FINAL REPORT

Cover Page

Title of the grant or project: Real-time Optimization of Irrigation Scheduling for Farmlands in Hawaii, Guam, and American Samoa

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Timeframe covered by the report: 02/15/2017 - 09/30/2021

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Deliverables identified on the grant agreement:

1. A "Web-based Irrigation Scheduling Tool" similar to that developed by our collaborator Dr. Michael Cahn and his colleagues.

2. "Time Series of Weather Data" (e.g., air temperature and humidity, wind speed, incoming solar radiation, and rainfall), and "Soil Properties" (e.g., soil type, soil field capacity and wilting point) at the investigated farmlands will be generated in this project.

3. "Crop Coefficients for Selected Crop Vegetables" similar to that developed by our collaborator Dr. Michael Cahn and his colleagues in California (http://ucanr.edu/blogs/blogcore/postdetail.cfm?postnum= 6934).

4. Outcomes of this project will be shared with on-going farmer education programs in Hawaii, Guam, and American Samoa.

Table of Contents

Executive Summary

Water is by far the major constraint to crop production in most regions of Hawaii and Guam and some parts of American Samoa. Despite the limited water resources as well as the high cost of water and energy in the Pacific Islands, growers irrigate their farmlands based on observation, past experience and perceived crop water requirements without considering key components of the water balance equation. The visual observation approach lacks precision and accuracy and can lead to over- or under-irrigation. Insufficient irrigation results in reduced yields whereas over-irrigation increases the susceptibility of the crop to diseases, water waste, inefficient use of nutrients, and environmental contamination due to leaching of fertilizer. Growing demands on the allocation of limited fresh-water resources and potential decreases in precipitation at the local scale make it imperative that farmers acquire the ability to match irrigation application with crop water needs (the so-called optimal irrigation scheduling) to increase water use efficiency and improve water conservation. Optimizing irrigation quantity is also the first concern for growers in the Pacific Islands due to the high cost of water, pumping energy, and increasingly variable and unpredictable precipitation patterns.

Recently, the University of California Cooperative Extension developed CropManage for the temperate and semi-arid climate of California. CropManage is an online database-driven tool that assists growers and farm managers determine water applications on a field-by-field basis. The software utilizes weather-based irrigation scheduling to guide growers. Unfortunately, this tool cannot be directly transferred to tropical islands as the soils and climate of California are very different from the soils and climate of tropical Pacific Islands like Hawaii, Guam, and American Samoa. Moreover, crop specific data developed in California cannot be used in tropical island environments, and must be measured on site.

We expanded on this proven technology and modified it for climates, soil types and crops in the Pacific Islands. Specifically, we 1) developed a user friendly weather-based irrigation scheduling tool by modifying the CropManage to suit the Pacific Islands' crops, soil type, and climate

(https://cropmanage.ucanr.edu/), 2) evaluated the developed weather-based irrigation scheduling tool to improve water use efficiency for selected high value vegetable crops, and finally 3) implemented an outreach program to increase farmers awareness and adoption of improved water management strategies.

Introduction, Background and Project Rationale

Water is by far the major constraint to crop production in most regions of Hawaii and Guam and some parts of American Samoa. Even areas with abundant rainfall experience a high seasonable variability that does not maintain adequate water for vegetable crops throughout the year. High temperature and evapotranspiration rates reduce water availability for crops.

Based upon the latest available statistics in 2015, there were 151,830 acres of active cropland in Hawai'i (Hawai'i State Department of Agriculture, 2016) of which 135,060 acres required irrigation to maintain crop productivity (https://water.usgs.gov/watuse). The majority of these farms irrigate their farmlands based on observation, past experience and perceived crop water requirements without considering key components of the water balance equation, especially soil water content and evapotranspiration (ET). The visual observation approach lacks precision and accuracy, and often leads to over-irrigation. Over-irrigation not only causes water wastage, but also results in inefficient use of nutrients, and environmental contamination due to leaching of fertilizers. Growing demands on the allocation of limited fresh water resources and potential decreases in precipitation at the local scale due to climate change make it imperative that farmers acquire the ability to match irrigation application with crop water needs (the so-called optimal irrigation scheduling) to increase water use efficiency and improve water conservation.

