply the water. One irrigation scheduling web-based tool called CropManage, created by the University of California, Davis (UC Davis) uses a water balance approach that integrates real time weather data to calculate PET, crop coefficients to quantify crop water use, along with soil property and soil moisture data to provide farmers with a recommendation for the amount and timing of irrigation events in real time (Cahn and Johnson, 2017). The CropManage web-based tool uses SWRCs in the soil moisture component of the computation to determine a soil moisture threshold to set the point where irrigation must be applied to prevent water stress on the crops. A research group in the College of Tropical Agriculture and Human Resources (CTAHR) at the University of Hawaiʻi is currently adapting the CropManage software to Hawaiʻi conditions. Given that water availability varies across soil types as a function of soil texture, soil organic carbon content, soil mineralogy, and bulk density, SWRC's representative of Hawaiʻi soils must be substituted into the CropManage computational structure.

1.7 Goals & Objectives

A SWRC provides valuable and necessary information for irrigation management, however gathering data and building a SWRC is a time consuming and difficult task. There is currently a knowledge gap in this area of irrigation management because only a few SWRC data have been collected for Hawaiʻi soils. To address this gap in knowledge, my research project has three objectives:

1. To characterize soil properties that affect water retention (texture, organic matter, and bulk density),
2. To develop water retention curves for three important soil types located on the Pioneer farm,
3. To use the SWRC to identify a moisture threshold to guide irrigation scheduling

These specific objectives are part of a larger project to adapt CropManage for Hawaiʻi agriculture.

2.0 METHODS

2.1 Study Area and Sample Collection

The study area for this project was at Pioneer Farm, a large seed corn operation located in Waialua on the North Shore of O‘ahu. The farm covers approximately 1,700 acres and consists of seven important agricultural soil series which belong to three different soil orders, Mollisol, Oxisol, and Vertisol (USDA-NRCS, 2018). The Mollisols, comprised of the Pulehu, Ewa, Waialua, Waipahu, and Kemo‘o series, are generally characterized by a surface horizon that is dark in color, rich in organic matter, and soft even when the soil becomes dry (Brady and Weil, 2010). The Oxisol, comprised of the Lahaina series, is generally characterized as the most weathered soil order that has a deep oxic subsurface horizon implying that they are rich in iron (Fe) and aluminum (Al) oxides and low-activity silicate clays (Brady and Weil, 2010). The accumulation of iron oxides gives the soil a reddish color, but may actually have a higher amount of organic matter (Soil Survey Staff, 2014). Lastly, the Vertisol comprised of the Ka‘ena series, is typically characterized as having similar properties as a Mollisol but does not contain as much organic matter (Brady and Weil, 2010). Vertisols are also characterized by the smectitic properties that the soil possesses which means the soil will swell up when it becomes moist and shrink when it becomes dry (Brady and Weil, 2010).

The USDA-NRCS Soil Web App and the USDA-NRCS Web Soil Survey online database were used to verify the location of each of the soil series on the farm. For the textural and organic matter analysis, we collected the soils at the 0-15 cm depth (surface) and the 15-30 cm depth (subsurface). The soil was collected in buckets and transported back to the lab.

Soils to construct the SWRC were collected at the 7-10 cm (A) and 22-25 cm (B) depths representing the surface and subsurface soil, respectively. We obtained undisturbed cores to measure the water retention curve by gently inserting a pre-weighed metal core ring with a height of 3 cm and a diameter of 5.5 cm at the two specific depths. We made a concerted effort to not alter field bulk density due to compaction of the soil during the insertion of the cores. The cores were carefully packed to retain the soil and brought back to the lab for analysis.

2.2 Soil Texture Analysis: Pipette Method

We used a modified standard pipette method to quantify sand, silt, and clay fractions of the seven soil series (Soil Survey Staff, 2014). The procedure required an initial pre-treatment step to remove the organic matter. The pre-treatment required the addition of 5 mL of H_2O_2 (to oxidize soil organic matter) and 50 mL of deionized (DI) water to 10 grams of air dry soil in a crucible, which was then placed on a hot plate at 90°C and covered with a watch glass. When the reaction ceased, an additional 5 mL of H_2O_2 was added in four successive increments and then left on the hot plate for 45 minutes to let the H_2O_2 decompose. The organic matter free soil was transferred to a 250 mL Erlenmeyer flask and placed in an oven at 110°C to dry overnight. We weighed the oven dry sample to the nearest milligram and subtracted the flask weight to obtain the total weight (TW) of the soil used in the texture calculations.

The first step in particle size analysis requires complete dispersion of the soil particles. We made a dispersing solution by dissolving 35.7 grams of sodium metaphosphate (Na-MP $(NaPO_3)_6$) and 7.94 grams of sodium carbonate (Na_2CO_3) in 1 liter of DI water. To disperse the sample we added 10.09 mL (for a weight of 0.4408g/sample) of the Na-MP solution (DW) and 175 mL of DI water to the weighed soils in a covered 250 mL Erlenmeyer flask, which we placed on a horizontal shaker at 120 oscillations per minute for 16 hours. Following the shaking, the soil and solution were carefully transferred through a 0.047 mm sieve into a 1000 mL graduated cylinder. The sample remaining on the sieve was transferred into a 150 mL beaker and placed into the oven to dry at 110°C overnight. Particles on the sieve represent the sand content (SaW) of the sample. The remaining solution in the graduated cylinder was brought up to 1000 mL with DI water. The particles in the cylinder represent the silt and clay contents of the soil.

