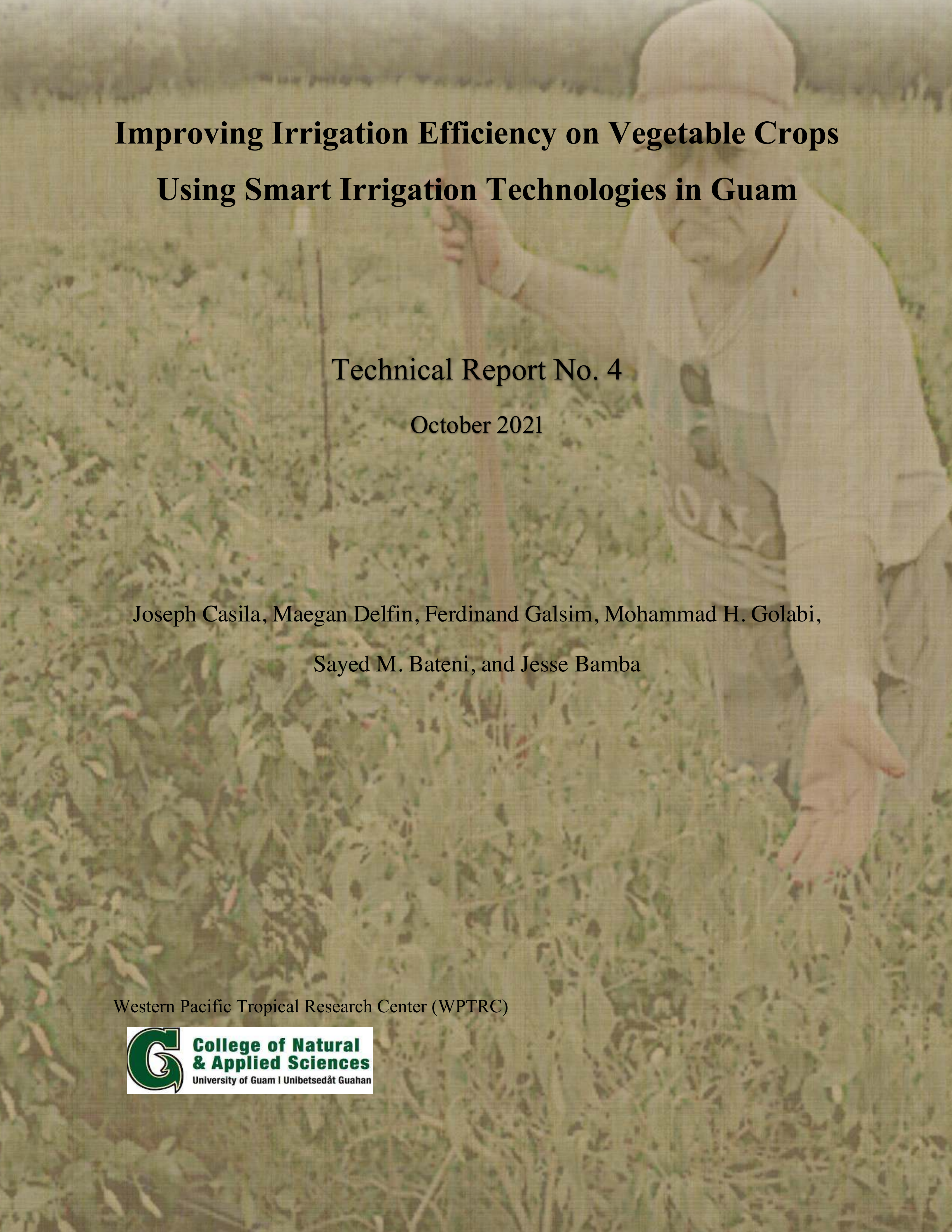

Improving Irrigation Efficiency on Vegetable Crops Using Smart Irrigation Technologies in Guam

Technical Report No. 4

October 2021

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University of Guam

August 2021

Acknowledgement

We want to extend our appreciation to the following staffs at the University of Guam's (UOG) College of Natural and Applied Sciences (CNAS) and Western Pacific Tropical Research Center (WPTRC):

Karl "Von" Nelson, agriculture research technician and Clancy Iyekar, chemist II (Soil Lab)

Grant sources

This research project was supported by the USDA-NRCS in cooperation with the University of Hawaii and the University of Guam under the Grant # 61-2F-243429-R

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Abstract

An irrigation system optimized in tandem with technological components can provide maximum water savings with minimal impact on soil health and water quality. Preliminary crop data collected during the year 2020 showed over 13,500 gallons of water saved when CropManage was used compared to a minimally managed irrigation system. In addition, there was noticeable increase in crop yield for CropManage study plots. However, damages to crops by insects, diseases, and weather conditions were encountered. Therefore, more data collection is necessary to confer the efficacy of a weather-based irrigation scheduling tool in Guam farmlands.

***Keywords*:** vegetable yield, plant canopy cover, CropManage, irrigation

Introduction

Water poses constraint in agricultural productivity and food security particularly in many Pacific regions including Hawaii and Guam and some parts of American Samoa. It is estimated that 20% of total irrigated agriculture contribute to the 40% of the total food produced worldwide (The World Bank, 2020). As the U.S. population doubled over the past 50 years, the demand for clean water consequently tripled (U.S. EPA 2021). On Guam, tourism industry receives approximately 1.2 million tourists annually (GEDA 2020). In addition, approximately 5,000 U.S. Marines and 1,500 family members are expected to be relocated from Okinawa to Guam as early as 2025. As a result of military buildup and urbanization, the Guam Waterworks Authority (GWA) has increased water-quality monitoring of the Northern Guam Lens Aquifer (NGLA), which supplies 80 percent of the island's drinking water. A dramatic growth in population and industry can result in increase in freshwater demand, which can ultimately cause negative impact to both crop production and water quality.

Guam Climate

Guam has two distinct seasons due to its geography: wet and dry. Despite the abundant annual rainfall, Guam's unpredictable precipitation presents inefficiency for crop irrigation resulting in overwater or underwatering of crops. In this study, we collaborated with local bona fide farmers (Figures 3a-c) to monitor their water footprint using CropManage, an online decision support tool for irrigation efficiency.

Figure 1a. Executive Director of Watson Farm, Mr. Bernard Watson (center) from the village of Yigo and UOG' Soil Scientist Dr. Mohammad (right) with Research Associate Ferdinand Galsim)

Figure 1b. Executive Director Mike Aguon of MEDA Farm (second from the left) in the southern village of Malojloj with soil scientist, Dr. Mohammad Golabi left. Clancy Iyekar & Karl Nelson (third & fourth from left)

Figure 1c. Farmer and owner of Island View Farm, Mr. Ernest Wusstig (May 28, 2020)

According to Lander and Guard (2003), rainfall in Guam is highly seasonal with 30% of annual total rainfall during the dry season (January through June) and 70% in the wet season (July through December). During the months of November, temperatures (<27ºC or 80ºF) and rainfall (<88 mm or 3.5 in) begin to drop and subsequently dry seasons begin (Figure 3a). Dry season is also dominated by dry northeasterly tradewinds (Lander 1994). As the temperatures rise during the months of March (dry season) (Figure 2) combined with strong presence of dry tradewinds and low rainfall, the evapotranspiration is impacted resulting in higher water cost for farmers (Table 1). Evapotranspiration (Figure 2) is the water lost to the atmosphere by evaporation (soil, lakes, rivers, etc.) and transpiration (water loss living-plant surface) (Hanson, R.L., 1991). Although bona fide farms use approximately 1.5% compared to 57% of water from residential (Hollyer J. et al. 2016), the increasing population and urbanization growth on Guam will likely affect the water use.

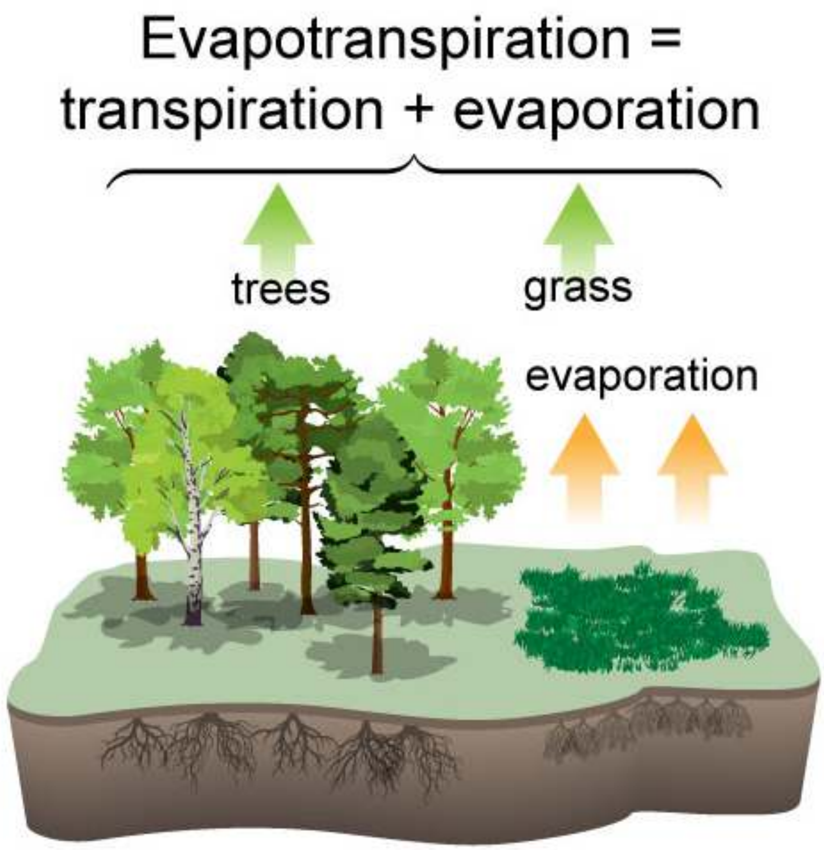


Figure 2. Soil-plant water cycle. Credit: ONSET Company

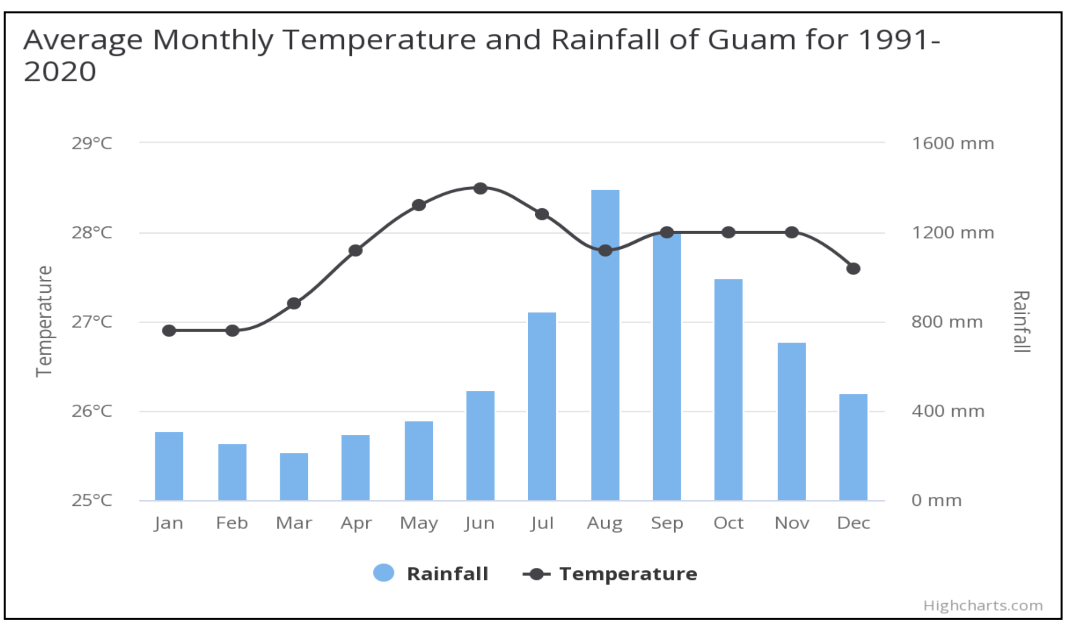


Figure 3a. Average monthly temperature and rainfall of Guam for 1991-2020 (The World Bank Group)

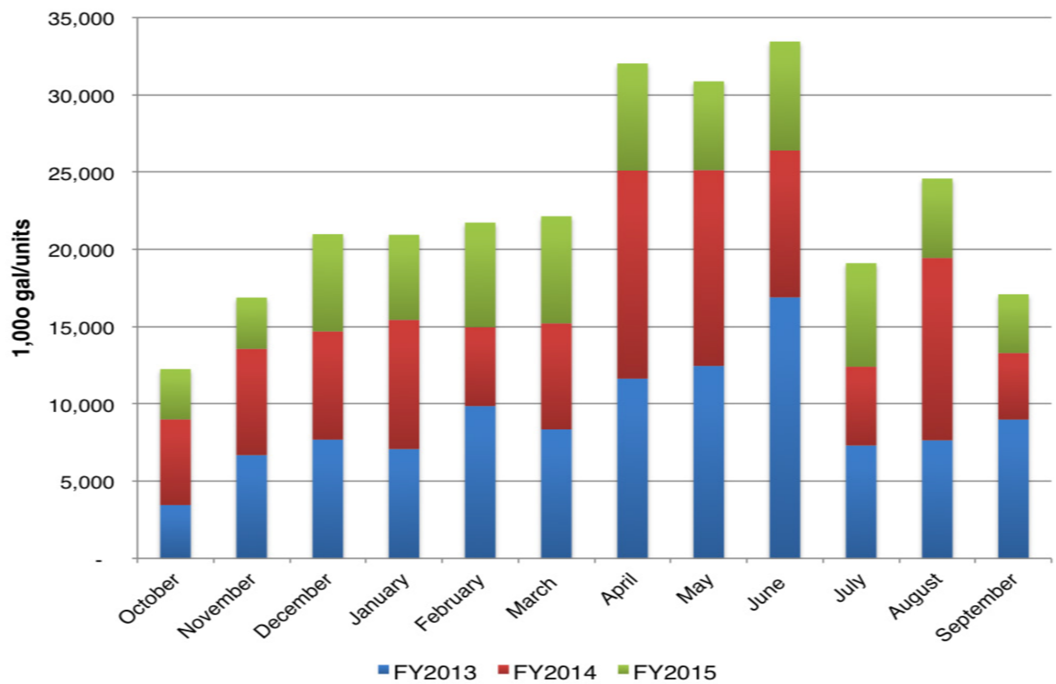


Figure 3b. Agricultural water-use in Guam Fiscal Year 2013-2015 (Hollyer J. et al. 2016). Data provided by GWA January 2016

Table 1. Agricultural water-use and cost on Guam for fiscal year 2013-2015 (Hollyer J. et al. 2016)

Year	1,000-gal units	Cost
FY2013	108,036	$363,419
FY2014	96,625	$392,105
FY2015	67,443	$330,222

Source: Data provide GWA (January 2016)

Scheduled irrigation for vegetable production

Due to limited resources in the Pacific Islands, most farmers and growers irrigate their vegetable crops based on visual observations or perceived crop water requirement. In addition, majority of farmlands in Guam are small with vegetable as common crops, which have short crop cycles. Because farm managers tend to simplify predetermined water schedule and the amount of water applied to avoid crop stress and maximize yield, water-use usually exceeds crop evapotranspiration (ET) (Cahn, Michael & Johnson, Lee. (2017). Without considering key components of the water balance equation often led to over- or under -irrigation of crops. As a result, this unnecessary stress results in reduction in yield, loss of nutrients, and sometimes environmental contamination from fertilizer leaching. Furthermore, farmers' cost of water and pumping energy also increase due to over-watering (Pardossi and Incrocci, 2011). The general water balance equation:

$$P = R + ET + \Delta S$$

Where P = Precipitation
R= Runoff
E= Evapotranspiration
ΔS= change in storage (in soil or the bedrock/groundwater)

The Model

To overcome abovementioned concerns, a web-based scheduling tool called CropManage was introduced in Guam to provide farmers and growers with accurate estimate irrigation water need to vegetable crops. Developed at the University of California's Cooperative Extension, "CropManage provides real-time recommendations for the most efficient, affective, and sustainable irrigation and fertilization application possible—all while maintaining or improving overall yield (CropManage, n.d)." This online tool uses combinations of plant growth stages, soil physical and chemical properties, and weather data to generate irrigation amounts that are optimized to meet a specific crop's daily water requirement at a given farm. By optimizing irrigation water, local farmers and growers can reduce their water costs while maintaining and improving crop yield. Irrigation Water Advisor for University of California, cooperative extension reported that CropManage is capable to consistently reduce 20% to 40% in water and fertilizer use, or in many cases, improved crop yield (CropManage, n.d. and national nut grower, 2021).