To overcome the abovementioned problems, this project was aimed at developing optimal irrigation scheduling strategies for farmlands in Hawaii, Guam, and American Samoa. Irrigation scheduling involves deciding how much water to apply to a field and at what time. It significantly affects the agronomy and economy of farms and is critical to water use efficiency, crop health, and environmental quality. Optimal scheduling strives to apply water in the right amount and at the right time in order to conserve water resources and energy, improve crop yields, and reduce negative environmental impacts.

Recently, the University of California Cooperative Extension developed CropManage (https://ucanr.org/cropmanage) for the temperate and semi-arid climate of California. CropManage is an online database-driven tool that assists growers and farm managers determine water applications on a field-by-field basis (Cahn et al., 2013). The software utilizes weather-based irrigation scheduling to guide grower to manage irrigation water. A rising number of commercial vegetable growers in California's Central Coast have begun to use this web-based tool to better manage scarce water resources. In fact, farmers in California can easily and inexpensively use the CropManage software via their computers and smart phones. Unfortunately, this tool cannot be directly transferred to tropical islands as the soils and climate of California are very different from the soils and climate of tropical Pacific Islands like Hawaii, Guam and American Samoa. Moreover, crop specific data developed in California cannot be used in tropical island environments, and must be measured on site. This project was designed to adapt CropManage, a viable online irrigation tool, for crops, soil types, and climates of tropical islands, and assist farmers to adopt it.

Project Objectives

With an overarching goal to improve water use efficiency in Pacific Island farmlands, the project had three specific objectives:

1. To develop a user-friendly web-based irrigation scheduling tool by modifying the online

CropManage software to suit the Pacific Islands' crops, soil types, and climate,

2. To evaluate the use of weather-based irrigation scheduling to improve water use efficiency for selected high value vegetable crops,
3. To implement an outreach program to increase farmers' awareness and adoption of improved water management strategies.

Project Methods

The central feature of the CropManage software is its capability to provide quick recommendations for irrigation water application rates appropriate to the development stage of the crop. The CropManage software uses the water budget method, which has shown to be reliable and affordable in many conditions (Jones, 2004). The water budget approach accounts for the amount of water that enters the soil column via irrigation and/or rainfall and the amount of water that leaves the soil reservoir through crop evapotranspiration (https://www.fao.org/3/x0490e/x0490e0e.htm#soil%20water%20balance). It can provide comprehensive irrigation scheduling as it takes into account the crop characteristics (root depth and crop coefficients (Kc)), the soil properties (i.e., soil type and texture, and soil water holding capacity), and the atmospheric evaporative demand (reference evapotranspiration (ET_o) calculated from climate data) (Prats and Pico, 2010).

The CropManage adaptation process focused primarily on developing Kc values and root growth dynamics for 6 crops in Hawaii (romaine lettuce, head cabbage, tatsoi, arugala, onion, and corn), 6 crops in Guam (pepper, zucchini, corn, watermelon, tomato, and eggplant), and 4 in American Samoa (chinese cabbage, pak choi, cucumber, and edible hibiscus). Kc values for each crop were developed based on the canopy model of Cahn et al. (2013), which included fraction of canopy cover and canopy growth rate. Fraction of canopy coverage and canopy growth rate were quantified using near-infrared photographs taken weekly for each crop (Fig. 1a). Software engineers incorporated the Pacific Islands specific Kc data into the CropManage software. In field final root depth and root growth rates were also quantified for each crop (Fig. 1b) and the data incorporated into the CropManage software. In addition, we developed soil water characteristic curves for five important agricultural soils in Hawaii to quantify plant available water behavior from 0 to -80 kPa (the range deemed important for the crops included in the CropManage database). We also identified key soil properties that predicted soil water at field capacity (-10 kPa).