The silt and clay contents were thoroughly mixed with a hand stirrer for exactly 1 minute to ensure full suspension of all particles. Once stirring ceased, a 25 mL volume was extracted after approximately 4 seconds, determined by the temperature of standing beaker water, at the 10 cm depth using a 25 mL pipette. The pipetted suspension was placed in a 150 mL beaker and the pipette was washed out twice with DI water into the same beaker. The sample was placed in an oven overnight at 110°C which represented the silt content (SiW). The clay extraction of a 25 mL volume was done exactly 4.5 hours later with an extraction depth of approximately 6 cm which was determined by the temperature of standing beaker water. The clay suspension was transferred into a beaker following the same process as the silt extraction which represented the clay content

(CW). Once the samples dried overnight, they were weighed to the nearest milligram and the following equations were used to determine the percent sand, silt, and clay present in the soil.

$$\text{Sand \%} = (\text{SaW}/\text{TW}) \times 100\% \qquad \text{EQN 2}$$

$$\text{Clay \%} = [(\text{CW}-[\text{DW}/\text{CF}]) \times (\text{CF}/\text{TW})] \times 100\% \qquad \text{EQN 3}$$

$$\text{Silt \%} = [100\% \times [(\text{SiW} - [\text{DW}/\text{CF}]) \times (\text{CF}/\text{TW})]] - \text{Clay\%} \qquad \text{EQN 4}$$

Where SaW is the weight of the oven dry sand content, TW is the total oven dry weight of the sample, DW is the weight of the Na-MP solution added to the solution, CF = 1000 mL/dispensed pipet volume of 25 mL, SiW is the weight of the oven dry silt content, and CW is the weight of the oven dry clay content.

2.3 Soil Organic Carbon Analysis by Combustion

Each of the seven soil samples were dried in an oven at 40°C overnight and then sieved through a 2 mm mesh (No. 10). The soil samples were then ground using a mortar and pestle and sieved through a 0.250 mm mesh (No. 60) and placed in glass tubes. The ground and sieved samples were analyzed for organic carbon by combustion using a Carlo Erba NC 2500 Elemental Combustion System/Pneumatic Autosampler manufactured in Cernusco sul Naviglio, Italy.

2.4 Soil Water Retention Curves

We developed soil water retention curves on three of the soils from the Pioneer farm. The soils chosen were based on total farm coverage (Ewa series) shown in Table 2.1 and contrast in texture and soil order (Pulehu and Lahaina series).

Table 2.1 The total land coverage in acres of each soil series being analyzed located on the Pioneer corn seed farm.

Series	Total Acres
Ewa	668.5
Waialua	552.9
Lahaina	260.0
Pulehu	135.4
Waipahu	52.5
Ka‘ena	23.4
Kemo‘o	22.7

We used tempe cells fitted with 0-0.5 bar ceramic plates for the 0 to -25 kPa portion of the curve and 0-1 bar ceramic plates for the -30 to -100 kPa portion. The undisturbed field cores were placed on the tempe cells that were weighed and soaked for at least 12 hours in a 0.01 M $CaCl_2$ solution prior to the core being added. Once the core was inserted into the bottom of the tempe cell, it was placed back into the $CaCl_2$ solution for approximately two days or until the soil had fully saturated by capillary rise. The top of the tempe cell was secured to ensure an airtight condition once the cores had saturated and weighed to get an initial saturated weight of the soil core. For the wet end of the curve (0 to -25 kPa), the tempe cells fitted with 0-0.5 bar ceramic plates were placed on a manifold connected to a vacuum, which was adjusted to -5 kPa of suction. The tempe cells were weighed at regular intervals until reaching a constant weight and recorded. The procedure was repeated in 5 kPa increments up to -25 kPa, after which the cores were carefully removed and transferred into a beaker to obtain a dry weight. A second set of cores of the same soil and depth were placed in tempe cells fitted with 0-1 bar ceramic plates, saturated as described above, and places on a manifold connected to a pressure hose to deliver pressure at -30, -40, -60, -80, and -100 kPa. At each pressure increment, the tempe cells were weighed until the cell had reached equilibrium, and the dry weight was obtained after the final pressure increment.

We determined soil volumetric water content at each suction/pressure interval in the following way:

$$\theta_v = D_s \times \theta_m \times D_{H2O} \qquad \text{EQN 5}$$

Where θ_v is the volumetric water content of the soil in the core, D_s is the bulk density of the soil (g/cm^3) calculated as the oven dry mass (g) of the soil in the core divided by the core volume (cm^3). θ_m is the gravimetric water content of the soil calculated by the difference between the moist soil (g) and the oven dry soil (g) by the oven dry soil (g) and dividing by the oven dry soil (g).

2.5 Modelling the SWRC

We used the SigmaPlot software (version 14) to fit a curve to the measured values of θ_v as a function of water tension. We used the dynamic regression wizard tool in SigmaPlot to assess the fir of a range of non-linear equations. Once the best-fit equation was identified, we used it to generate a predicted SWRC where we explored the effect of the different parameters on the shape of the SWRC to understand their physical significance. Finally, we used the first-derivative of the best fit equation to determine the point at which the slope approached zero, which we used as an estimated soil moisture threshold.

3.0 RESULTS

3.1 Soil Texture and Organic Carbon Analysis

The soil texture analysis data presented in Table 3.1 shows the average sand, silt, and clay content for each series at both depths. There were generally only small differences in particle size distribution between the surface and subsoil layers for each soil with a few exceptions. For example, sand content was 5% higher in the subsoil of the Pulehu soil and silt and clay contents in the Ewa soil differed by 11% between the two different depths. Based on the soil texture triangle, the Pulehu series is a clay loam and all the other soil series belong to the clay textural class. The Pulehu series had the lowest clay content for both depths of 30% for Pulehu A and 29% for Pulehu B. The Ka‘ena series had the second lowest clay content between 55-56% for both depths and a sand content of 13-14% for both depths. The other soil series had a clay content of 60% or greater and a sand content lower than 6%.

Depth differences in soil organic carbon (SOC) content were more pronounced than texture. As expected, SOC in the surface layer was higher than the sub-soil (Table 3.2) ranging from a high of 1.96% in the Ka‘ena and Waialua series and a low of 1.42% in the Lahaina series. SOC in the sub-soil ranged from a high of 1.89% in the Waialua series and a low of 1.15% in the Lahaina series. The Lahaina series had the lowest amount of SOC in both the surface layer and subsurface layer. The Ka‘ena series had the biggest difference in SOC between the two depths of 57%.

Table 3.1 Soil texture analysis of each soil series with an average of depths A and B with a standard error.