CropManage Components

1) Rigorously studied crops that are in demand in California.
2) Major soil types documented from the National Resource Conservation Service Soil Survey Geographic Database.
3) Weather stations that are part of the California Irrigation Management and Information System operated by the California Department of Water Resources.

CropManage Algorithm

Equation used by CropManage to generate recommended irrigation amount:

$$\text{Recommended Irrigation Amount} = \frac{\text{Total Crop Evapotranspiration}}{\text{(1- Leaching Requirement)}} - \text{Total Precipitation}$$

Total crop evapotranspiration (ET_C) is the amount of water transpired by a crop at a specific growth stage and the amount of water that evaporates from the soil. Leaching requirement is the percentage of water that must pass through the root zone to control soil salinity at a specific level. Total precipitation is the amount of rainfall that has been applied throughout the previous day. Calculation of the total crop evapotranspiration is the most labor intensive when finding the recommended irrigation amount but is completely handled within CropManage. The general equation used by CropManage in computing the total crop evapotranspiration is shown below:

Total Crop Evapotranspiration = Crop Coefficient x Crop Reference Evapotranspiration

The crop coefficient (K_C) is the factor that accounts for crop's specific characteristics such as the length of growth stages. This factor is crucial when determining the recommend irrigation amount on a given day because the amount of water required by a crop varies depending on its growth stage. One stage might need plenty of water while another stage might not need as much and can be time when irrigation can be conserved. The crop reference evapotranspiration (ET_O)

is the factor that accounts for water loss by the atmospheric parameters such as radiation, temperature, wind speed, and humidity. As atmospheric parameters vary every day, the amount of water loss also changes and needs to be factored in when calculating recommend irrigation amount for each day. More information about the crop coefficient (K_C) and crop reference evapotranspiration (ET_O) can be found at Food and Agriculture Organization of the United Nations Irrigation and drainage paper 56: Crop Evapotranspiration - Guidelines for Computing Crop Water Requirements (Allen, R. G., et al., 1998).

Extension of CropManage outside of California (i.e., Guam)

At the time of CropManage's first developmental phases, the list of crops, soil type, and weather data used to generate irrigation amounts were specific only to California regions. Important information such as crop coefficient (K_C) and crop reference evapotranspiration (ET_O) were already available. Soil types in certain areas were profiled through various soil analyses. Crop coefficients for certain crops in California were calculated by means such as measuring canopy cover throughout planting seasons and determining the length of each growth stage of each crop. Daily crop reference evapotranspiration was calculated for solar radiation, temperature, wind speed, and humidity data retrieved from weather stations within the California Irrigation Management and Information System. These crop and area-specific information were necessary components for CropManage to generate personalized irrigation amounts outside of California. The Smart Irrigation project sought to gather crop, soil, and weather data specific to Guam to enable local farmers to use CropManage's irrigation scheduling tool. The project was divided into two main parts: the first was to gather data and incorporate them into CropManage and the second was implement CropManage irrigation recommendations in local farms to see if it will improve irrigation efficiency while maintaining or increasing crop yield.

Objective of the Project

1. To improve water application efficiency by developing a user-friendly web-based smart irrigation scheduling system exclusive to Guam farmlands.
2. Evaluation for the benefits of weather-based irrigation scheduling for high value vegetable crops.

3. Implement an outreach program to increase farmers and growers' awareness of irrigation management strategies.

The goal of this project is therefore to develop an online database-driven tool that assists growers and farm managers in Guam to schedule irrigation water on a field-by-field basis. Hawaii and American Samoa are concurrently conducting similar studies as they share common water constraint in crop production.

Phase I: Data Collection Methodology

The gathering of type of crop, soil, and weather data for Guam was collectively known as Phase I. Collaborations were formed with local farms and the University of Guam's soil lab to monitor crops being grown. A list of cash crops was determined. Soil samples were analyzed, and profiles were created within CropManage. Weather stations were installed at the same sites where crops were being monitored to record weather data. The data gathered in Phase I helped produce important information such as crop coefficient (K_C) and crop reference evapotranspiration (ET_O) for CropManage to be used for crops and areas specific to Guam.

Farm Monitoring Sites

The Smart Irrigation project encompasses four monitoring sites: University of Guam's Yigo Triton Research & Education Station (UOG Yigo Station) (Figure 4c-d), the Watson Farm (Figure 4b), and the MEDA (Figure 4a) farm, and the Island View Farm (Figure 6). Valuable information on irrigation schedules of the three bona-fide farmers as well as crops that are commonly grown at their farms were collected through the collaboration. In addition, field data such as weather, soil, and crop growth were obtained. The UOG Yigo Station is a research farm managed by the University of Guam research division (WPTRC) while the other monitoring sites are owned by bona-fide farmers. Figures 4a-f show various crops planted at different times within the four monitoring sites.

Figure 4a. The hot pepper and eggplant fields in southern Guam (MEDA Farm in Malojloj)

Figure 4b. The hot pepper field in northern Guam (Watson Farm inYigo)


Figure 4c. Watermelon field taken near harvest at 12.5 weeks (UOG Station, Yigo)

Figure 4D. Big Red tomato field taken at 11 weeks (UOG Station, Yigo)

Figure 4e. Eggplant field taken at 9 weeks (UOG Station, Yigo)

Figure 4f. Side view of the cornfield and its location in Google Maps (Island View Farm, Yigo)

Various crops health concern

At the beginning of the project and before data were collected, we observed that approximately 10% of the hot pepper plants in the Malojloj (MEDA Farm) have died and another 10% were dying due to possible wilting (Figure 5). During a root depth determination, large limestone rocks were found below the plant roots. Since the soil (Pulantat series) is a slowly permeable over a shallow limestone, roots are vulnerable to oxygen deprivation (over-watering) or lack of water in the root zone due to high amount of limestone rocks, which divert the water away from the roots. Presence of ant colonies, aphids, and scales on dead plants were also present.

Figure 5: Plant on the right is experiencing wilting due to possible water deprivation from the limestone rocks in the root zone

Island View Farm

The Island View Farm is a 40-acre land located in the village of Dededo (Figure 3A, 13°54’55” N, 144°86’69” E). Sweet corn, being an annual crop, is the main commodity of this farm and planted throughout the year.

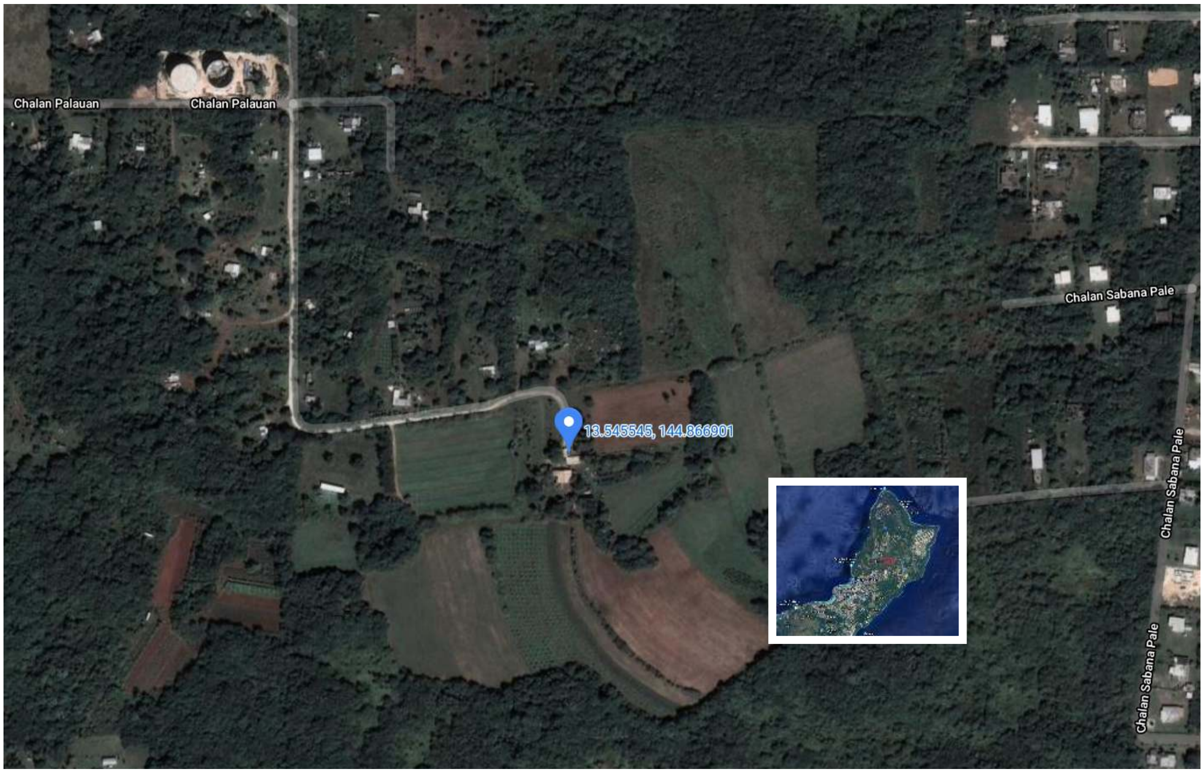


Figure 6. Google Map screenshot of Island View Farm, and its location in Northern Guam. Accessed October 26, 2020

Materials & Methods

Crops

The crops listed below were selected based on demand in Guam and monitoring feasibility. Fraction of canopy cover and root length were measured for the following crops:

Little Thumb Eggplant	Cherry Tomato
Pingtung Long Eggplant	Big Red Tomato
Nadia Eggplant	Chili Pepper
Heirloom Dark Green Zucchini	Empire 2 Watermelon
Elite Hybrid Zucchini	Bok Choy
*Hawaiian Super Sweet Hybrid corn #10	

*Data collected incomplete

Soil types

The soil at Watson Farm in the village of Yigo (northern Guam) is 'Guam Series', which is well-drained with moderately rapid permeability from Entisols order (Young, 1986). It mainly composed of 'Guam Cobbly Clay Loam' soils (Figure 7) that is used extensively for agricultural practices (Dementrio et al., 1986).

Figure 7. Guam cobbly clay loam in Watson Farm in the village of Yigo of northern Guam

As shown in Figure 8, the soil in southern farmland in the village of Malojloj is a 'Pulantat clay Series', which are generally found on upland plateaus and hills (USDA, 2007). It is a very fertile soil with a slightly acidic surface and alkaline subsoil (University of Guam College of Natural and Applied Sciences n.d).

Some of the characteristics of these soils are described below:

0-1 inch of the soil surface: includes undecomposed leaves, twigs and tangantangan seed pods.

1-3 inches of the soil profile: contains black and dark brown clay.

3-7 inches of the soil profile: formed from grayish and dark brown clay in a very fine pattern.

Figure 8. Pulantat clay series soil in MEDA Farm located in the village of Malojloj (southern Guam).

Root Depths

Root measurements were conducted once for every wet and dry seasons. Pickaxe, shovels, and knives were used around the plant roots and a ruler to measure plants root (figures 9 a-b).

Figure 9a: Root vertical measurement (MEDA Farm) of two different hot pepper varieties.

Figure 9b: Root measurement of an eight-week-old pepper plant (Watson Farm)

Canopy cover

In order to calculate the crop coefficient (Kc), crop canopy cover measurements were taken throughout a crop's growing season. A Sony A6000 camera with a SEL1855 lens was used to take multi-spectral near-infrared (NIR) digital photos from above the plant canopy. A special holding device for the camera was also used along with a cellular phone to remotely control the camera (Figure 10 a-b). The NIR photos are then cropped and edited via Microsoft Word (using the image tool to remove excess background) and analyzed with Tetracam PixelWrench 2 software as shown in Figure 11. The digital photos processed by PixelWrench 2 software provide the percent coverage of the plant canopy. As shown on Figure 11C, green and orange areas represent soil and canopy, respectively. Canopy cover is an important indicator of growing and stage patterns of the plant, which is used for irrigation scheduling (Trout et al., 2008).

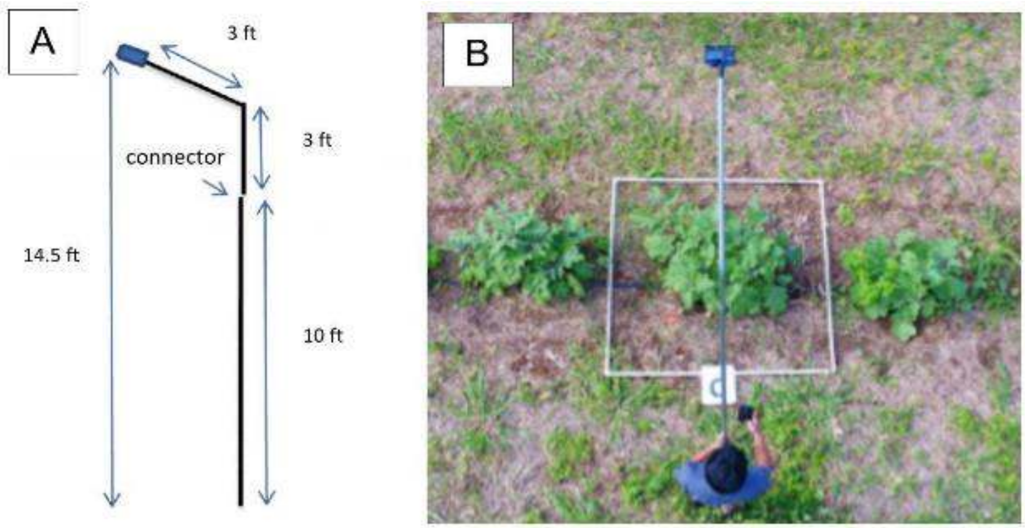


Figure 10. A) Schematic of the special holding device used for the multi-spectral near infrared camera. B) Digital camera operated remotely using a cellular phone to capture canopy photos

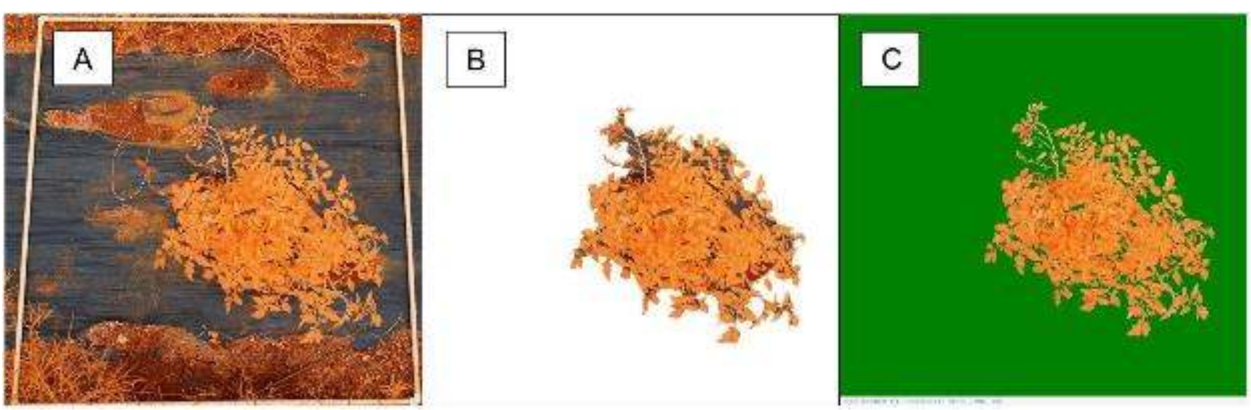


Figure 11. Near-infrared photo of tomato canopy cover that undergone the A) cropping, B) editing, and C) PixelWrench analysis process of a Big Red Tomato plant

Canopy Cover and Root Length Analysis

Fraction of the growing period is obtained by dividing the number of days that the crop has been growing in the field at time of measurement by the total number of days in which the crop reaches its full maturity. For example, for a crop with 100-day growing season, a measurement taken on day 25 implies 0.25 of the growing period. Each point for canopy coverage and root depth represents a mean of three to four measurements for canopy coverage and three measurements of root depth. The fraction of canopy cover measurements from different fields will be used in CropManage to estimate crop coefficients during the crop cycle. The root depth will be used to estimate soil water storage during cropping cycle.