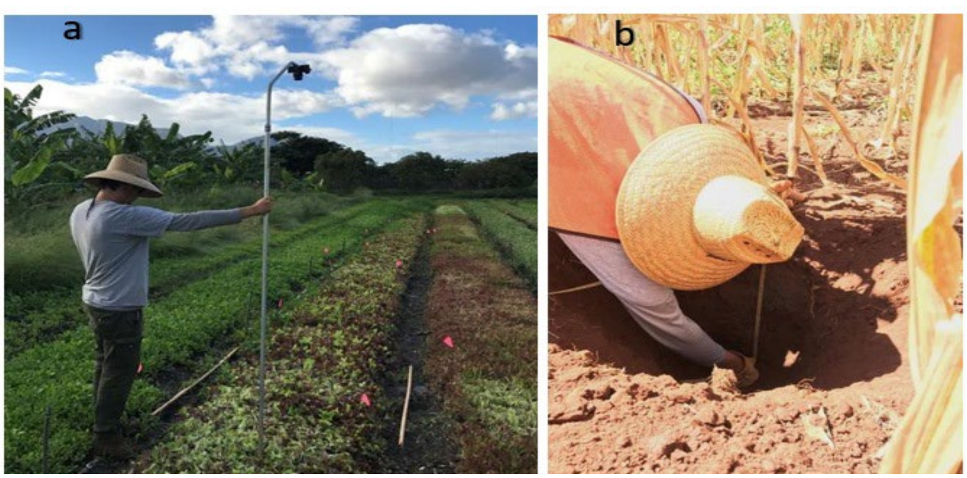

Figure 1. Field technician obtaining (a) overhead near-infrared photographs of a lettuce crop, and (b) root depth for a corn crop.

Once the *Kc* and root growth data were incorporated into the CropManage algorithms, we moved to the validation phase of the project, which consisted of a virtual phase, followed by a series of on-farm side-by-side trials. The validation phase allowed us to compare water usage in plots irrigated according to current farmer practice and adjacent plots irrigated based upon CropManage recommendations. The virtual phase consisted of shadowing a planting at MA'O and Corteva where we compared CropManage recommendations developed from an onsite HOBO weather station with the farmer practice. The on-farm side-by-side trials were conducted at two farms on Oahu (MA'O Organic Farms and Corteva, see Fig. 2a), the Experimental Agricultural Farm on Maui (Fig. 2b), and the University of Guam (UOG) Research Station (Fig. 2c). At each location, a field was selected and partitioned into two equally sized plots - one plot was designated with an irrigation schedule controlled by CropManage and the other plot was controlled by the farmer or farm irrigator and water applied according to farmer practice. Each plot had a Netafim flow meter to allow for accurate monitoring of water delivered (Figs. 3 and 4). CropManage used real time local weather data obtained from on-site HOBO weather stations and crop specific algorithms to produce daily irrigation recommendations (Figs. 3 and 4).

Figure 2. Locations of on-farm trials on (a) Oahu, (b) Maui, and (c) Guam.