Soil series	% Sand	% Silt	% Clay
Pulehu A	24.964 ± 0.381	44.680 ± 0.626	30.355 ± 1.007
Pulehu B	29.537 ± 0.991	41.285 ± 0.235	29.178 ± 0.742
Kaʻena A	13.596 ± 0.038	30.414 ± 0.295	55.990 ± 0.257
Kaʻena B	14.243 ± 0.054	29.229 ± 0.929	56.528 ± 0.983
Kemoʻo A	3.266 ± 0.044	31.555 ± 0.230	65.179 ± 0.274
Kemoʻo B	4.466 ± 0.237	35.995 ± 0.778	59.539 ± 0.542
Ewa A	3.103 ± 0.074	28.803 ± 1.465	68.095 ± 1.539
Ewa B	4.366 ± 0.000	38.561 ± 0.782	57.073 ± 0.782
Waipahu A	3.602 ± 0.273	26.268 ± 0.813	70.130 ± 0.540
Waipahu B	4.264 ± 0.449	29.211 ± 0.632	66.524 ± 0.183
Waialua A	4.547 ± 0.193	27.858 ± 1.350	67.595 ± 1.543
Waialua B	5.797 ± 0.136	26.237 ± 0.606	67.967 ± 0.742
Lahaina A	3.900 ± 0.193	26.374 ± 0.419	69.727 ± 0.226
Lahaina B	3.939 ± 0.190	28.791 ± 0.487	67.270 ± 0.296

Table 3.2 Soil organic carbon content analysis of each soil series with an average of depth A and depth B with a standard error.

Soil series	% Organic Carbon
Pulehu A	1.57 ± 0.01
Pulehu B	1.44 ± 0.02
Kaʻena A	1.96 ± 0.00
Kaʻena B	1.39 ± 0.01
Kemoʻo A	1.85 ± 0.01
Kemoʻo B	1.34 ± 0.00
Ewa A	1.84 ± 0.02
Ewa B	1.53 ± 0.01
Waipahu A	1.74 ± 0.00
Waipahu B	1.61 ± 0.01
Waialua A	1.96 ± 0.03
Waialua B	* 1.89
Lahaina A	1.42 ± 0.00
Lahaina B	1.15 ± 0.03

* only 1 sample

3.2 Soil Water Retention Curves

The general shape of the SWRC for all soils showed three regions of change in water content as a function of water potential (Ψ): a region of relatively rapid decline at high Ψ (0 − -10 kPa), which represented water loss due to gravity. A second region of intermediate change (-10 − -30 kPa), which corresponds to optimum soil water for plant use, and a third region of minimal change in water content (-30 − -100 kPa) representing water that was less available for plant use (Figure 3.1A and 3.1B). However, there were some important differences between the Pulehu and Lahaina soils on one hand, which were more similar in behavior, and the Ewa series on the other hand.

In Figure 3.1A, curves for the surface soils are presented where the Pulehu series had the greatest decline in water content between the range of 0 to -10 kPa and the Ewa series has the lowest decline for the same tension increment. Expressed in terms of mm of water, the Pulehu lost 36.0 mm, the Lahaina 30.0 mm, and the Ewa 12.0 mm (Table 3.3) assuming a soil depth increment of 15 cm corresponding to the surface layer. In the intermediate region (-10 to -30 kPa) representing plant available water, the Lahaina soil retained the largest amount of water and the Pulehu soil retained the lowest amount of water content. The Lahaina soil retained 12.0 mm, the Ewa soil retained 10.5 mm, and the Pulehu soil retained 4.5 mm of water. The third region, water retention showed small changes as Ψ decreased with the Pulehu and Lahaina soil retained similar amounts of water (4.5 mm) and the Ewa soil retained the least (3.0 mm).

For the subsoil depths (Figure 3.1B), the Lahaina and Ewa soils showed the same trend as their corresponding surface soils where there were three regions of the curve and relatively the same amount of water loss for the first region (0 to -10 kPa). In the first region, representing a rapid water loss due to gravity, the Lahaina soil lost 25.5 mm and the Ewa soil lost 13.5 mm of water. In the intermediate region (-10 to -30 kPa) representing the optimum water for plants to absorb, the Lahaina and Ewa soils retained nearly the same amount of water of 4.5 mm (Lahaina) and 3.0 mm (Ewa). In the third region of the curve, water retention showed similar trends to the surface soil with small changes of water retention as the Ψ decreased. The Lahaina soil retained a lower amount of 3.0 mm compared to the Lahaina surface soil, however the Ewa subsoil retained a higher amount of 4.5 mm compared to the Ewa surface soil.

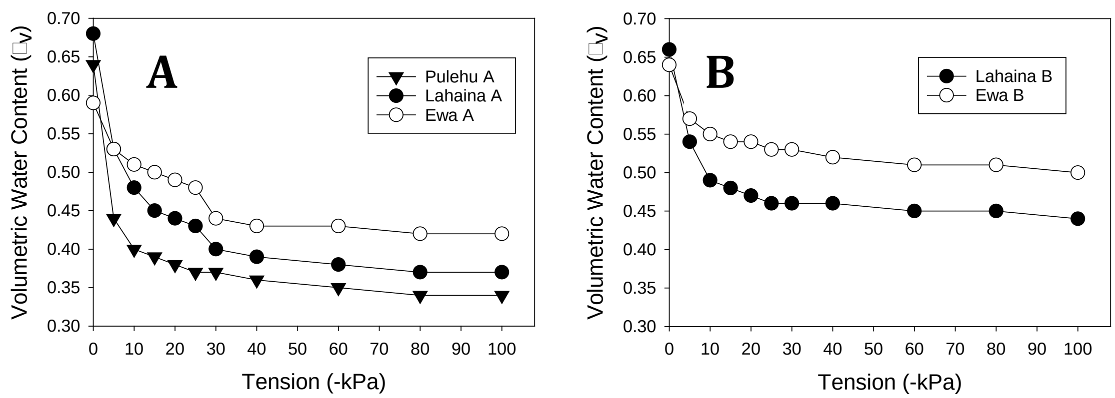

Figure 3.1 Soil water retention curves for the three soil types showing the difference in the change of volumetric water content of the surface soils (A) and the subsoils (B).

Table 3.3 The change in volumetric water content and change in water storage (mm) for three different increments of matric potentials.