Weather Stations

The Onset HOBO RX3000 Remote Monitoring Station Data Loggers (Figures 12-14) were installed at each monitoring site to record meteorologic data. Each weather station has smart sensors capable of measuring temperature, wind speed, gust speed, relative humidity, dew point, solar radiation, and rainfall every hour, which are necessary for generating CropManage irrigation recommendations.

Figure 12. Weather station from Watson Farm was reinstalled at UOG Yigo Station on June 28, 2019.

Figure 13. The RX3003 weather station on a pepper field at the MEDA Farm in Malojloj

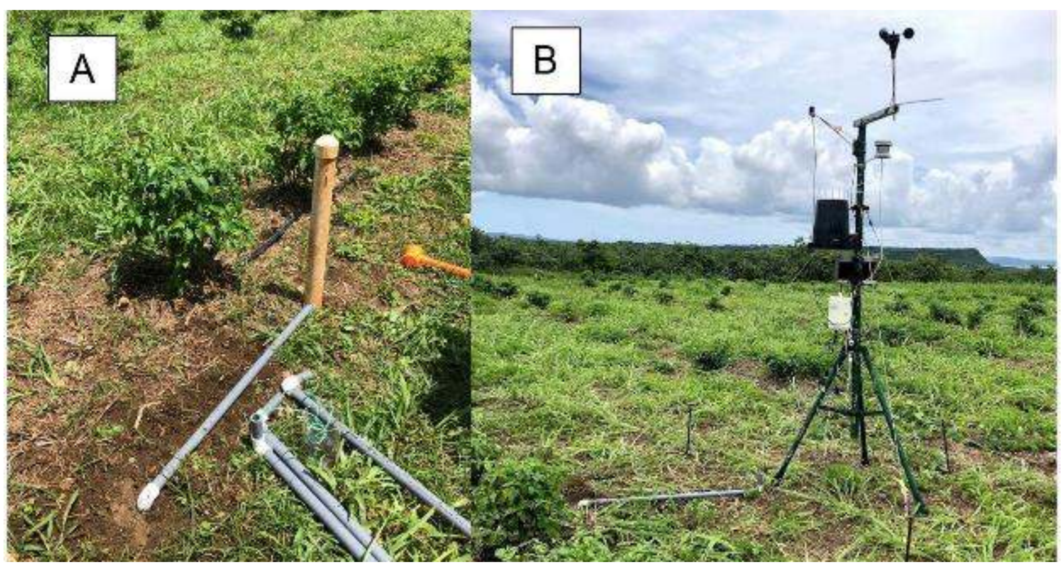


Figure 14. Watermarks installed on a pepper field at the MEDA Farm in Malojloj with three of the sensors A) installed alongside irrigation drip lines, and one sensor B) installed and connected to the RX3003 weather station

Phase I: Crop Monitoring Trials

Table 2a-d. Summary of the entirety of crops monitored throughout Phase I

Table 2a. MEDA Farm Trials

Location	Soil type	Crop Variety	Number of Cycles	Start Date	End Date	Total Days
MEDA Farm (Malojloj)	Pulantat clay series	Eggplant (Nadia)	1	11/13/17	2/8/18	87
		Eggplant (Little Thumb)	1	4/27/18	7/24/18	88
		Watermelon (Empire 2)	1	5/16/18	7/31/18	55
		Pepper	2	7/2/17	1/2/18	185*
				5/25/18	2/19/18	95

* Pepper plants were approximately over a year old during the initial sampling

Table 2b. Watson Farm Trials

Location	Soil type	Crop Variety	Number of Cycles	Start Date	End Date	Total Days
Watson Farm (Yigo)	Guam series	Pepper (unknown)	1	7/2/17	12/27/17	179
		Cherry tomato	1	7/27/18	1/3/19	160

Table 2c. UOG Station Trials

Location	Soil type	Crop Variety	Number of Cycles	Start Date	End Date	Total Days
UOG Station (Yigo)	Guam series	Squash (hairloom dark green hybrid)	1	5/15/18	6/29/18	45
		Cherry tomato	2	6/22/18	9/7/18	77
				6/22/18	9/7/18	77
		Corn (Hawaiian supersweet hybrid	1	7/16/18	8/27/18	42
		Bok choy	1	8/10/18	9/7/18	23
		Squash (Elite hybrid zucchini	2	2/19/19	3/22/19	35
				5/29/19	8/9/19	72
		Watermelon (Empire 2)	2	2/15/19	3/22/19	35
				6/3/19	8/30/19	88
		Eggplant (Pingtung long)	2	2/24/19	7/3/19	129
				7/15/19	10/27/19	104
		Tomato (Big Red)	1	6/27/19	11/27/19	153

Table 2d. Island View Farm Trials

Location	Soil type	Crop Variety	Number of Cycles	Start Date	End Date	Total Days
Island View Farm (Yigo	unknown	Corn (Hawaiian supersweet #9)	1	6/1/20	7/28/20	58

UOG Yigo Station Eggplant, Zucchini, and Watermelon Monitoring Trials

After collaborating with local farmers for canopy and root depth data collection in the MEDA farm (July 2017 to February 2019) and Watson Farm (July 2017 to August 2019), monitoring was focused at the UOG Yigo Station to grow a variety of crops that were not previously measured. Canopy and root depth data collection activities were continued within the UOG Yigo Station until September 2019. The initial field design, as shown in Figure 15 was prepared in February 2019.

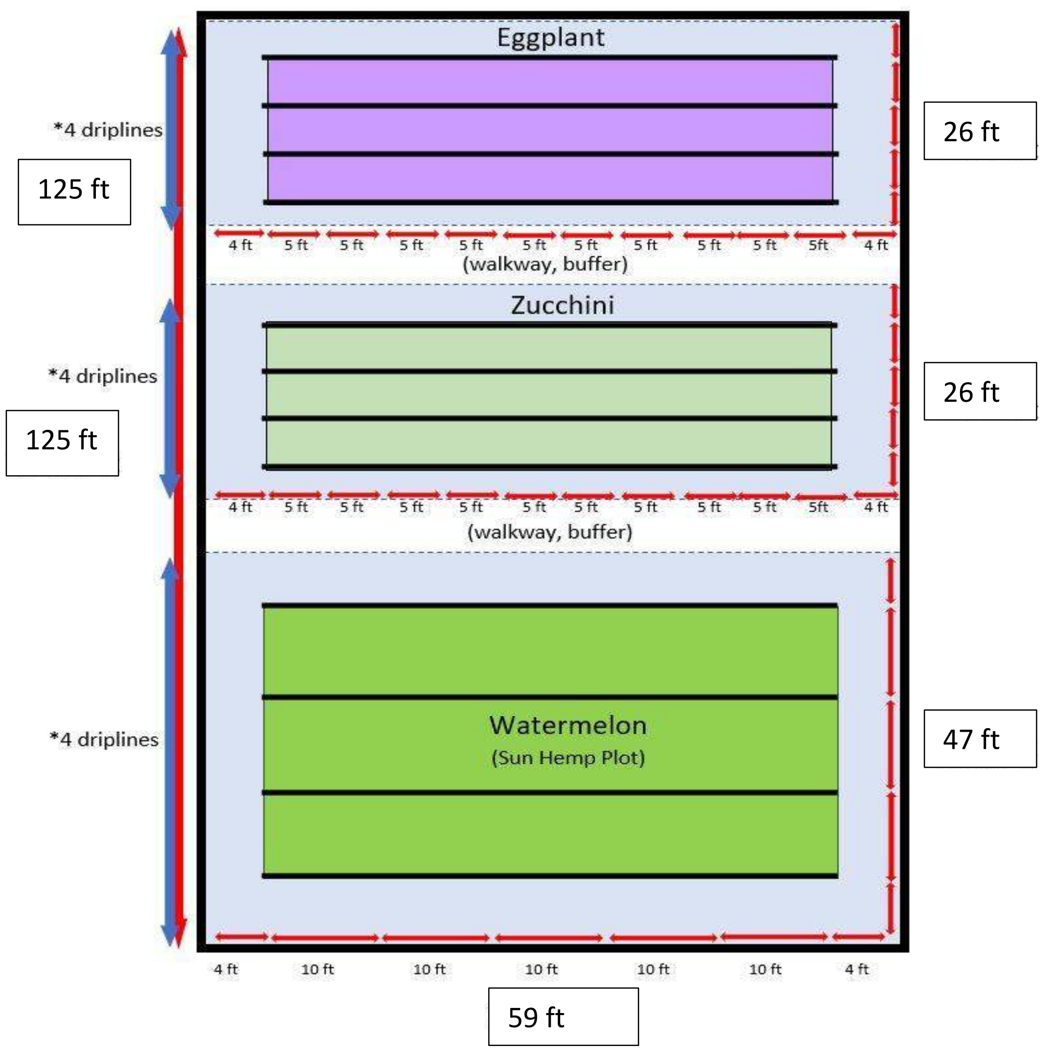


Figure 15. Initial field design for crops grown at the UOG Yigo Station for watermelon, zucchini, and eggplant for February 2019

Island View Farm's Sweet Corn Crop Monitoring Trials

Sweet corn was grown in the Island View Farm from June 1 to July 28, 2020, growing season. A total of 126 rows of corn with approximately 21,000 feet of irrigation lines were used. Irrigation application times were solely based on farmer's discretion. The following fertilizer grades (Nitrogen-Phosphorus-Potassium or NPK) were used throughout the crop cycle: 10-20-20, 11-58-0, 0-45-0, 46-0-0, and 0-0-62. To measure rainfall and reference evapotranspiration, an Onset HOBO RX3000 was placed in the Island View farm at the start of the crop cycle (Figure 16).

Figure 16. Front and back views of weather station positioned in the field (13°32'47" N, 144°52'9" E. 560 ft Elevation) along with its position in the Island View Farm (June 3, 2020).

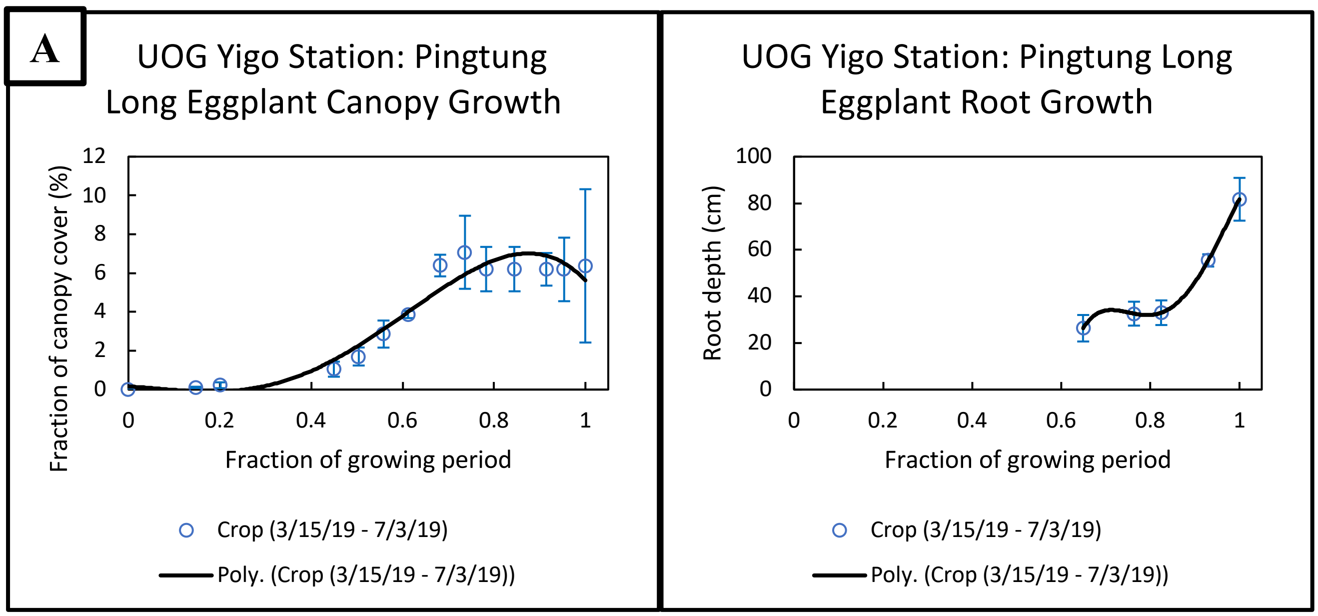
Three samples were taken when measuring the fraction of canopy cover (%). For each sample, a 5 ft x 5 ft PVC quadrat was placed over 2-3 rows of corn, and any sweet corn canopy that fell within the area of the quadrat was included in the canopy cover percentage. Measurements were taken in a span of five weeks from June 17 – July 15, 2020. Figure 17 shows the relative height and canopy cover of the sweet corn field after 6 weeks since the seeds were planted in the ground. Root depth measurements were taken only during harvest for crop damage concerns.

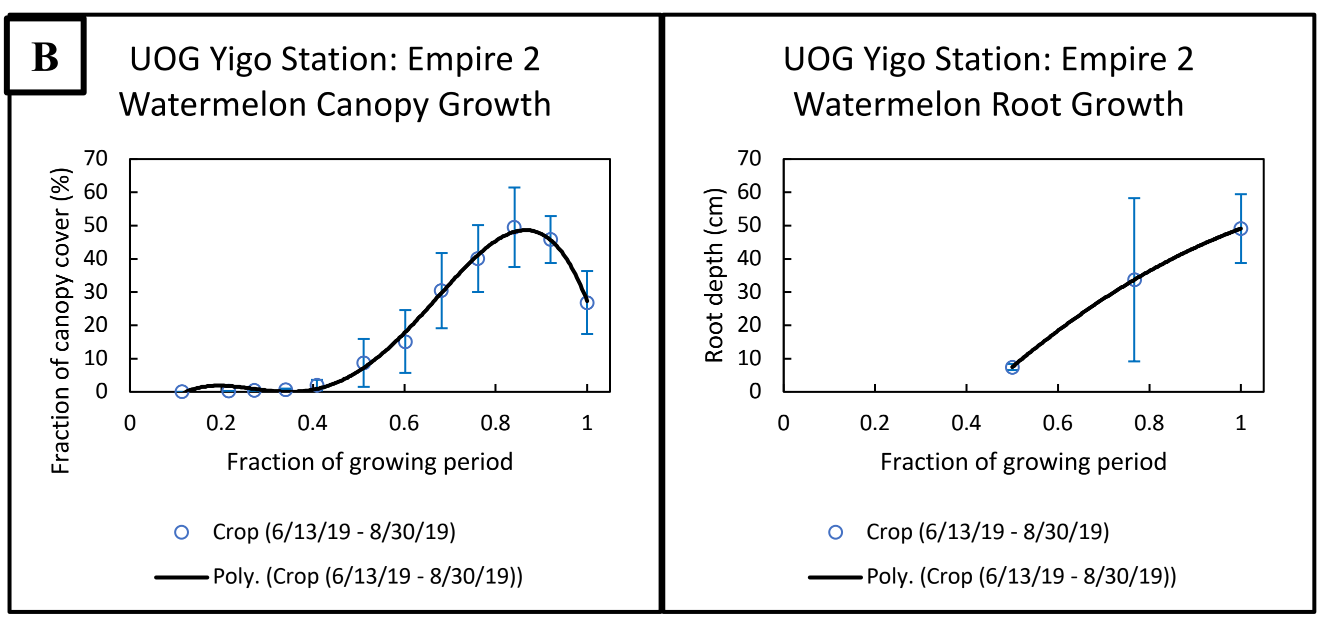
Figure 17. Weather station within the Island View farm cornfield approximately in the 6 weeks of the growing period (July 15, 2020)

Crop Monitoring Results

Figure 18 shows the average canopy growth (canopy cover fraction, %) of the sweet corn plants (three samples) from the Island View farm within 44 days since planting. The curve indicates that most of the growth occurred between the middle and the end of the growing period observed during the span of measurements.