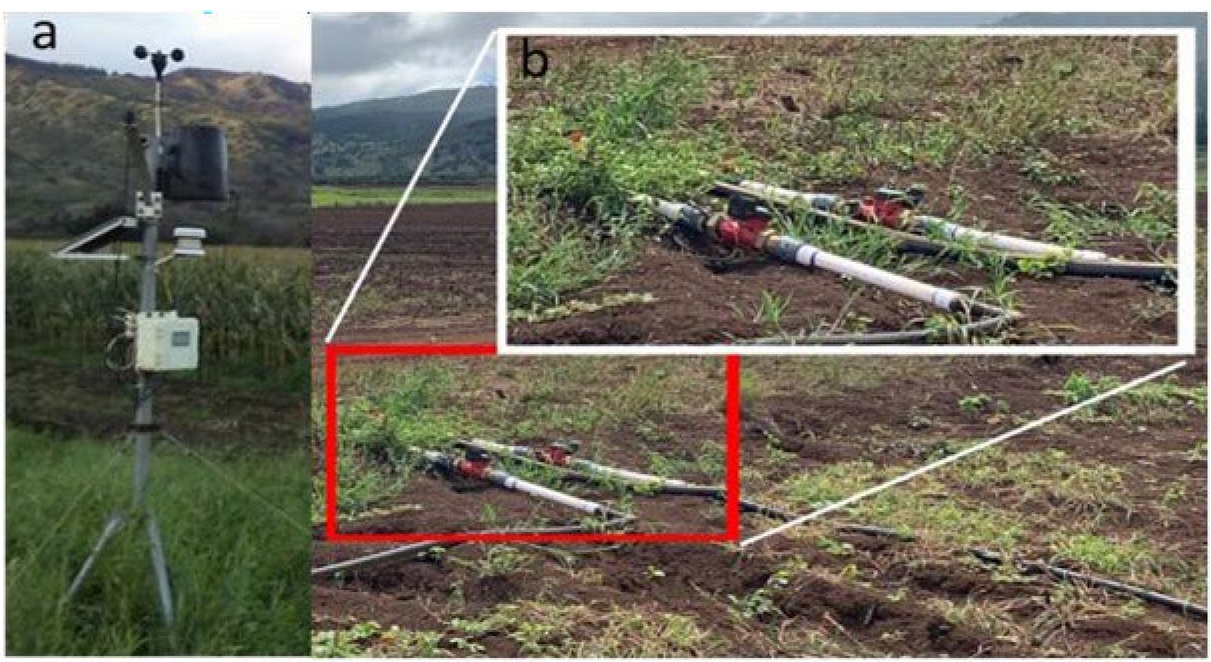

Figure 3. (a) HOBO weather station, and (b) automated Netafilm water flow meters used in the side-by-side trials.

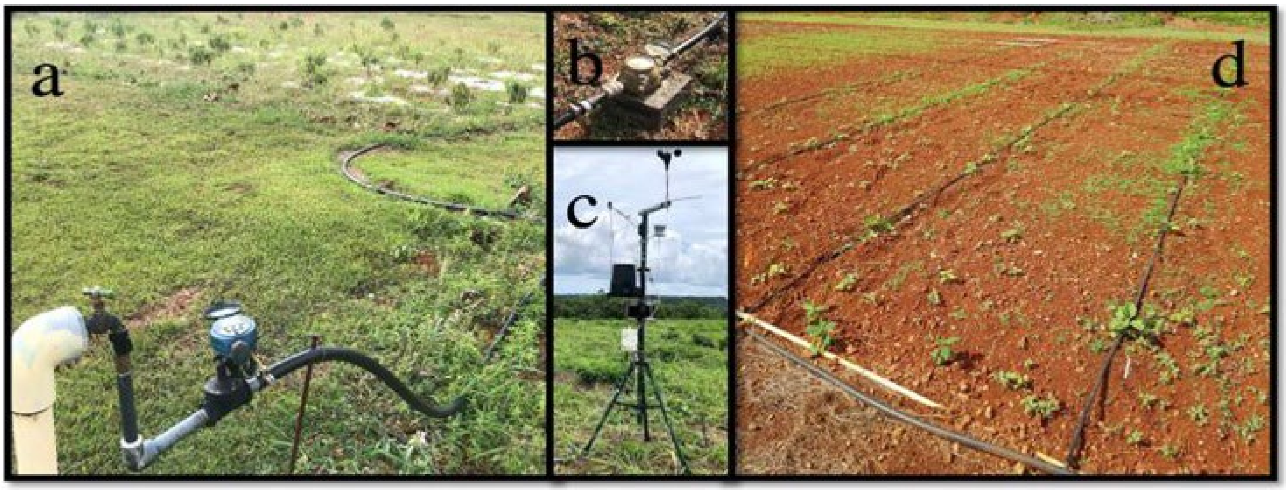

Figure 4. Side-by-side trial set up in Guam. (a) CropManage and (d) control plot, which are adjacent to (c) the HOBO weather station. (b) Each plot is connected to separate flow meters.

Two virtual trials were conducted in 2019 – one at MA'O Organic Farms with an arugula crop and the other at Corteva with a seed corn crop. In both cases, the Farmer Practice plots received substantially more irrigation water than the plots irrigated based upon CropManage recommendations (2.6X more at MA'O and 1.7X more at Corteva). The virtual trials served a key purpose as they allowed the research team to have an initial discussion with each farmer on water use, which influenced irrigation scheduling in the follow-up side-by-side trials.