	0 to -10 kPa		**-10 to -30 kPa**		**-30 kPa to -100 kPa**	
Surface Soils (0-15 cm)	**$\Delta\theta_v$**	**Δ mm H_2O***	**$\Delta\theta_v$**	**Δ mm H_2O**	**$\Delta\theta_v$**	**Δ mm H_2O**
Pulehu	0.24	36.0	0.03	4.5	0.03	4.5
Lahaina	0.20	30.0	0.08	12.0	0.03	4.5
Ewa	0.08	12.0	0.07	10.5	0.02	3.0
Sub Soils (15-30 cm)	**$\Delta\theta_v$**	**Δ mm H_2O**	**$\Delta\theta_v$**	**Δ mm H_2O**	**$\Delta\theta_v$**	**Δ mm H_2O**
Lahaina	0.17	25.5	0.03	4.5	0.02	3.0
Ewa	0.09	13.5	0.02	3.0	0.03	4.5

*mm H_2O = θ_v x 15 cm (depth) x 10 mm to express soil water content in terms of length (depth)

3.3 Curve Fitting

The curve fitting procedures using the SigmaPlot dynamic regression wizard module resulted in the identification of an exponential linear combination equation which provided the best fit of the SWRC data across all three soils. The equation (EQN 6) consists of an exponential decay component and a linear component with the form:

$$y = y_0 + ae^{-bx} + cx \qquad \text{EQN 6}$$

Where y is the predicted volumetric water content, y_0 is the y-intercept when the exponential component goes to 0, a controls the magnitude of the change in volumetric water content in the exponential region, b controls the curvature of the exponential component where more negative values produce a steeper curve and less negative values flatten the curve, and c controls the slope of the linear component at lower matric potentials (Figure 3.2). In terms of soil water retention, highly negative *b* values represent less water retention or less plant available water at a given Ψ. The combined equation produced a good fit to the data for all soils with an adjusted R^2 ranging from 0.997 to 0.948 (Table 3.4). In other words, with this equation 94.8% to 99.7% of the variation in the predicted Y values (θ_v) are explained by variation in the X values (Ψ). The values of the R^2 were close to 1 which means the equation fits the data well.

Table 3.4 The exponential linear combination equation components and values for each SWRC.

Soil Series	**adj R^2**	y_0	a	b	c
Pulehu A	0.9955	0.3876	0.252	0.2921	-0.0005
Lahaina A	0.9839	0.4284	0.2476	0.1489	-0.0007
Lahaina B	0.9972	0.4696	0.1904	0.1964	-0.0003
Ewa A	0.9481	0.411	0.1697	0.0476	-7.42E-05
Ewa B	0.9897	0.5422	0.0974	0.2221	-0.0004

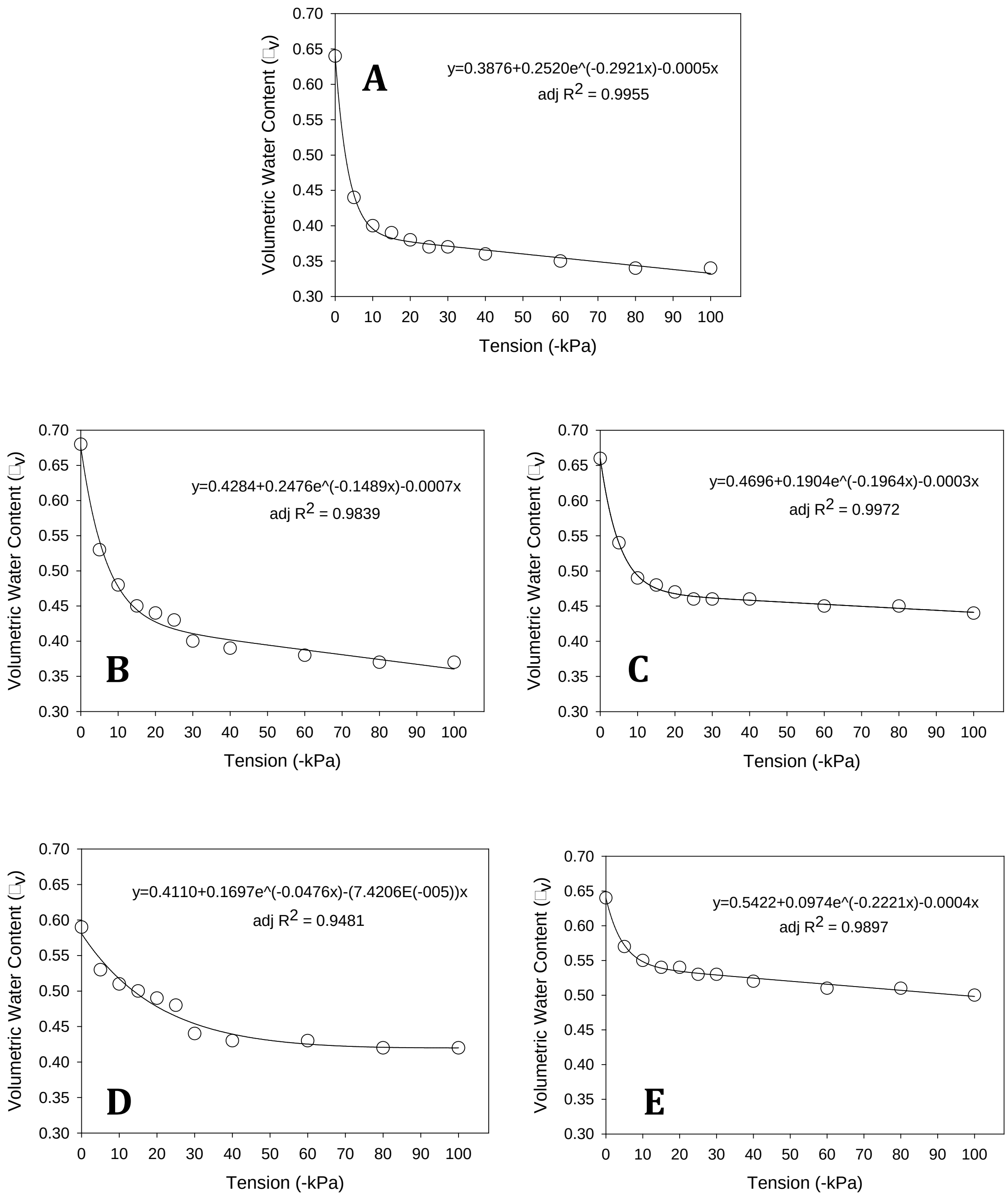

Figure 3.2 Curve fitting results for the Pulehu surface (A), Lahaina surface (B) and subsoil (C), and Ewa surface (D) and subsoil (E) with exponential linear combination equation. The lines represent the predicted response of θ_v to increasing values of Ψ.