Phase I: UOG Yigo Station's Eggplant, Zucchini, and Watermelon Crops





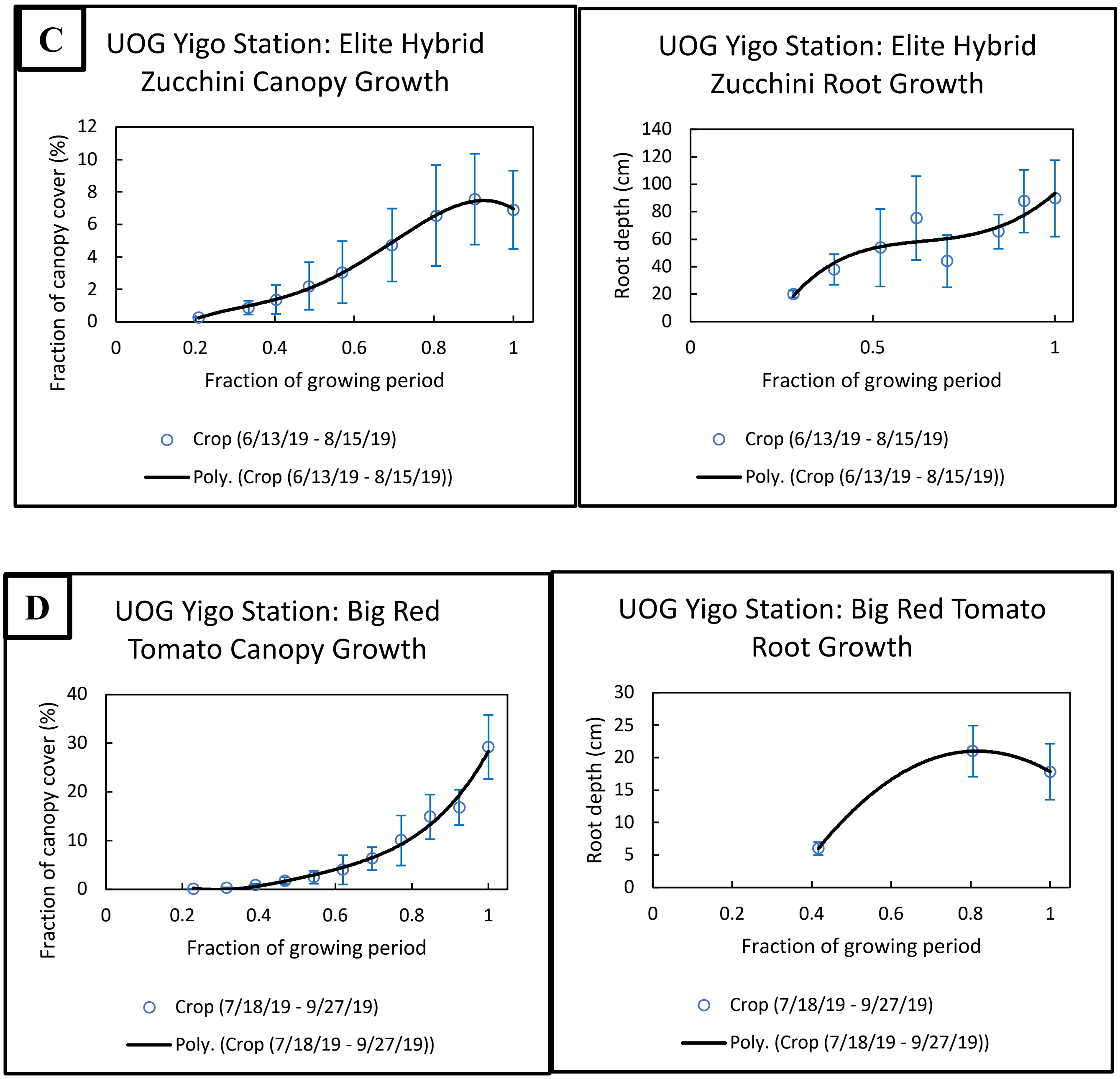


Figure 18. Variation of fraction of canopy cover (%) (left column) and root depth (right column) versus the fraction of growing period for A) Pingtung Long Eggplant, B) Empire II Watermelon, C) Elite Hybrid Zucchini, and D) Big Red Tomato grown at the UOG Station

Island View Farm Sweet Corn Crop Monitoring

Figure 19 shows the average canopy growth (canopy cover fraction, %) of the three samples of sweet corn from the Island View farm within 44 days since planting. The curve indicates that most of the growth occurred between the middle and the end of the growing period observed during the span of measurements.

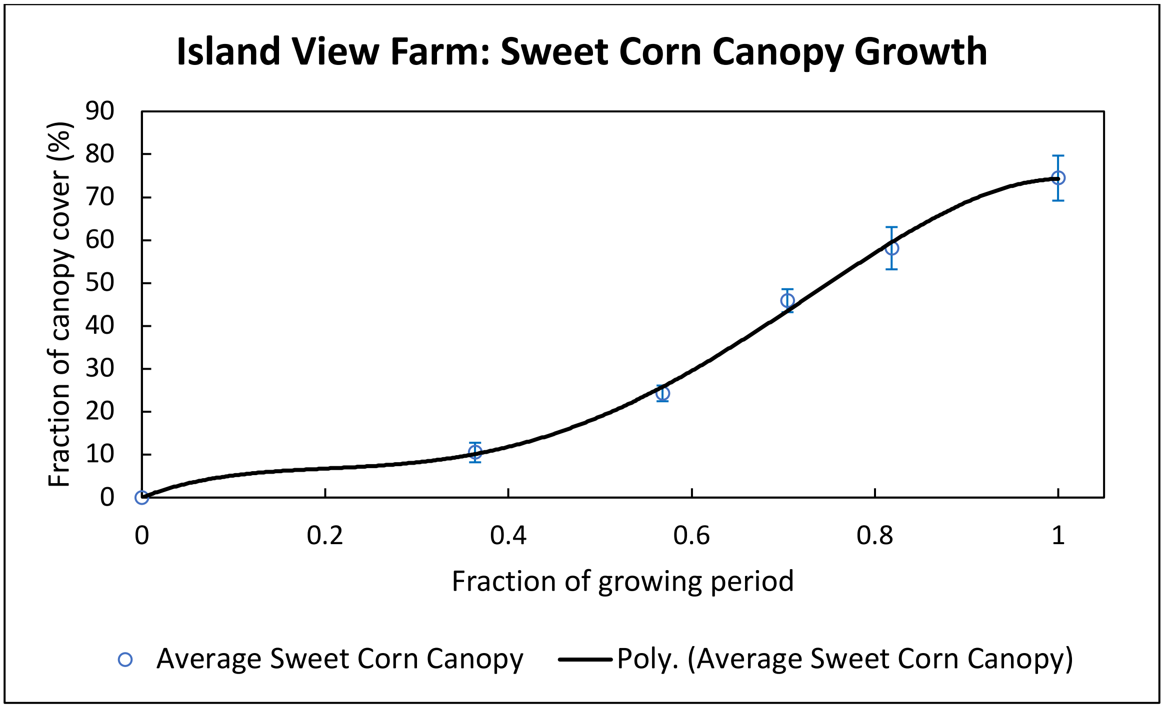


Figure 19. Variations of canopy cover fraction (%) versus days since planting (June 17-July 15, 2020) for sweet corn in the Island View Farm

As shown in figure 20, the lower and upper edges of the box indicate the first and third quartiles, respectively. The median position is marked within the box. Lines extending from the box ends represent the minimum and maximum values of root depth measurements. Also, a box plot of 11 root depth measurements taken on the same day of harvest on July 28, 2020. The maximum of 20.8 cm and average of 14.5 cm root depth indicate that the roots did not penetrate deep enough. This may be due to the high soil water availability, root obstruction, or both.

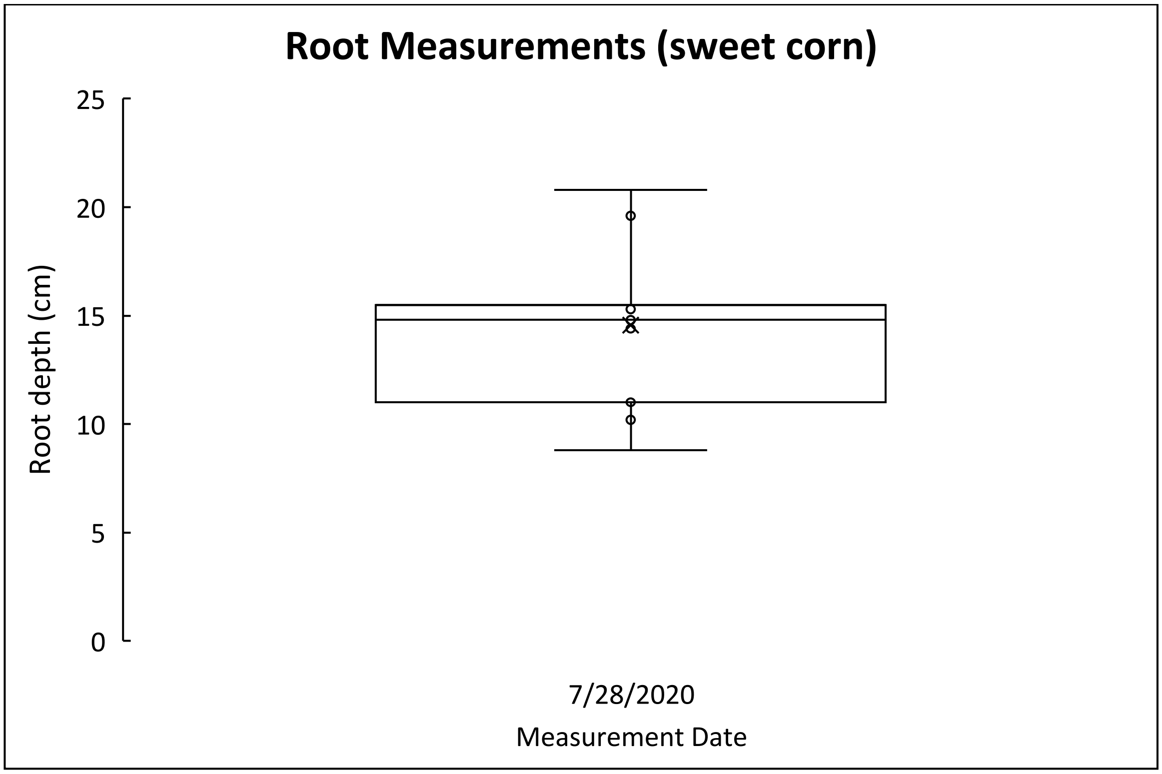


Figure 20. Box plot of 11 sweet corn root measurements at the Island View Farm taken on the day of harvest (July 28, 2020)

Phase I: Complications Encountered during Crop Monitoring Trials

Insects

In both crop cycles of zucchini, high numbers of pumpkin beetles were present as shown in figure 21A. In addition, red fire ants (Figure 21B) would attack seedlings, which delayed the growth or in some cases, cause premature death of the plants at the UOG Yigo station farm. On the third cycle of eggplant, once the rains had subsided, the sunny weather had brought on the introduction of insects on the field that began attacking the eggplant leaves as shown in Figure 21C. Subsequently, commercial pesticides Sevin® (carbaryl (1-naphthyl methylcarbamate) and Amdro® (hydramethylnon-based hydrazone) were introduced to control insect damage.

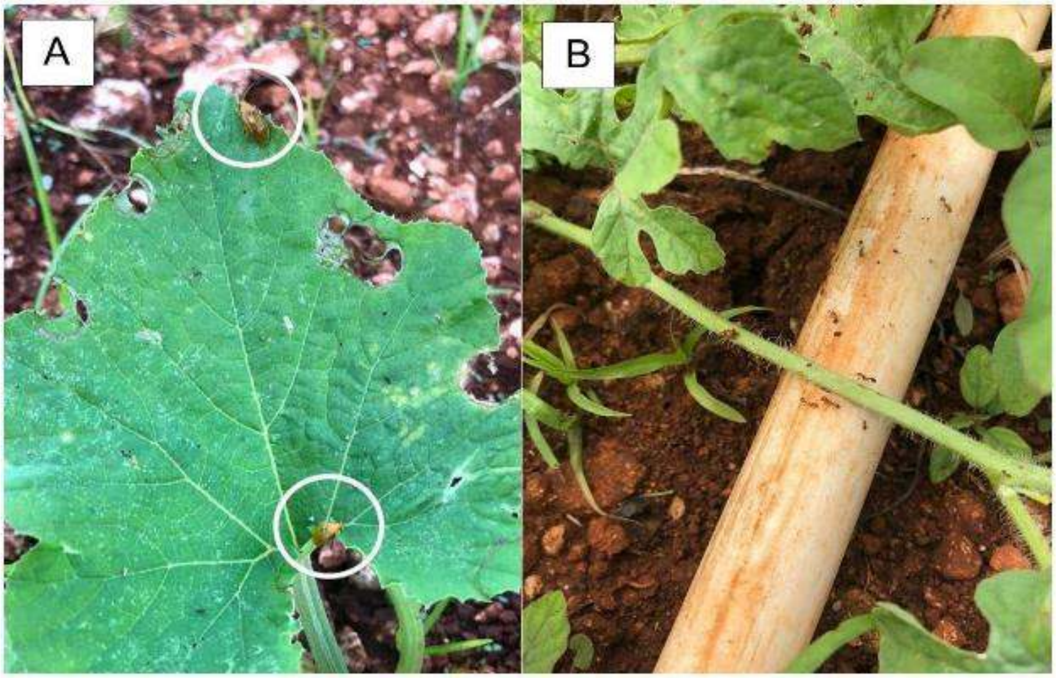


Figure 21(a-b). Pumpkin beetles on a zucchini leaf (A). red fire ants on a watermelon vine (B)

Figure 21C. Insect damage to a 10-week-old eggplant

Field and Crop Maintenance and other issues

MEDA Farm

- MEDA Farm owner was concern with the possible root damage on his pepper plants since roots measurements can be invasive as digging around the plants is necessary. Root measurements was stopped as a result.