Despite farm access limitations due to State-wide pandemic associated lockdowns, we were able to complete four in-field side-by-side trials in 2020-21 comparing crop production and water usage in plots irrigated according to farmer practice (control) and according to a schedule developed by CropManage. The trials and their corresponding crops occurred at the following locations: two trials at MA'O Organic Farms (baby tatsoi, Feb. 2020 & baby arugula, Aug. 2020) in Waianae (Oahu), one trial at Kula Ag Park (onion, Oct – Nov 2020) in Kula (Maui), and one trial at Corteva (seed corn, Jan – Feb 2021) in Waialua (Oahu). The side-by-side trials were setup according to the design used for the virtual trials as described above. Results for the baby arugula trial at MA'O Organic Farms are not reported as there were technical problems associated with the trial (see the Challenges section).

In Guam, side-by-side trials were conducted in two equally sized plots at the University of Guam (UOG) Yigo Research Station (Figures 4a-d). During the July-September 2020 cropping season, the control plot was compared to the CropManage plot. The control plot received irrigation based on farmers' traditional water recommendations. Each treatment plot was also connected to a flowmeter (Figure 4b) to measure the amount of water used at each plot. CropManage plot used only about 2,000 gallons compared to almost 16,000 from the control plot during this event.

Results

<u>Water Retention</u>

Water retention varied among the six soils commonly found in important agricultural areas of Hawaii. The allophanic Andisol showed distinctly different behavior from all other soils (Fig. 5A): 1) it had the highest porosity, 2) it had the highest water content between 0 and -10 kPa, and 3) it showed the largest change in water content across the range of measured tensions. The ferrihydritic Andisol and the Oxisol showed similar water retention behavior across the measured range (Fig. 5A): 1) both soils showed similar porosities and 2) similar changes in water content across the measured range.

The Mollisol and two Vertisols were more similar to each other and different from the Andisols and Oxisol (Fig. 5B) with the Mollisol and Vertisols showing lower porosities than the Andisols and Oxisol. The halloysitic Mollisol and Vertisol showed near identical water retention behavior whereas the smectitic Vertisol was distinctly different.

Available water capacity (defined here as water between saturation 0 kPa and -80 kPa) also varied among the six soils. The allophanic Andisol (A) had the highest available water capacity retaining 11.8 inches of water (Fig. 6) or the equivalent of 119,000 gallons per acre. The Oxisol and ferrihydritic Andisol (F) also retained amounts of available water with 9.8 inches (99,000 gal/acre) and 9.4 inches (95,000 gal/acre), respectively. The Mollisol showed intermediate available water capacity with 8.7 inches (87,000 gal/acre), whereas the two Vertisols showed the lowest capacity at 6.3 inches (63,000 gal/acre) for the halloysitic one and 5.1 inches (51,000 gal/acre) for the smectitic one. The Vertisols retained as much as twofold less available water as the allophanic Andisol. The water retention data has been incorporated into CropManage and is being used in the irrigation scheduling routines.