4.0 DISCUSSION

4.1 Effects of Soil Texture and Bulk Density on the SWRCs

Water availability in a soil is quantified using a SWRC where our results may indicate that soil texture and bulk density pose a significant effect on water retention as it is depicted in the SWRCs. Soil texture plays a key role in soil water retention through surface area properties and pore size. The Pulehu series contained the highest amount of sand sized particles, which suggests that this soil may have the most macropores. From the SWRC (Figure 3.1A and 3.1B) we see that the Pulehu soil lost water most rapidly at high values of Ψ (0 − -10 kPa). We know that sandy soils have more relative macropore spaces and we infer that the Pulehu contained more macroporosity. The Lahaina soil lost a similar amount of water at low Ψ compared to the Pulehu soil despite low sand content. We attribute this relatively large water loss to pseudosand properties present in oxidic mineralogy which provides the soil with high porosity and results in clay particles acting like a sand particle. The Ewa soil lost the least volume of water at low Ψ which had very low sand content and is not characterized by oxidic mineralogy in the clay fraction. This suggests that the Ewa soil contains less macropore space or presence of inter-aggregate macropores than the Pulehu and Lahaina soils. The sand-like behavior of the Lahaina soil despite very low measured sand content, shows the difficulty of using soil texture alone to explain water retention properties in tropical soils with high oxide mineralogy. The same behavior occurred in the subsoil where the Lahaina soil lost more water compared to the Ewa soil. Both subsoils relatively had the same saturation point but the Ewa soil that does not contain the oxidic mineralogy did not lose water as rapidly as the Lahaina soil at the high values of Ψ (0 − -10 kPa).

Soil water present from -10 to -100 kPa is not moving due to the force of gravity and is retained within the soil for plants to absorb. This is water that is considered to be plant available water (PAW). In the surface soil, the Pulehu soil with the high sand content had the lowest amount of PAW for a total of 9.0 mm and the Ewa soil with the poorly aggregated clay had the second lowest amount of PAW for a total of 13.5 mm. The Lahaina soil that possesses the pseudosand properties with a high clay content had the highest amount of retained water for plants to use for a total of 16.5 mm.

Bulk density varies with soil texture and aggregation and also plays a key role in soil water retention in relation to pore space. Generally, pore space decreases with increased bulk density values. The Ewa soil showed the highest bulk density and could be felt during the core collection – the Ewa soil was the hardest soil core to collect likely due to compaction of the soil. The Lahaina soil had a similar soil texture to the Ewa soil, but its pseudosand properties impart better aggregation and more pore space so the soil was not as compact. The bulk density of the Lahaina soil was significantly lower than the Ewa soil with nearly the same soil texture.

4.2 Effects of Soil texture and Bulk Density on the *b* parameter

Using the SWRC best fit line, we were able to make preliminary interpretations of the relationship between the *b* parameter of the equation (EQN 6) and certain soil properties identified above. We found relationships between the *b* parameter and the % clay, % silt, and bulk density. As the clay content of a soil increases, the *b* parameter becomes less negative, which means an increase in clay content reduces curvature in the exponential region SWRC; less curvature represents more water retention. In Figure 4.1A, the R^2 value of 0.610 states that 61% of the variance *b* parameter is explained by change in clay content. In Figure 4.1B, the % silt had a positive correlation with the *b* parameter where the increase in silt content produced a more negative *b* value and make the water relatively moveable. This relationship between the *b* parameter and silt content implies that there is a fair amount of macropores in relation to micropores in all three soils which allows water to be removed.

The relationship between bulk density and the *b* parameter are not as straight forward as the clay and silt content due to an outlier point in Figure 4.1C. The outlier is from the Ewa subsoil which had a high bulk density of 1.23 but a relatively highly negative *b* value of -0.2221. The R^2 value of the graph not including the outlier is 0.953 which means bulk density explains 95% of the variation in the b parameter. Disregarding the outlier, there is a negative correlation between bulk density and the *b* parameter. As the bulk density increases, the *b* value becomes less negative making the curvature of the graph less pronounced suggesting decreasing macro- and meso-porosity and more tightly held water.