- During the initial field design of the watermelon plots at the UOG Research Station, watermelon plats died after weeds were removed around the plants.
- During the second trial of the watermelon, there were four rows of watermelon and about five plants per row. When roots were measured during early growth stages, the watermelon plants would be unsuccessful in recovering and thus would be terminated. After measuring the watermelon roots for 3 weeks, the number of plants had been reduced to about 1-2 plants per row, which included the 3 plants that were used for measuring canopy growth. When watermelon seedlings were replanted onto the field, their growth was unsuccessful due to red fire ants within the field attacking the plant. Furthermore, as weeds can rob the soil of moisture and nutrients needed for the crop, a plastic weed mat was applied to three of the four rows of watermelon during the second cycle of watermelon. In addition, mulch was added to suppress the growth of weeds. However, as a result of the addition of weed mats and mulch, root analysis was discontinued as it became too difficult to measure roots. Weeds around each plant are removed twice a week.

Weather

As Guam shift toward the wet season, rainfall distribution is more consistent due to wind breeze (gentle and slow-moving wind), which weak but more variable wind circulations increases rain in the middle clouds (Jordan 1955). This consistent rainfall for several days or even weeks can cause root rots particularly to watermelons. In addition, the injection of fertilizers into the irrigation system or fertigation can lead water and fertilizer inefficiency.

Thunderstorm is also common during the wet season as strong winds and heavy rains and caused damage to tomato plants as shown in Figure 22. Precautionary measures such as the application of trellis and supporting the plant with string were used to reduce the amount of strain the plant may receive, as branches grow larger. On October 7, 2017, super typhoon ‘Hagibis’ passed though Guam with heavy rains and damaging winds peaked late Monday night. An assessment of the storm’s damage was taken the following day and noticed majority of the eggplants have been blown to the side as shown in Figure 22A and the tomato plants have been heavily damaged from the strong winds as shown in Figures 22B and 22C. Remedial measures such as applying more string to support the tomato branches, have been taken to assist in the plant's growth.

Figure 22a. Tomato branch at UOG Yigo Station damaged from strong winds due to passing tropical storm

Figure 22b. Damage to eggplant from super typhoon Hagibis

Figure 22c. Eggplant damaged from strong winds

Figure 22d. Fallen tomato plants due to strong winds caused by Super Typhoon Hagibis

CropManage Mode of Operation and Setup for Phase II

The following is the general description of CropManage's mode of operation to generate irrigation recommendations. First, crop growth data pertaining to canopy and root measurements were sent to the University of Hawaii for the crop type to be added into the CropManage website. Crop data such as maximum canopy, min/max root depth, canopy development coefficient, and canopy Kc coefficient will be used in calculating irrigation amounts appropriate to a crop's growth stage. Weather data on the other hand, are used to generate irrigation amounts that are appropriate to the soil water available. CropManage combines both crop and weather data to calculate the plant water requirement for reach day throughout the planting cycle. Daily, CropManage retrieves weather data early morning ranging from 12:00AM to 3:00AM on the HOBOlink server to account for recent significant factors such as rainfall that may increase or decrease the daily plant water requirement. Once all data points for each hour (12:00AM to 11:00PM) from the previous day is received, CropManage pulls pre-calculated rainfall/evapotranspiration numbers from the California Irrigation Management Information System (CIMIS) database and is then able to generate an optimized irrigation amount for that day. This description of CropManage's mode of operation shows why the Smart Irrigation Project was divided into 2 phases.

Upon completion of field data collection from the 3 different study sites during Phase 1, the Smart Irrigation project proceeded to Phase 2 in incorporating CropManage into the study sites. To use CropManage, a profile for a specific farm/ranch was first created on the CropManage website (https://cropmanage.ucanr.edu). Farm details such as land size, coordinates, soil type, active weather stations, and commodities were entered under the ranch settings. Next, a planting profile was created for each crop that was chosen to get irrigation recommendations. Within the planting profile, the commodity and crop type were selected from a list generated from previous planting trials done in Phase 1. As programed in CropManage, selection of the crop type also inputted the following crop data into the planting profile:

- maximum canopy
- fraction of crop cycle
- Canopy development coefficient
- Canopy coefficient, K_c
- minimum/maximum root depth
- To complete the CropManage set up, the following logistical data were entered under the planting profile:
- wet/end of crop dates
- drip application rate (in./hr.)
- number of drip tapes per bed
- bed width

- plant rows per bed.

After setup, recommended irrigation amounts were generated through CropManage and recorded for virtual and side-by-side trials.

UOG Station CropManage Profile

On July 26, 2019, a CropManage manual had been introduced to the Smart Irrigation project on Guam; and through using the CropManage program, the recommended amount of water was officially implemented into the irrigation system on September 17, 2019, at the UOG Station. An account was created on the CropManage website, and a profile for the UOG Station was created. The following settings were inputted to set up the ranch/farm profile for UOG station:

Size: 0.17 acres
Coordinates: 13.5314097211872 N,144.871656173534 E
Soil Type: Guam cobbly clay loam, 3-7 percent slope
Weather Station: Yigo Watson HOBO (#403)
Commodities: Eggplant, Squash, Tomato, Watermelon

For each crop being monitored in Phase 2, a planting profile was created with their own respective logistical settings and crop-specific settings as mentioned in the CropManage Mode of Operation and Setup section. In general, equation below was used to determine the drip application rate of the drip tapes:

$$\text{Drip Application Rate (in/hr)} = \frac{231.1 \times \text{Emitter Flow Rate (gph)} \times \text{Irrigation Uniformity}}{\text{Space Between emitters (in)} \times \text{Space Between Drip Tapes (in)}}$$

Phase II: UOG Yigo Station Virtual Trials

When enough baseline field data was accumulated from Phase 1, the study proceeds on to Phase 2 which implemented CropManage recommendations through first virtual trials then Side-by-side trials. Side-by-side trials compare crop growth, crop yield, and the amount of water used throughout the cycle between crops grown in CropManage's irrigation schedule versus crops grown in a farmer's regular irrigation schedule. For crop plots where irrigation scheduling cannot be applied or where crop growth and yield cannot be consistently monitored, virtual trials will be used only to gather data on the amount of water used. The comparisons from both trials will show how much water can be saved if CropManage is implemented – CropManage's effectiveness as a smart irrigation tool or sustainable agriculture. Table 3 below summarizes crops that have been monitored thus far for Phase 2 of the Smart Irrigation project.

Table 3. Virtual trials of crops in with start and end dates.

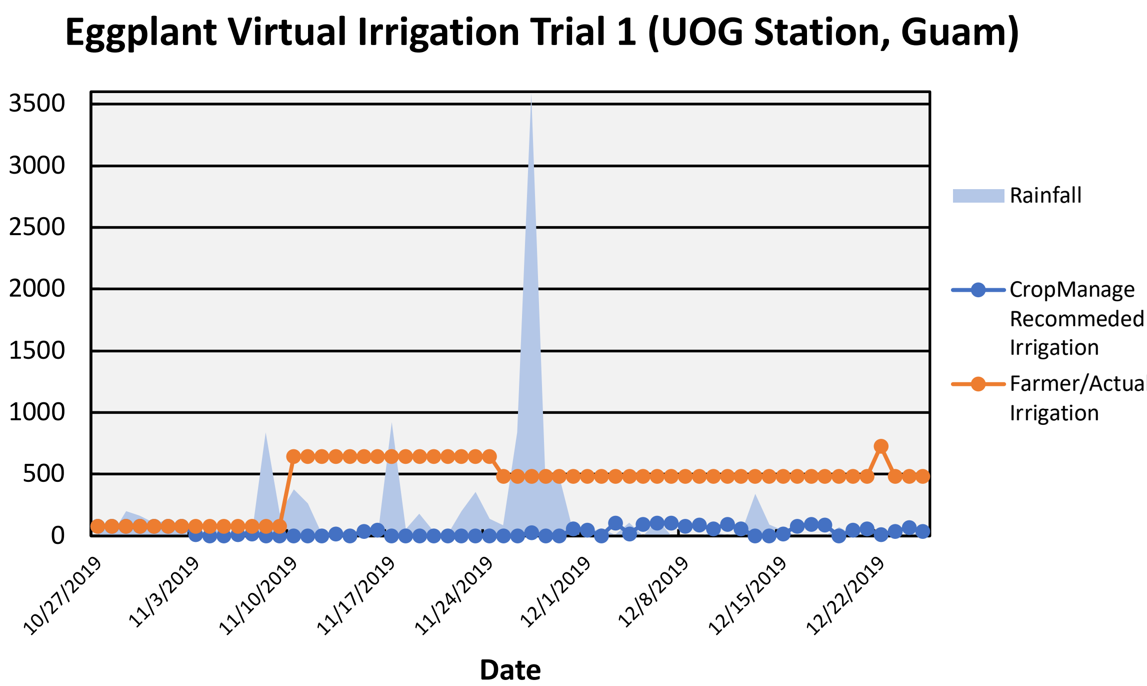
<table>
<tr><th>Island</th><th>Location</th><th>Crop (Variety)</th><th>No. of Trials</th><th>Start Date</th><th>End Date</th><th>Total Days</th></tr>
<tr><td rowspan="2">Guam</td><td rowspan="2">Yigo,
UOG Station
(Guam series from Entisols order)</td><td>Tomato</td><td>1</td><td>10/25/2019</td><td>12/24/2019</td><td>61*</td></tr>
<tr><td>Eggplant
(Pingtung Long)</td><td>2</td><td>10/25/2019
1/6/2020</td><td>12/24/2019
3/31/2020</td><td>61*
86</td></tr>
</table>

* Virtual Trials were done after actual planting because of data retrieval limitations on HoboLink

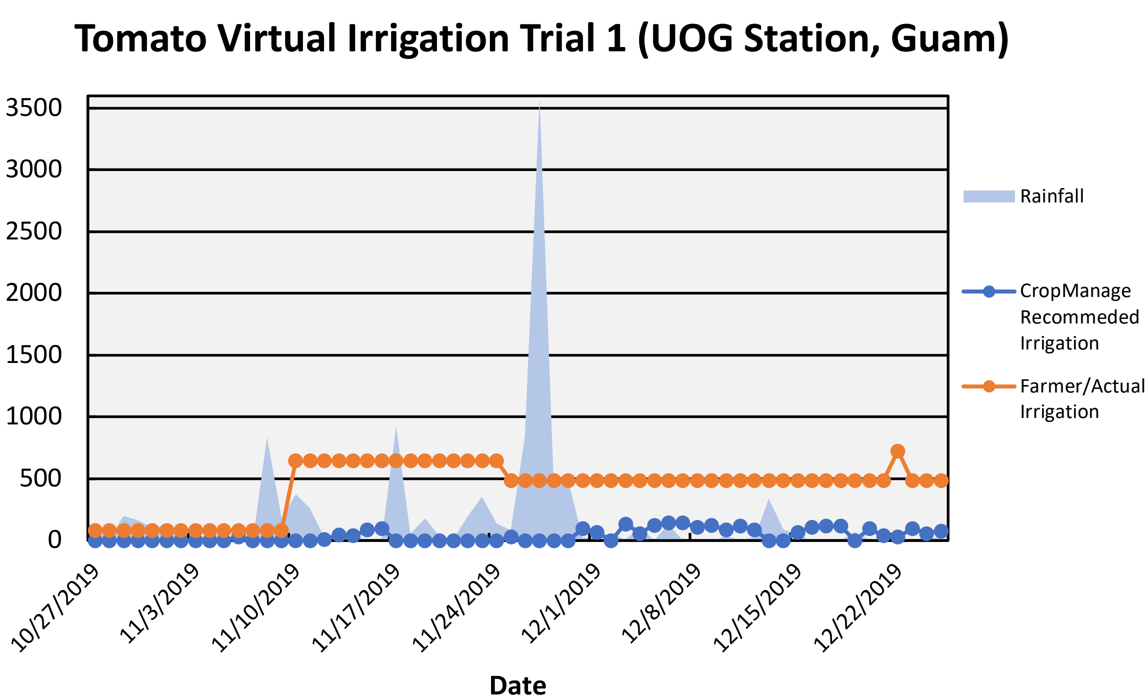
Prior to establishing side-by-side field trials, a set of virtual trials were conducted to compare farmer irrigation practices to scheduled irrigation recommendations from CropManage. A flowmeter connected to the main irrigation line within the field was used to determine the gallons of water used during an irrigation event. Using this data along with the weather data collected by the HOBOlink data logger, an estimation of the amount of irrigation water delivered daily as well as the irrigation amount recommended by CropManage was recorded.

PHASE II UOG YIGO STATION VIRTUAL TRIAL RESULTS

A



B



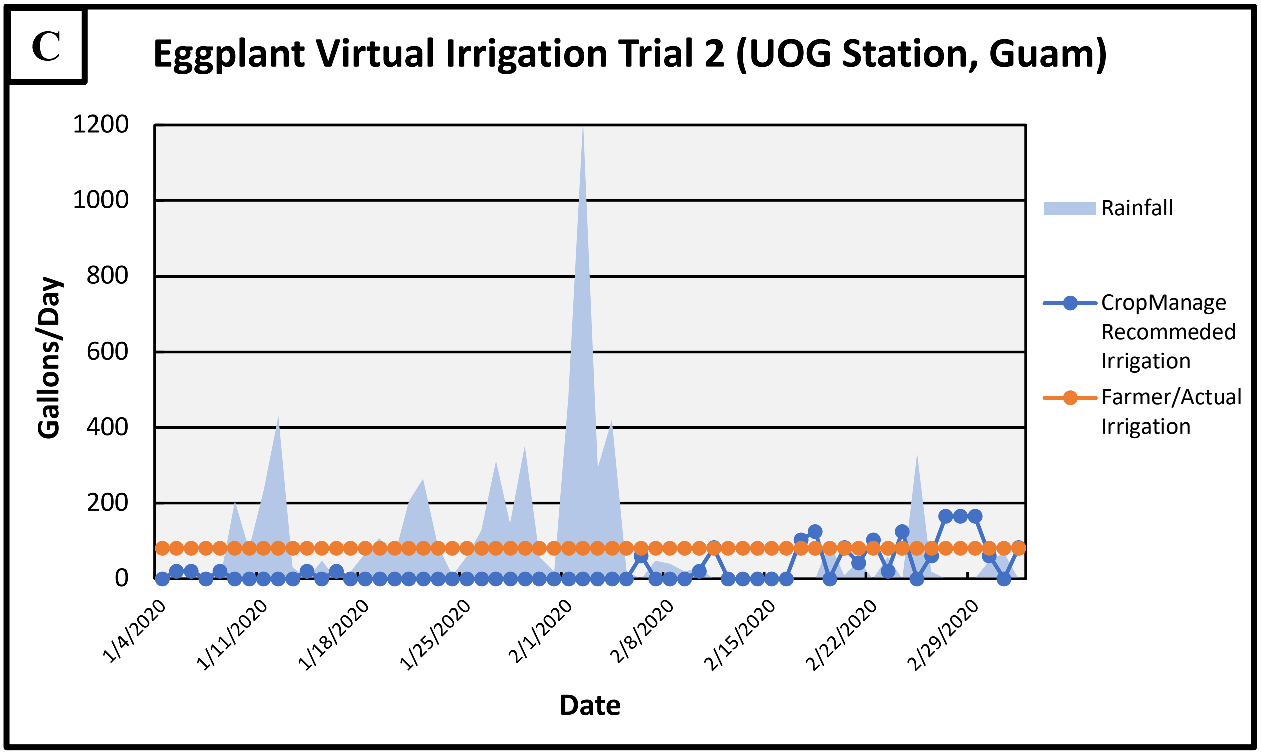


Figure 23. Virtual trials showing the amount of water used per day by both Farmer's and CropManage's irrigation. Amount of rainfall also included. A) Pingtung Long Eggplant Virtual Trial from 10/25/2019 to 12/25/2019 (wet season) B) Big Red Tomato Virtual Trial from 10/25/2019 to 12/25/2019 (wet season), C) Pingtung Long Eggplant Virtual Trial from 1/4/2020 to 3/31/2020 (wet to dry season)

Table 4. Virtual trials of crops in with results.