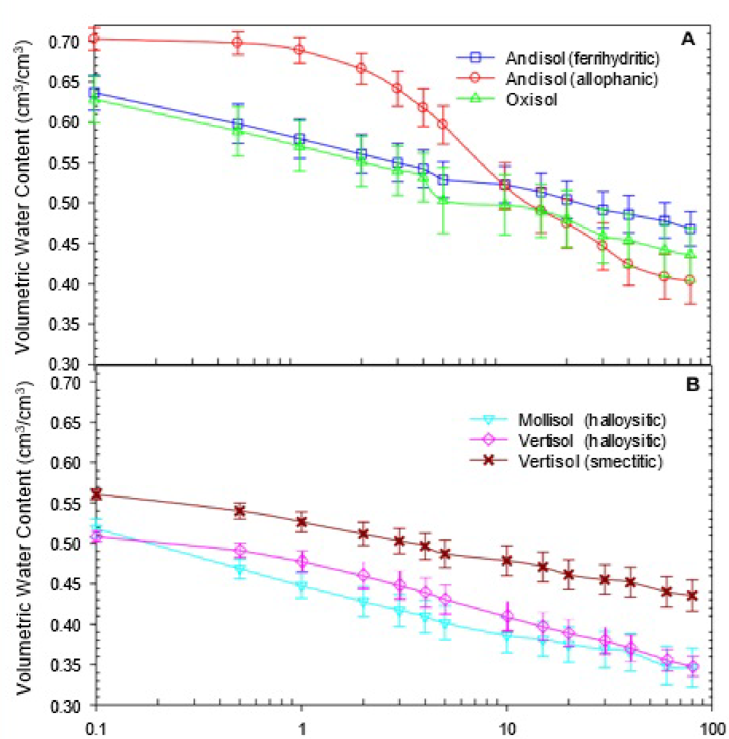

Figure 5. Soil water characteristic curves for two Andisols and an Oxisol (A) and two Vertisols and a Mollisol (B). This soils represent a diverse range in clay mineralogy.

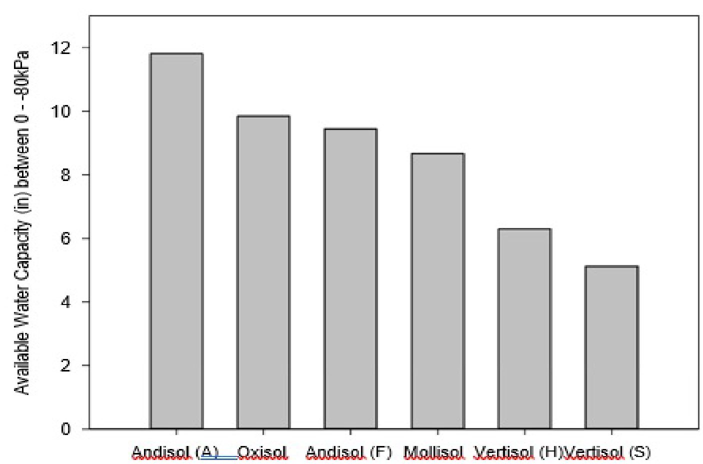

Figure 6. Available water capacity (inches) for the six agricultural soils (Andisol (A) = allophanic, Andisol (F) = ferrihydritic, Vertisol (H) = halloysitic, Vertisol (S) = smectitic.

Developing soil water characteristic curves for individual soils is time consuming, labor intensive, and expensive. Developing pedotransfer functions is one way to estimate soil water behavior without developing individual water characteristic curves. A pedotransfer function uses routine soil measurements (i.e., texture, bulk density, organic carbon, etc.) from existing soil databases to predict soil field capacity for crop productivity. Predicting soil water content at field capacity (i.e., -10 kPa) is an important component in the irrigation scheduling procedure in CropManage. Among 15 measured soil properties including texture, organic matter, pH, and iron and aluminum fractions, we identified four easily measurable properties that were well-correlated with field capacity across the range of studied soils. The properties were bulk density, total organic carbon, reactive aluminum, and amorphous or non-crystalline aluminum. We also found that gene expression programming (GEP), an artificial intelligence-based modelling technique, was superior to the traditional multi-regression approach in predicting field capacity. It was found that GEP can estimate soil field capacity relatively accurately, using two soil properties (total organic carbon and amorphous aluminum).

Side-by-Side Trials

Water usage and corresponding crop yields for the on-farm side-by-side trials are summarized in Table 1. At MA'O Organic Farm, in the first side-by-side trial, there was no significant difference in tatsoi yields between the two irrigation plots, indicating that water usage could be reduced by 6% without negatively affecting crop yield, which is equivalent to a savings of 21,252 gallons of water per acre per crop. At the Kula Ag Park, there was a large difference in water usage between the two plots with the Farmer Practice using 2.3 times more water that the CropManage plots. While, mean grade A onion yield was higher in the Farmer Practice plots, the high degree of variability in bulb weight resulted in no significant difference in yield compared to the CropManage plots. Furthermore, the proportion of grade A bulbs in the CropManage plots was higher at 82% compared to 74% in the Farmer Practice. The data suggest that water can be substantially (55%) saved if CropManage irrigation recommendations are followed without adversely affecting yields. On the seed corn crop at Corteva, water usage was only slightly lower (5%) in the CropManage plot compared to the Farmer Practice plot, but there was a large difference in the number of kernels with a larger number produced in the Farmer Practice plot.