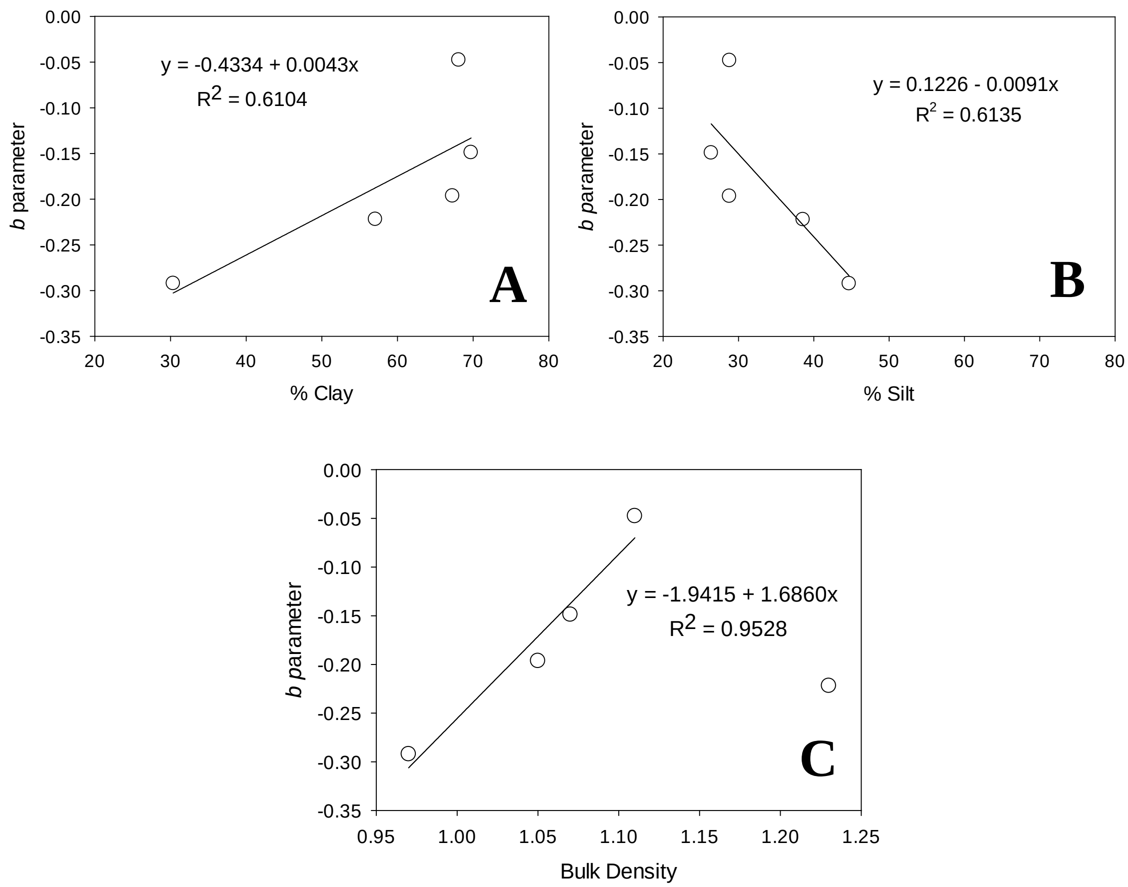

Figure 4.1. The relationship between the *b* component vs soil texture (% siltB and % clayA) and bulk density C.

4.3 Determining a Soil Moisture Threshold

Irrigation scheduling depends on weather conditions (warm dry weather increases evapotranspiration), plant physiology (crop water use in relation to a drying soil varies among species and varieties), and water retention properties as depicted in the SWRC. A soil water threshold represents the point at which plants begin to experience difficulty in accessing soil water. On the SWRC, this point occurs when θ_v does not change with decreasing Ψ. We can estimate this point by taking the first derivative of the exponential linear combination equation (EQN 6) which gives us the slope of θ_v in relation to the decreasing Ψ. As the slope goes to 0, the θ_v is not being affected by the lower matric potential, and therefore the water in the soil is not easily accessed by plant roots. The plants will need to lower the energy potential within their tissues and will result in water stress if it becomes too low. A soil moisture threshold can be determined by plotting the first derivative and noting the tension at which the slope goes to 0. The threshold for each soil varies by series and depth and ranges from -15 kPa to -70 kPa. The Ewa subsoil had the lowest threshold (Table 4.1) that may be attributed to the high clay content, high bulk density, and relatively higher microporosity. The Ewa surface soil had a threshold that was slightly higher which is expected due to the higher clay content in the deeper parts of the soil profile. The Lahaina soil showed the same trend as the Ewa soil where the surface soil had a higher threshold compared to the subsoil. The Pulehu surface soil reached a threshold at the highest Ψ due to its high sand content that does not allow as much water retention as the other soils that were high in clay content. While this approach may provide an initial estimate, a soil water thresholds depend not only on soil properties, but also on the crop species and their water use.

The soil moisture threshold combined with daily potential evapotranspiration (PET) rates and specific crop coefficients are used to produce irrigation recommendations. Here we present a hypothetical irrigation recommendation based upon average PET rates for the three soil sites at Pioneer Farm and estimated soil moisture thresholds. PET rates were obtained from the Hawaii Evapotranspiration Atlas (Giambelluca et al., 2014) for the month of September. In real life, the calculation would include specific crop coefficients and real-time PET estimates calculated from a local weather station. The days till the next irrigation can be calculated by dividing the PAW by the PET daily rate (Table 4.2). A higher PAW compared to the PET daily rate will result in a longer period where farmers can go without adding irrigation. In the Lahaina surface soil, the PAW is nearly three times the PET daily rate and according to the calculation, farmers may go between three to four days without adding irrigation. When the PAW is lower than the PET daily rate, irrigation must be added more frequently which can be observed in the Pulehu and Ewa surface soil as well as the Lahaina and Ewa subsoil. Using the surface soil calculations, farmers will need to irrigate their fields every day for the Pulehu soil and nearly every day for the Ewa soil.