Island	Location	Crop (Variety)	Season	Gallons Used by Farmer	Gallons Used by CropManage	Gallons Saved
Guam	Yigo, UOG Station (Guam series from Entisols	Tomato (Big Red)	Wet	26114.55	2638.944	23,475.60
		Eggplant (Pingtung Long)	Wet	26114.55	2205.588	23,908.96

	order)	Eggplant (Pingtung Long)	Wet-Dry	7114.8	6594.126	520.674

Phase II: Attempted Eggplant Side-by-side Trial

At the UOG field Station, side-by-side trials was conducted to test the CropManage irrigation recommendations and divided into two equally sized plots (Figure 24A-F). The first plot on the top was labeled as the control plot, which received irrigation based on a farmer's regular irrigation schedule. The second plot at the bottom is considered as CropManage treatment plot and be watered with CropManage recommendations. Each plot was given a main irrigation line with a flowmeter to measure the amount of water used during each irrigation event.

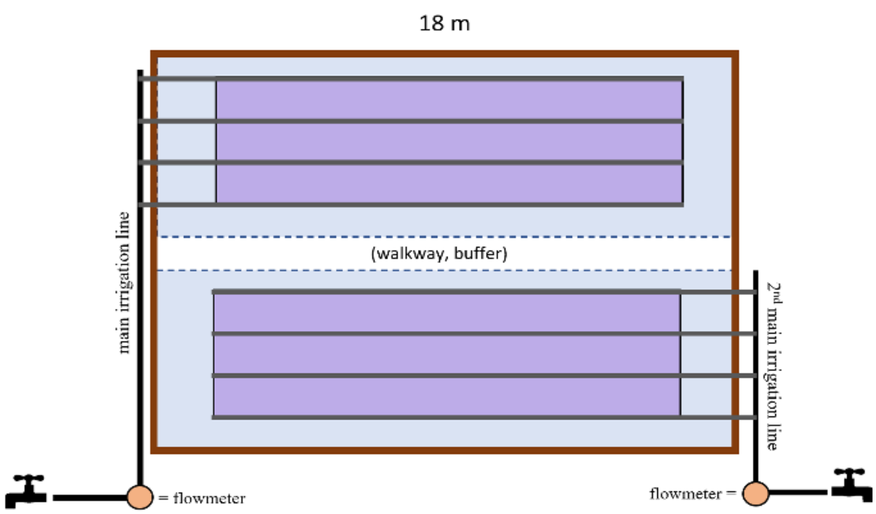


Figure 24A. The field design for a side-by-side trial of CropManage.

Figure 24B. Digital timer for scheduling irrigation times

Figure 24C. CropManage plot with water lines

Figure 24D. Farmer Practice/Control Plot with water lines (left sideview)

Figure 24E. Irrigation timer with water meter (left). Farmer setup (control)Right: CropManage

Figure 24F. CropManage irrigation setup including timer, water meter, crops, and plot

UOG station side-by-side trial complication

Pingtung Long eggplant variety was chosen for the first side-by-side trial. Both plots were treated similarly by giving them the same amount of irrigation water (30 minutes daily) and fertilizer for a period of 2 weeks. After 2 weeks of similar treatment, the control plot was observed to be growing at a slower rate than the CropManage plot. Equal treatment for both plots was continued for six more weeks, and the control plot was still growing at a slower rate. This was further supported with canopy growth plots and crop yield data (Figure 18). Because the amount of water and fertilizer applied to both plots were kept constant, yet the growth rates still differed, it was hypothesized that each plot may have a difference in soil nutrient or composition that was significant enough to manifest an effect in crop growth. Weather and pest concerns were ruled out as both plots were closely monitored for those differences throughout the growth period. Soil chemical analysis will be carried out to confirm the hypothesis. With this unforeseen observation, the first true side-by-side trial was converted to the virtual trial. Additionally, the field design in Figure 24A was terminated. Pending on the soil analysis, further side-by-side trials at the UOG station field is on hold to prevent mistakenly attributing CropManage irrigation as the significant factor in effects observed. A work-around that is being explored is to randomize by interchanging CropManage and control rows as seen in Figure 25.

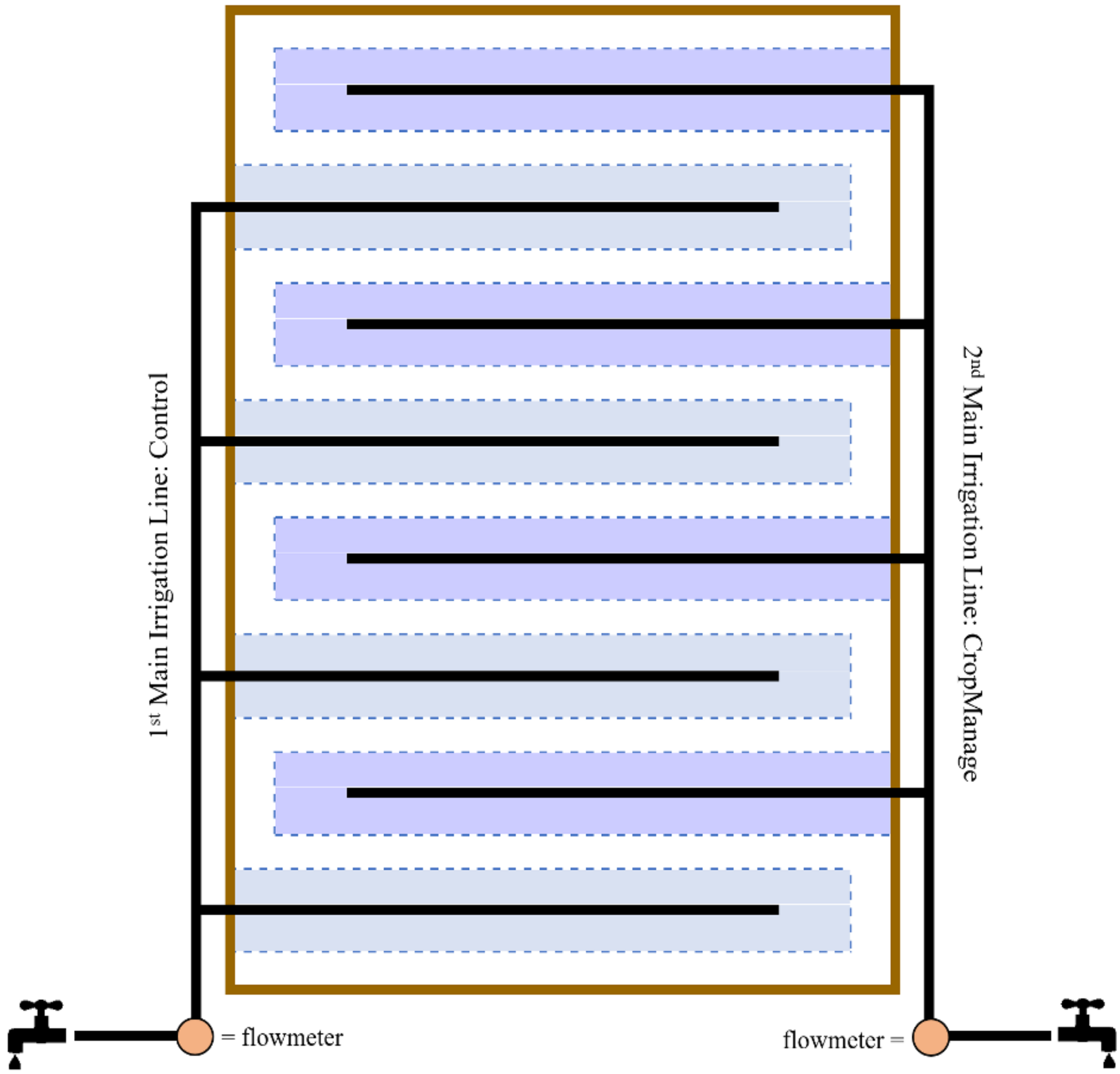


Figure 25. Revised field design for a side-by-side trial of CropManage.

Phase II: UOG Yigo Station Eggplant Side-by-side Trial

A side-by-side field trial (local variety name: short purple) was performed to compare CropManage irrigation recommendations with the farmer's traditional irrigation times stated in previous literature (University of Guam). Seedlings were obtained from the Guam Department of Agriculture and the trial began on June 24, 2020.

Experimental Design and Methods

Irrigation Setup

Figure 26 shows the irrigation setup of the side-by-side field trial for eggplant at the UOG Yigo Station. The experimental layout follows a "paired comparison" experimental design method to compare two different treatments assigned randomly within blocks (Chaney, 2017). One main water line was split to feed water to both CropManage and control irrigation fields. This would produce a constant water pressure for both fields regardless of pressure variations in the main water line throughout the days, weeks, or months. Two water meters were installed after the split junction to record the different irrigation amounts separately.

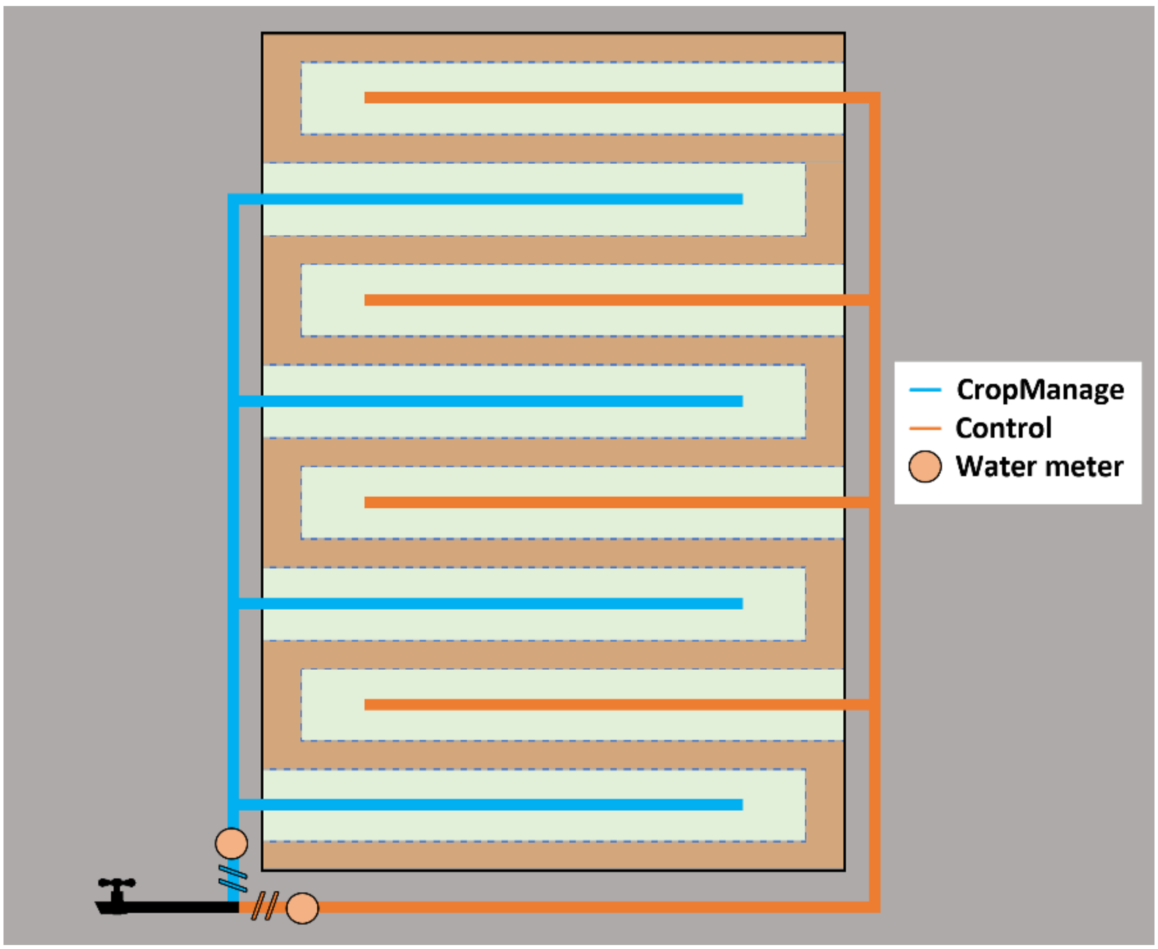


Figure 26. The irrigation setup of the short purple eggplant side-by-side field trial.

There are eight rows of irrigation fields/lines: four rows of CropManage lines and four rows of control lines. The CropManage and control irrigation lines were placed in alternating order. Instead of CropManage and control irrigation lines being placed separately where each irrigation treatment takes either the front or back side of the plot, this design enables eggplants from both irrigation treatments to be equally dispersed throughout the plot. This reduces effects that may arise due to the condition of plants within the plot. For example, should the front side of the plot have slightly more nutrients available, both the CropManage and control eggplants positioned in the front would exhibit those effects rather than only the irrigation system in the front (CropManage or control). The following are possible positional variations that are mitigated through the alternating order design:

- soil composition – some areas of the plot may have more rocks or obstructions, while other parts may have soil more conducive to root development.
- soil nutrients – some areas of the plot may more/less nutrients available for root uptake
- light exposure/availability – some areas of the plot may have better/more exposure to light
- wind damage vulnerability – some areas of the plot may experience slightly more force from winds.
- pest vulnerability – some areas of the plot may be more accessible or near pests like fire ants

Plot Setup

A 0.08-acre plot from the previous Phase 1 trials in the Triton Farm was used. The plot measured approximately 60.7 ft.in length and 55.4 ft in width. Since the plot incorporated both CropManage and control irrigation in alternating order, the plot was divided equally into two 0.038 acres collectively for each irrigation treatment. For each row of irrigation line across the plot, bed width was about 30 in with 47 in of buffer space in between to ensure irrigation for each row remains separate and does not affect any adjacent rows. Eleven eggplant seedlings were transplanted on each row being separated about 5 ft apart. In total, the side-by-side field trials started with 88 eggplants.

Control Irrigation Settings

Control irrigation times were set for a total of two 1-hour irrigation sessions at 9:00 AM – 10:00 AM and 1:00 PM – 2:00 PM. This schedule was followed except in fertigation days.

The tape discharge rate (gpm/ft) was determined first by averaging water meter readings for 8 days, i.e., July 15 – July 22, 2020. Next, the drip application rate was calculated using the related equation on the CropManage Website. The drip application rate was also calculated using Equation 3 below (Washington State University Extension and Hunter Industries, (2021)):

$$\text{Drip Application Rate (in/hr)} = \frac{231.1 \text{ x Emitter Flow Rate (gph) x Irrigation Uniformity}}{\text{Space Between emitters (in) x Space Between Drip Tapes (in)}}$$

The drip application rate from both methods yielded similar results. The control irrigation's drip application rate from the CropManage website is used for comparison. Table 4 shows the values used in both methods:

Table 5. Drip application rate calculations for control irrigation.

CropManage Calculator		Equation 1	
gpm	1.82	gph	109.51
ft	224.73	Number of emitters	227
gpm/100 ft	0.81	Emitter flow rate	0.48
Bed width (in)	30	Space between emitters (in)	11.75
Drip lines per bed	1	Space between driplines (in)	30
		Distribution uniformity	1
Drip Application rate (in/hour)	0.31	Drip Application rate (in/hour)	0.31

A drip application rate of 0.31 in/hr yields a daily irrigation water application of 0.62 inches for two hours or approximately a daily application of 219 gallons for two hours. This is comparable to the "9,000 gallons of water per acre a day" or 345.6 gallons for a 0.0384-acre plot recommendation from literature produced by the University of Guam. The control irrigation times of 2 hours a day applies about 63% of the literature's recommended value, which is a more conservative amount to further extenuate the potential effects of water on crop growth and yield.