Table 1. Water usage and corresponding crop yield data in plots comparing Farmer Practice and CropManage generated irrigation scheduling.

Site	**Total Water Usage (gallons per acre)**		**Crop Yields (pounds per acre)**	
	Farmer Practice	CropManage	Farmer Practice	CropManage
MA'O (Tatsoi)	358,160	336,908	6,040(±552)	6,244(±348)
Kula Ag Park (Onion)	646,446	282,055	58,633(±19,518) †	45,584(±11,779) †
Corteva (Seed Corn)	485,613	461,284	781,280§	616,000

† No significant difference between means (P<0.05); §units are number of kernels per acre

Figure 7 shows the difference in eggplants yields between the CropManage and control irrigation plots in Guam over the September-October 2020 harvest season. The eggplant yields from the CropManage and control irrigation plots are 458 (kg/ha) and 261.2 (kg/ha), respectively. Hence, CropManage had 196.8 (kg/ha) higher eggplant yield than control, while it causes a significant water saving of 13,551 gallon during the cropping season. The produce weight was measured 48 and 34 times respectively in the CropManage and control plots during the six weekly harvest events in September and October 2020.

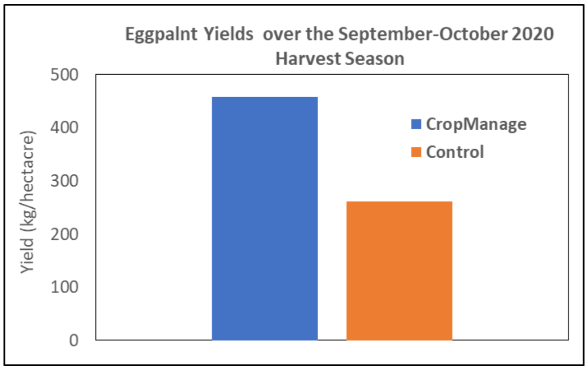

Figure 7. Eggplant yields at the University of Guam (UOG) Yigo Research Station using CropManage and Control Irrigation Systems.

The average and standard deviation of measurements in each week are shown in Figure 8. As can be seen, the average fresh weight of fresh eggplant from the CropManage plot is more than that of control plot almost in all weeks.

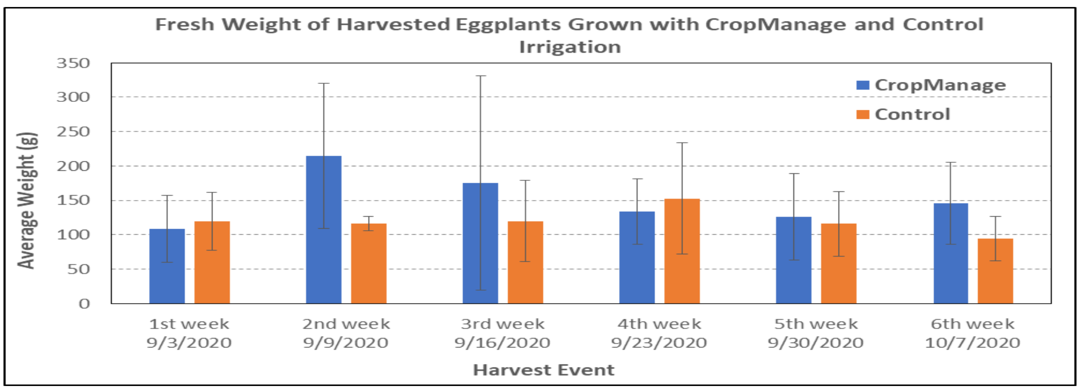

Figure 8. Average (bars) and standard deviation (lines extending from bars) of weight of harvested eggplants in each week at the UOG Yigo Research Station.