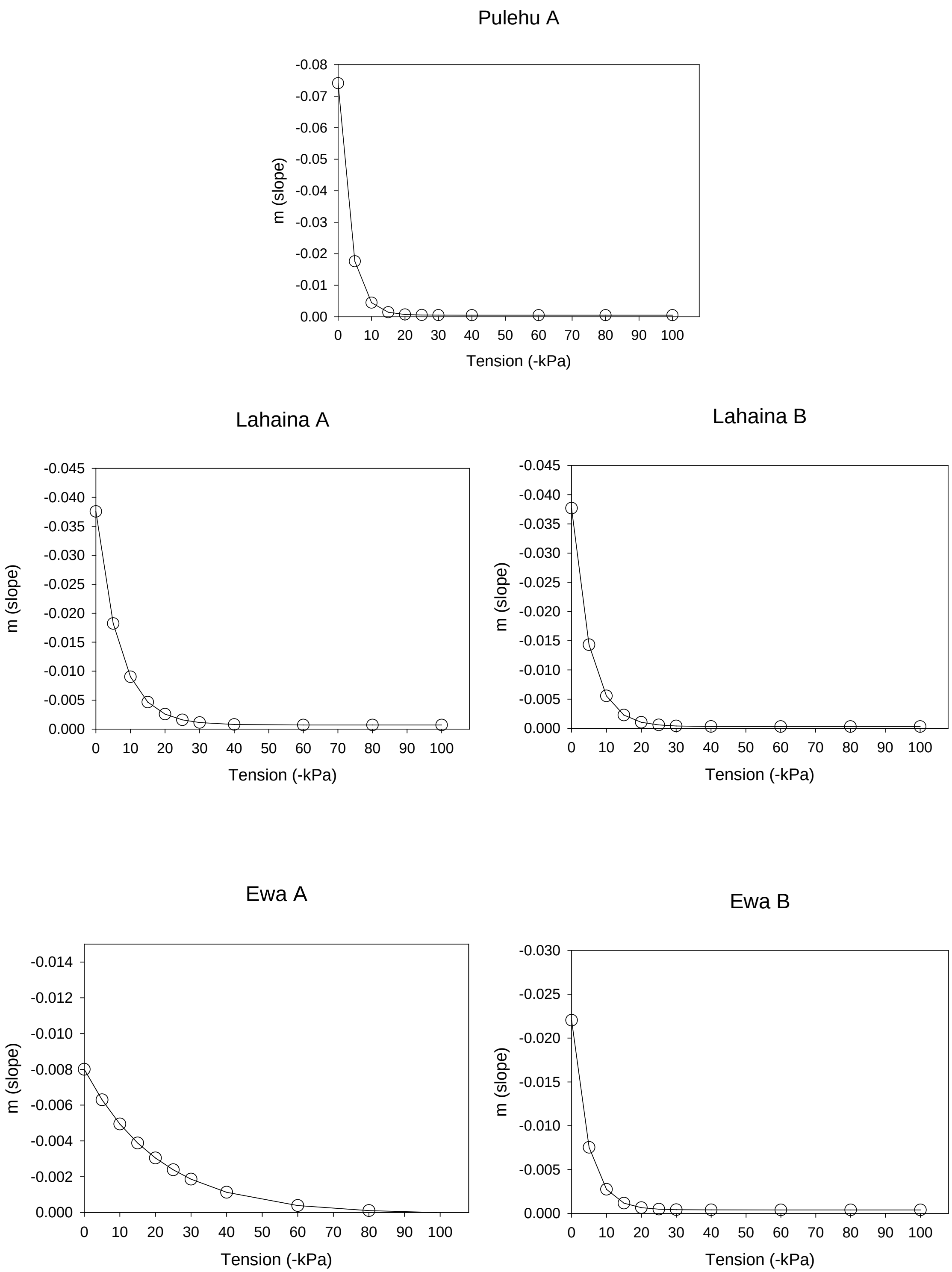

Figure 4.2 Results of each SWRC first derivative for each soil series equation where a soil moisture threshold could be determined based when the slope approaches 0 implying no PAW.

Table 4.1. The soil moisture threshold for each surface soil and sub soil based on the first derivative of the predicted SWRC equation.

Surface Soil	**Soil Moisture Threshold (kPa)**
Pulehu	-20
Lahaina	-40
Ewa	-70
Sub Soil	**Soil Moisture Threshold (-kPa)**
Lahaina	-25
Ewa	-15

Table 4.2 The change in volumetric water content from -10 kPa to the determined threshold for the surface soil and converted into PAW. The days till next irrigation application is determined using the PAW and daily PET rates.

Surface Soil	**$\Delta\theta_v$ (-10 kPa to threshold)**	**Plant Available Water (mm)**	**PET daily (mm)**	**Days Till Next Irrigation Application**
Pulehu	0.02	3.0	4.0	0.8
Lahaina	0.09	13.5	3.9	3.5
Ewa	0.03	4.5	4.1	1.1
Subsoil	**$\Delta\theta_v$ (-10 kPa to threshold)**	**Plant Available Water (mm)**	**PET daily (mm)**	**Days Till Next Irrigation Application**
Lahaina	0.03	4.5	3.9	1.6
Ewa	0.01	1.5	4.1	0.4

5.0 CONCLUSION

Based on our preliminary results, soil texture and bulk density show a relationship with water retention. Plant available water decreases in soils with a high sand content compared to soils with a high clay content. The Pulehu soil had the least amount of PAW and had a sand content of 30%. The soil with the highest PAW was the Lahaina soil that possesses pseudosand properties giving the soil a high porosity. Soil water retention is also affected by bulk density. The relatively higher bulk density in the Ewa soil with high clay content and low sand content resulted low PAW similar to the Pulehu soil. The Lahaina soil, with high clay content and pseudosand properties imparting high porosity resulted in the highest amount of PAW.

Soil water retention curves provide essential data to enable calculations associated with irrigation recommendations. A soil moisture threshold is used to determine the matric potential at which plant available water is no longer present within the soil. Soils with a high sand content, such as, the Pulehu series reached the soil moisture threshold more quickly (i.e., at a higher Ψ) than the more clay-rich soils. As the clay content increased in the Ewa and Lahaina soils, the threshold was reached at lower Ψ representing increases in PAW. Using estimated thresholds for the three surface soils, we determined that PAW varied from a high of 13.5 mm for the Lahaina soil and lows of 3.0 and 4.5 mm for the Pulehu and Ewa soils, respectively. The data show that the well aggregated Lahaina soil retained the most PAW, and had the longest interval between irrigation events.

A SWRC is a useful tool to estimate the amount of PAW which depends on several different soil properties. For a small sample collection, our data showed that soil texture (silt and clay content), bulk density, and clay mineralogy will affect soil water retention and PAW. A larger sample size will provide a more accurate representation of the effects of soil properties, including soil texture, soil organic carbon, clay mineralogy, and bulk density, on soil water retention.

The objectives of this study covered one aspect of the irrigation equation – the soil water storage component. However, irrigation scheduling requires soil water data along with site specific weather data, crop canopy growth and root depth dynamics. A team of researchers from CTAHR is working closely with researchers from the University of California, Davis to adapt CropManage for Hawai‘i agriculture. They are collecting crop specific evapotranspiration data, root depth data, and soil moisture data which are key components for CropManage to produce an accurate irrigation recommendation. CropManage will allow farmers to receive real time irrigation scheduling recommendations that will be easy to access.

APPENDIX

Appendix 1. 7 soils analyzed in the paper including the full taxonomic name.