CropManage Irrigation Settings

For June 24 – July 23, 2020, CropManage was irrigated the same amount as control (2 hours per day) because the seedlings required more water during their early growing stage. From July 24, 2020, CropManage irrigation recommendations were followed except in times of fertigation, which watering time may get extended.

Daily CropManage irrigation times were based on recommendations generated by the CropManage Triton Farm profile. Irrigation amounts were calculated mainly from rainfall and evapotranspiration measurements, which are transferred into the CropManage server.
Similar to the control irrigation, the drip application rate for CropManage irrigation was calculated from the CropManage calculator and Equation 3. The drip application rates from both methods were similar. Table 6 shows the values used in both methods:

Table 6. Drip application rate calculations for CropManage Irrigation

CropManage Calculator		Equation 1	
gpm	1.52	gph	91.3
ft	224.7	Number of emitters	227
gpm/100 ft	0.68	Emitter flow rate	0.4
Bed width (in)	30	Space between emitters (in)	11.75
Drip lines per bed	1	Space between driplines (in)	30
		Distribution uniformity	1
Drip Application rate (in/hour)	0.26	Drip Application rate (in/hour)	0.26

Canopy Cover Measurements

Canopy cover measurements were taken on a weekly basis (June 26 – September 24, 2020). Five samples from both CropManage and control irrigation were monitored every week. The five samples were taken from different locations in the plot in order to capture a more representative crop canopy growth.

Harvest Procedure and Fresh Weight Measurements

A total of six weekly harvest events were completed from September 3 – October 7, 2020. Instead of sampling random crops from each irrigation treatment, the entire plot of eggplants was harvested and weighed. Each crop was labeled by its place in rows and columns.

Results and Discussion

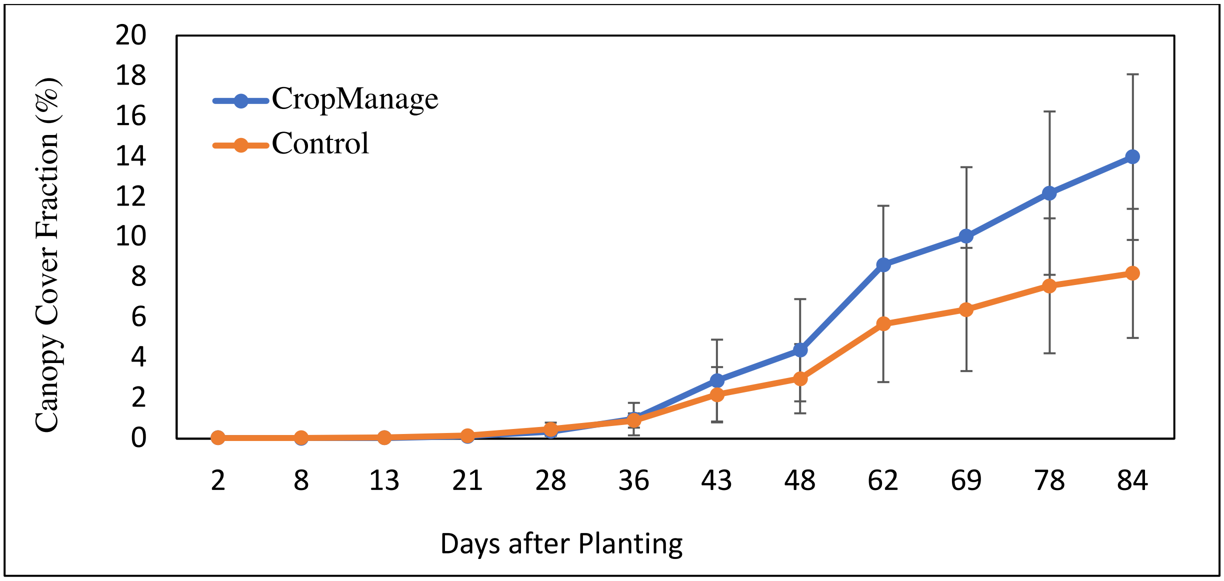


Figure 27. Side-by-side trials. Growth curves (June 24 – September 26, 2020) of eggplants for both Irrigation settings at the UOG Triton farm. Whiskers represent the standard deviation of measured canopy cover fraction (%) for each irrigation treatment plot.

Figure 27 shows the average canopy growth (canopy cover, %) of the 10 sample eggplants from both CropManage and control irrigation at the UOG Triton farm within 84 days since transplanting. Days since planting instead of fraction of growing period since trial is still ongoing and the end of crop cycle has not been reached yet. The curve shows that most of the growth after around 45 days since transplanting. It can also be seen that for the latest canopy cover fraction measurement (84 days since transplanting, September 26, 2020), the eggplants irrigated with CropManage had a larger average canopy cover fraction (13.97 ± 4.11, %) than control (8.2 ± 3.2, %).

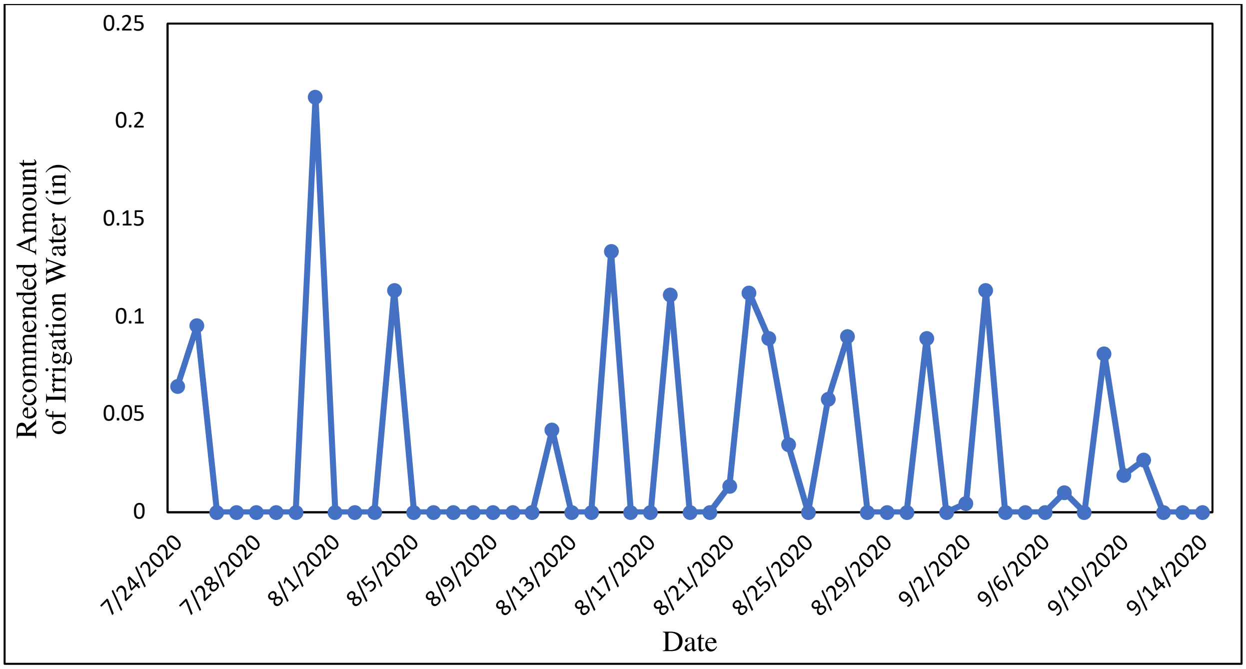


Figure 28. Daily irrigation recommendations generated by CropManage for side-by-side trial at the UOG Triton farm (July 24 – September 14, 2020)

Figure 28 shows the daily irrigation recommendations generated by CropManage (July 24 – September 14, 2020). During a high rainfall, low evapotranspiration rate, or combination of both from the same period, CropManage will recommend zero amount of water and vice versa.

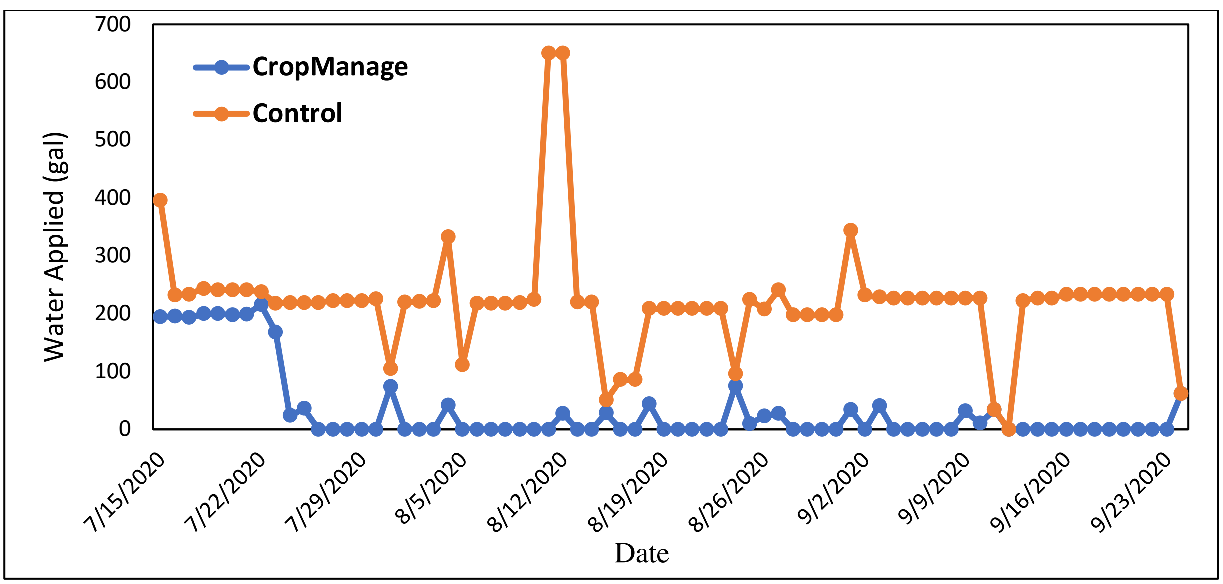


Figure 29A. Daily irrigation events measured from water meters in gallons at the UOG Triton farm (July 15 – September 24, 2020)

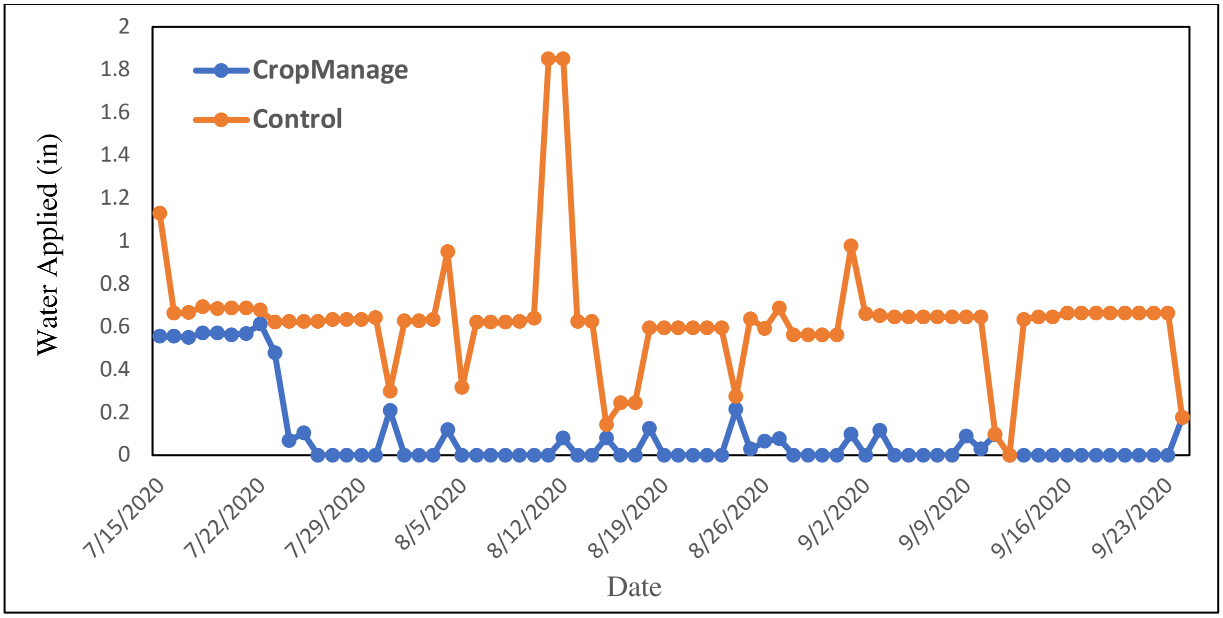


Figure 29B. Daily irrigation events calculated from water meters in inches at the UOG Triton farm (July 15 – September 24, 2020)

Figures 29A and 29B show daily irrigation events for both CropManage and control irrigations based on measurements taken from water meters (July 15 – September 24, 2020). Figure 29A shows daily irrigation events in gallons as directly recorded from the water meters whereas Figure 29B shows daily irrigation events in inches by converting gallons recorded from the water meters to inches using each irrigation's respective average gallons per minute flow rate and drip application rate (inches per hour) conversion factor. Irrigation events include days of fertigation and days when irrigation lines burst due to possible changes in water pressure or faulty equipment.

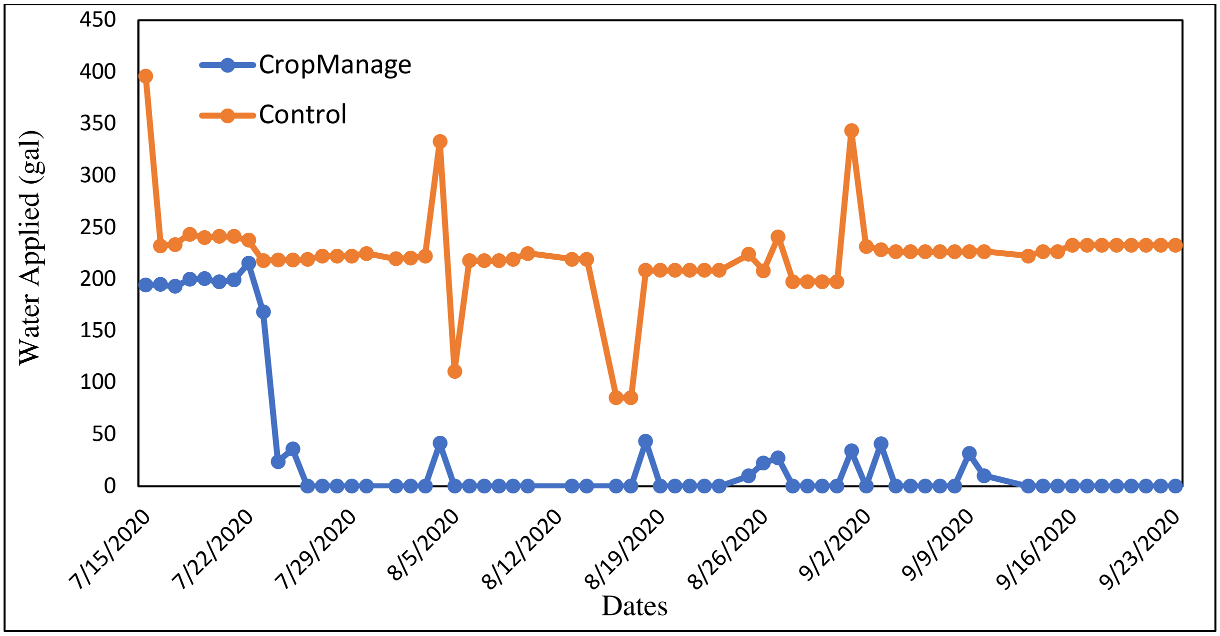


Figure 30A. Daily irrigation events measured from water meters in gallons at the UOG Triton farm excluding days of fertigation and irrigation line burst (July 15 – September 24, 2020).