Challenges

The imposition of statewide lockdowns in March 2020 due to the COVID19 pandemic severely impeded the establishment of on-farm side-by-side trials limiting our ability to adequately field validate the CropManage technology. Once the regulations allowed for on-farm access, there were additional challenges including heavy pest pressure and unreliable irrigation infrastructure, which further impeded on-farm trial progress. At Corteva, two side-by-side trials were derailed by severe infestations of the maize mosaic virus, which destroyed both crops. At MA'O, subpar irrigation infrastructure, resulting in highly variable and unpredictable water delivery to trial plots, caused a number of trials to abort. From the technological perspective, the CropManage scheduling software uses the average of long-term historic ET_o data to make forecasts into the future. However, average ET_o computed based on historic averages seldom matches ET_o into the future, which results in erroneous ET_o predictions and subsequent errors in irrigation recommendations. The research team is currently augmenting the CropManage ET_o predictions by incorporating artificial neural network approaches to improve ET_o forecasting. Lastly, the lack of a functioning network of real-time weather stations in the State of Hawaii poses an obstacle to widespread adoption of irrigation scheduling technology that relies on the acquisition of real-time weather data to calculate ET_o.

Impacts

Prior to this project, there were no weather-based real-time irrigation scheduling tools for farmers in Hawaii and Guam, using site-specific crop coefficients and soil data. During the first phase of the project, we developed a database of crop coefficients for 6 commercially important vegetables in Hawaii (romaine lettuce, head cabbage, tatsoi, arugala, onion, and corn), 6 crops in Guam (pepper, zucchini, corn, watermelon, tomato, and eggplant) and 4 crops in American Samoa (chinese cabbage, pak choi, cucumber, and edible hibiscus). We developed soil water characteristic curves for the six most important soil types in Hawaii. Additionally, we established a network of automated weather stations capable of calculating ET on Oahu, Maui, Big Island, Guam, and American Samoa. The crop coefficient and water retention data were incorporated into the CropManage software and linked to the weather station network via the internet, which now makes the web-based CropManage irrigation tool functional in Hawaii, Guam, and American Samoa.

Through our on-farm interactions and trials, we have transferred science-based knowledge to our growers that motivated them to re-think their irrigation strategies. For example, when we first implemented the virtual trials at MA'O Farms, they were applying high amounts of irrigation water to their fields. When the research team shared the results of the first virtual trial with MA'O where we showed that CropManage recommended 2.6 times less water than they were applying, the farm manager immediately reduced irrigation to the fields. The results were apparent when we implemented the in-field side-by-side trials and the farmer practice irrigation aligned closely with the CropManage recommendations.

While the CropManage system is fully operational and adapted to Hawaii, Guam, and American Samoa cropping systems, it will take more outreach efforts and the implementation of a more robust network of weather stations to increase farmer use of the system.

Conclusions and recommendations

The University of California Cooperative Extension developed CropManage for the climate of California. We expanded on this proven technology and modified it for climates, soil types and crops in the Pacific Islands. The CropManage is tested at the MA'O Farm, Kula Ag Park Station, and Corteva Farm in Hawaii, and University of Guam (UOG) Research Station in Guam. The results show that CropManage could reduce irrigation water in all the farms and research stations. By using CropManage instead of farmers practice, irrigation water was reduced from 358160 (gal/acre) to 336908 (gal/acre) at the MA'O Farm, 646446 (gal/acre) to 282055 (gal/acre) at the Kula Ag Park Station, and 485613 (gal/acre) to 461284 (gal/acre) at the Corteva Farm. Similarly, there was a significant irrigation water saving of 13,551 (gal) at the UOG Research Station in Guam.

Reference evaporation (ET_o) and rainfall (R) forecasts have a key role in real-time decision on water resources management by quantifying the prospective changes in agricultural and hydrological processes. In fact, the accurate forecast of ET_o and R has a vital importance in the optimal irrigation scheduling and efficient management of water resources. CropManage provides daily irrigation recommendations for the following 7 days by utilizing the long-term ET_o and R averages respectively as the ET_o and R forecasts during these days. This often can lead to erroneous irrigation scheduling because ET_o and R in the next 7 days can be very different from their corresponding long-term average. It is evident that feeling the online irrigation tools with accurate ET_o and R forecasts is of vital importance. Currently, our research team is trying to incorporate accurate ET_o and R forecasts into the CropManage online tool to improve its performance.

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