Soil Name	**Taxonomy Name**	**Soil Order**
Pulehu	Fine-loamy, mixed, semiactive, isohyperthermic **Cumulic Haplustolls**	Mollisol
Ewa	Fine, kaolinitic, isohyperthermic **Aridic Haplustolls**	Mollisol
Waipahu	Fine, mixed, active, isohyperthermic **Torrertic Haplustolls**	Mollisol
Waialua	Very-fine, mixed, superactive, isohyperthermic **Pachic Haplustolls**	Mollisol
Kemo'o	Fine, parasesquic, isohyperthermic **Vertic Paleustolls**	Mollisol
Ka'ena	Very-fine, smectitic, isohyperthermic **Typic Natraquerts**	Vertisol
Lahaina	Very-fine, kaolinitic, isohyperthermic **Rhodic Eutrustox**	Oxisol

Appendix 2. Raw data for the soil texture analysis using the modified pipette method.

Date	Soil Series	Soil Depth	Sand (%)	Fine Silt (%)	Clay (%)	**Total (%)**	Coarse Silt (%)
12/4/2017	Waipahu	A - 1	3.329	19.67	69.59	92.589	7.411
12/4/2017	Waipahu	A - 2	3.875	20.194	70.67	94.739	5.261
12/4/2017	Waipahu	B - 1	3.815	23.478	66.342	93.635	6.365
12/4/2017	Waipahu	B - 2	4.713	23.755	66.707	95.176	4.824
12/18/2017	Pulehu	A - 1	24.583	31.373	31.363	87.319	12.681
12/18/2017	Pulehu	A - 2	25.346	31.804	29.348	86.498	13.502
12/18/2017	Pulehu	B - 1	28.546	29.944	29.934	88.424	11.576
12/18/2017	Pulehu	B - 2	30.527	29.43	28.422	88.38	11.62
12/20/2017	Waialua	A - 1	4.353	20.694	69.138	94.185	5.815
12/20/2017	Waialua	A - 2	4.74	24.206	66.051	94.997	5.003
12/20/2017	Waialua	B - 1	5.661	22.247	68.708	96.616	3.384
12/20/2017	Waialua	B - 2	5.933	23.73	67.225	96.888	3.112
12/26/2017	Kemoo	A - 1	3.556	-	-	-	-
12/26/2017	Kemoo	A - 2	4.179	22.839	64.874	91.892	8.108
12/26/2017	Kemoo	B - 1	4.23	26.632	58.997	89.859	10.141
12/26/2017	Kemoo	B - 2	4.703	25.082	60.081	89.865	10.135
1/8/2018	Kaena	A - 1	13.558	22.402	55.733	91.693	8.307
1/8/2018	Kaena	A - 2	13.635	21.878	56.247	91.759	8.241
1/8/2018	Kaena	B - 1	14.189	20.87	57.511	92.571	7.429
1/8/2018	Kaena	B - 2	14.297	23.445	55.545	93.287	6.713
1/15/2018	Lahaina	A - 1	3.706	19.443	69.501	92.65	7.35
1/15/2018	Lahaina	A - 2	4.093	17.976	69.953	92.022	7.978
1/15/2018	Lahaina	B - 1	4.13	19.522	67.566	91.218	8.782
1/15/2018	Lahaina	B - 2	3.749	20.495	66.973	91.217	8.783
1/15/2018	Ewa	A - 1	3.177	22.189	66.556	91.921	8.079
1/15/2018	Ewa	A - 2	3.028	19.682	69.634	92.344	7.656
1/15/2018	Ewa	B - 1	4.366	27.629	56.291	88.286	11.714
1/15/2018	Ewa	B - 2	4.366	28.151	57.855	90.371	9.629
2/5/2018	Kemoo	A - 1	3.31	24.73	64.905	92.944	7.056
2/5/2018	Kemoo	A - 2	3.222	21.649	65.454	90.325	9.675

Appendix 3. Raw data of the soil organic carbon analysis.

Sample ID	***Weight (mg)***	***μg C***	***% C***
Kemoo B	24.246	324	1.34
Kemoo B	31.255	419	1.34
Waipahu A	22.328	389	1.74
Waipahu A	22.251	388	1.74
Kemoo A	27.690	510	1.84
Kemoo A	16.643	309	1.86
Waialua A	23.035	457	1.98
Waialua A	20.767	401	1.93
Ewa B	28.324	434	1.53
Ewa B	24.925	378	1.52
Waipahu B	18.559	298	1.61
Waipahu B	22.808	370	1.62
Lahaina A	24.942	355	1.42
Lahaina A	25.528	361	1.41
Ewa A	15.076	273	1.81
Ewa A	19.194	357	1.86
Kaena A	17.080	336	1.96
Kaena A	18.018	353	1.96
Lahaina B	19.144	226	1.18
Lahaina B	14.288	161	1.12
Pulehu B	10.530	150	1.42
Pulehu B	16.512	241	1.46
Pulehu A	16.495	261	1.58
Pulehu A	17.365	271	1.56
Kaena B	18.530	255	1.38
Kaena B	18.508	257	1.39
Waialua B	13.941	264	1.89

Appendix 4. Raw data of the soil water retention curve analysis where two separate cores were the vacuum manifold was used for higher matric potentials (0 to -25 kPa) and the pressure manifold was used for the lower matric potentials (-30 to -100 kPa).

Tension (-kPa)	Pulehu A (θv)	Lahaina A (θv)	Lahaina B (θv)	Ewa A (θv)	Ewa B (θv)
0	0.64	0.68	0.66	0.59	0.64
5	0.44	0.53	0.54	0.53	0.57
10	0.40	0.48	0.49	0.51	0.55
15	0.39	0.45	0.48	0.50	0.54
20	0.38	0.44	0.47	0.49	0.54
25	0.37	0.43	0.46	0.48	0.53
Bulk Density (BD)	**0.97**	**1.05**	**1.07**	**1.09**	**1.23**
30	0.37	0.40	0.46	0.44	0.53
40	0.36	0.39	0.46	0.43	0.52
60	0.35	0.38	0.45	0.43	0.51
80	0.34	0.37	0.45	0.42	0.51
100	0.34	0.37	0.44	0.42	0.50
Bulk Density (BD)	**0.97**	**1.08**	**1.02**	**1.13**	**1.22**

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