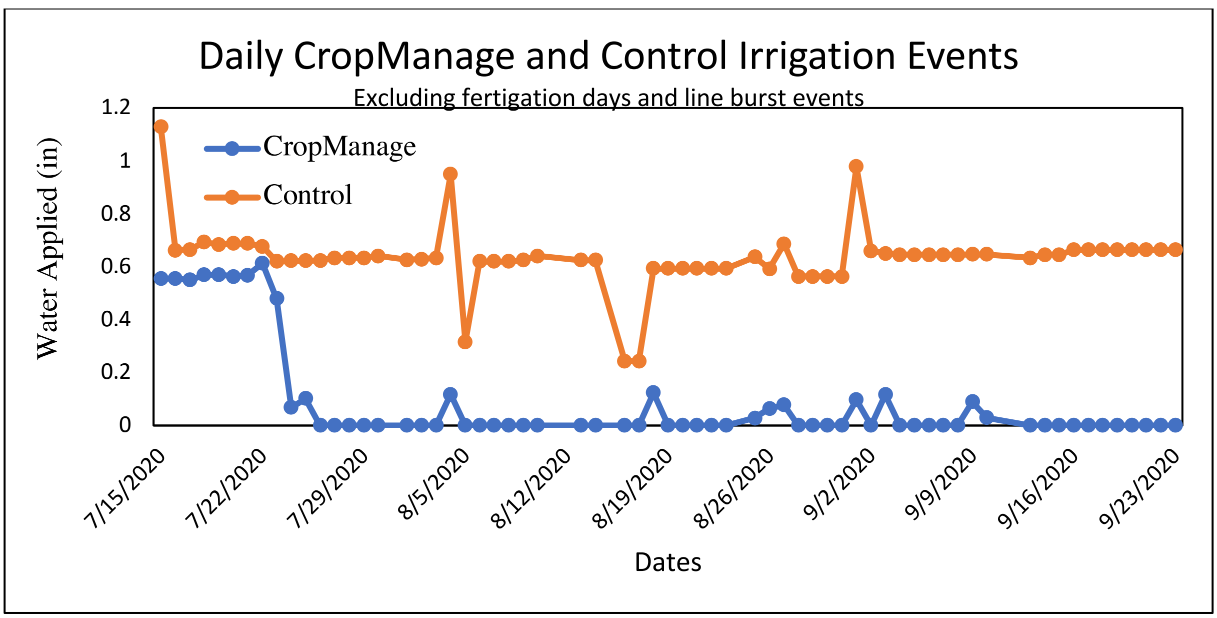


Figure 30B. Daily irrigation events measured from water meters at the UOG Triton farm excluding days of fertigation and irrigation line burst (July 15 – September 24, 2020).

Figures 30A and 30B similarly show daily irrigation events for both CropManage and control irrigations based on measurements taken from water meters (July 15 – September 24, 2020) excluding fertigation days and events when irrigation lines burst. Figure 30A shows daily irrigation events in gallons as directly recorded from the water meters whereas Figure 30B shows daily irrigation events in inches by converting gallons recorded from the water meters using each irrigation's respective average gallons per minute flow rate and drip application rate (inches per hour) conversion factor. Irrigation events also include days of fertigation and days when irrigation lines leaked or burst.

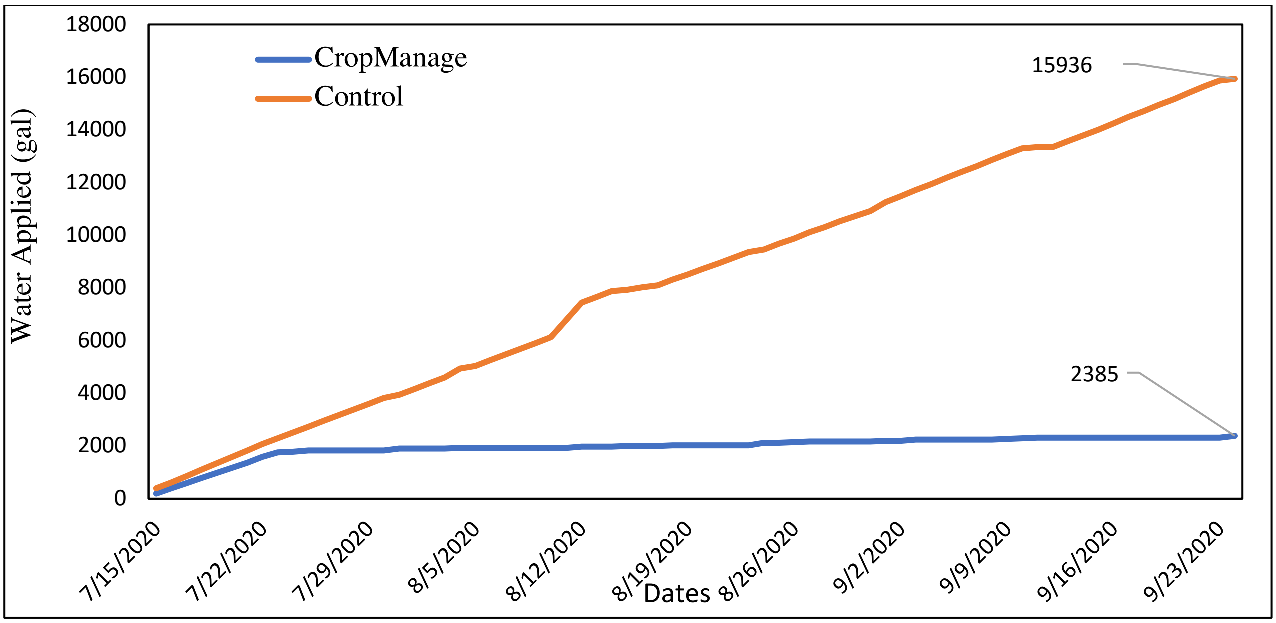


Figure 31A. Cumulative amount of water applied in gallons as monitored with water meters with CropManage and control irrigation at the UOG Triton farm (July 15 – September 24, 2020)

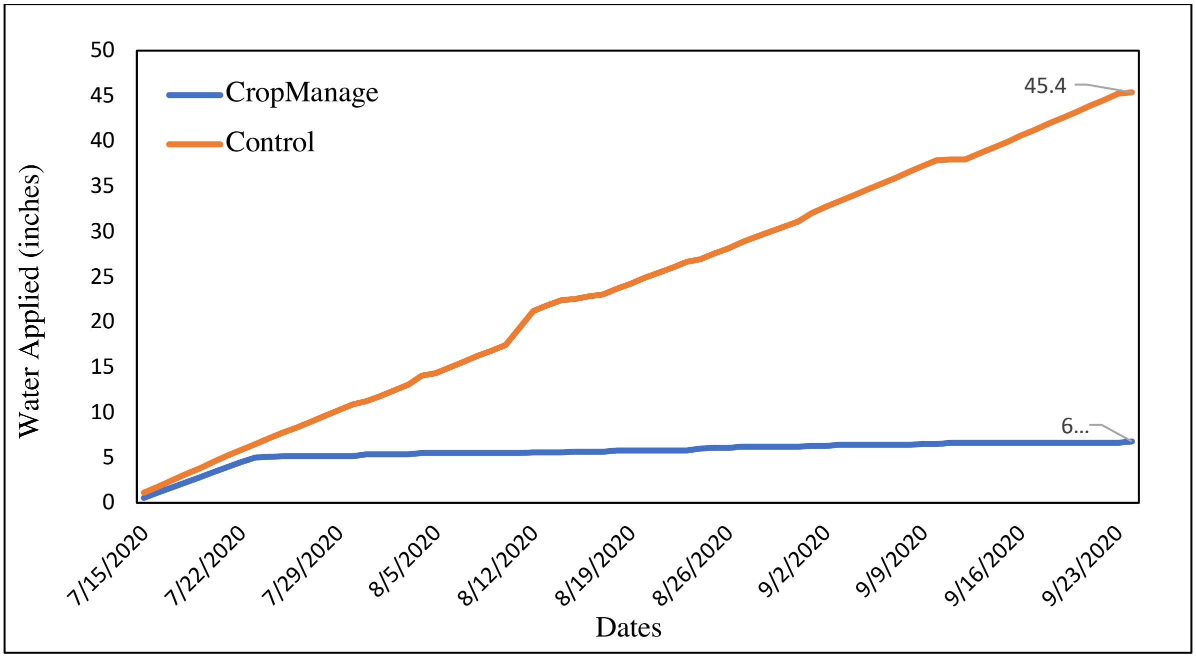


Figure 31B. Cumulative amount of water applied in inches with CropManage and control irrigation at the UOG Triton farm (July 15 – September 24, 2020)

Figures 31A and 31B show the cumulative amount of water applied with CropManage and control irrigation based on measurements taken from water meters (July 15 – September 24, 2020). Figure 31A shows the cumulative amount of water applied in gallons as directly recorded from the water meters whereas Figure 31B shows the cumulative amount of water applied in inches by converting gallons recorded from the water meters to inches using each irrigation's respective average gallons per minute flow rate and drip application rate (inches per hour) conversion factor.

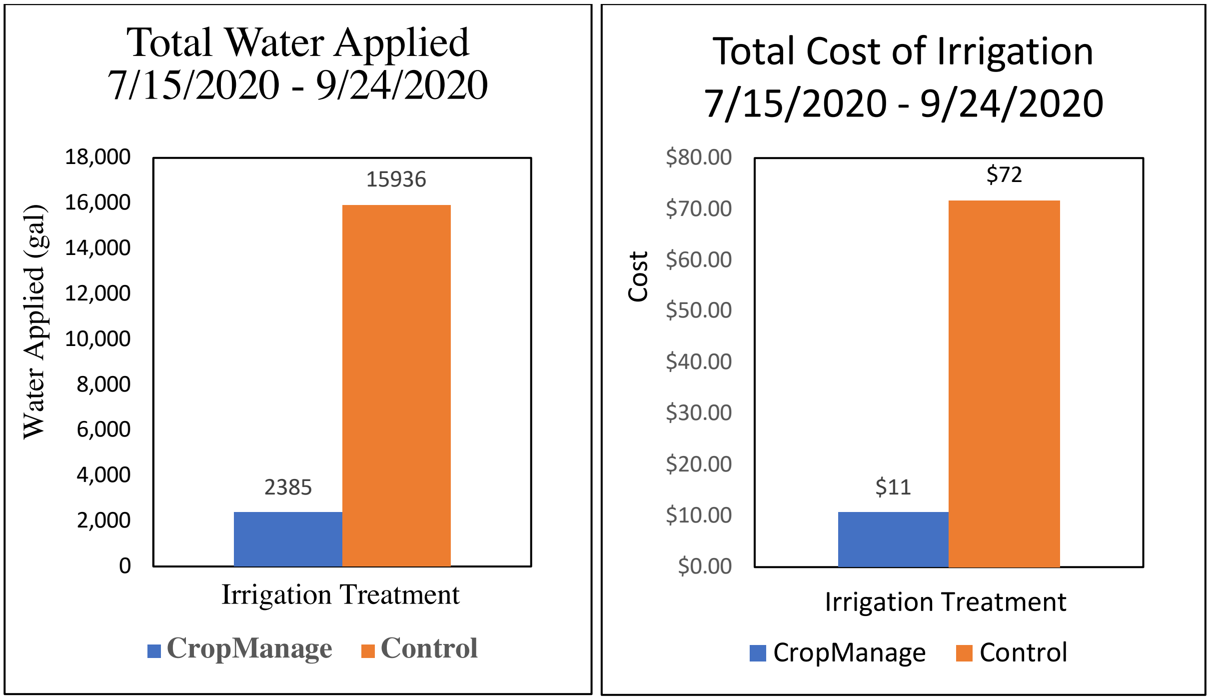


Figure 32. (left) Total Water applied for CropManage and control irrigation at the UOG Triton farm and (right) total cost of both irrigations setting from July 15 – September 24, 2020

Figure 32 highlights the difference in water used between CropManage and control irrigation along with the associated costs. Using recommended irrigation amounts based on literature from the University of Guam, the control used a total of 15,936.36 gallons (July 15 – September 24, 2020). Using primarily daily rainfall and reference evapotranspiration, CropManage used a total of 2,385 gallons (July 15 – September 24, 2020). The number of gallons applied costs $10.7 and $71.7 from CropManage and control respectively. Cost of irrigation was based on Guam Waterworks Authority rate of $4.50 per 1,000 gallons accessed on October 1, 2020.

Crop Yield

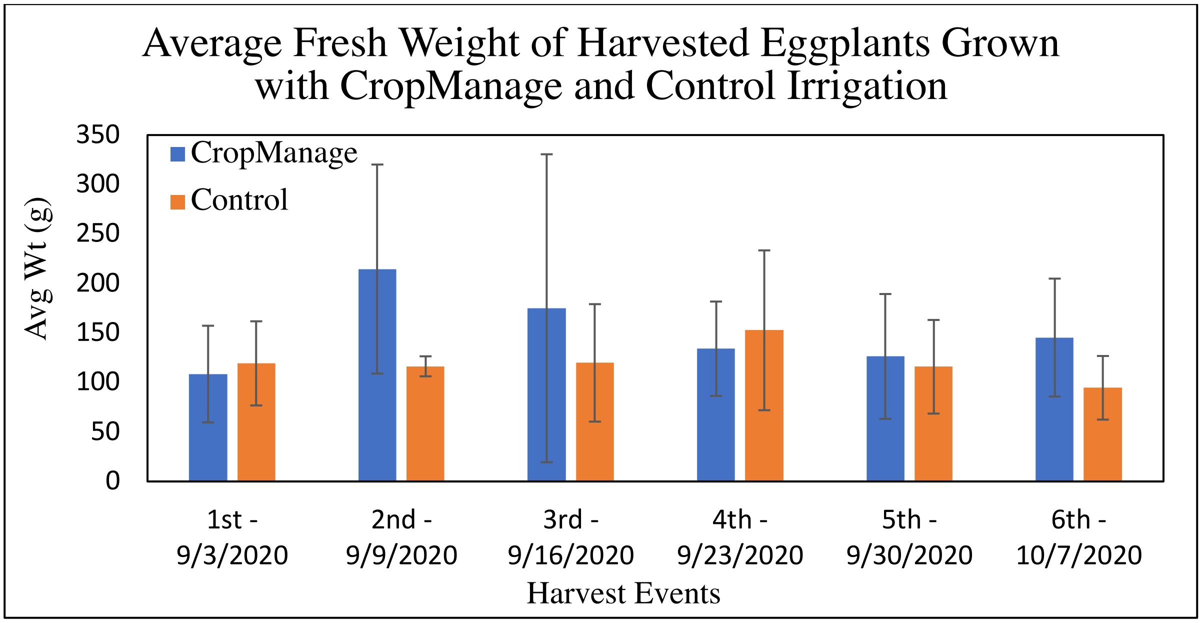


Figure 33. Average fresh weight (g) of harvested eggplants grown with Cropmanage and control irrigation for each harvest events at the UOG Triton farm (September 3 – October 7, 2020)

Whiskers represent the standard deviation of measured weights for each irrigation treatment plot. Figure 33 shows the average fresh weight of harvested eggplants grown with CropManage and control irrigation for each harvest events. To date, there were six harvest events from September 3 to October 7, 2020. In two-thirds of the harvest events, CropManage eggplants produced a greater average fresh weight than control. The second and third harvest events mark the events with highest average weights recorded out of the six events for CropManage while the third and fourth harvest events mark the highest average weights recorded for control. The relative time positions within the 2nd and 4th event may represent the peak harvest time.

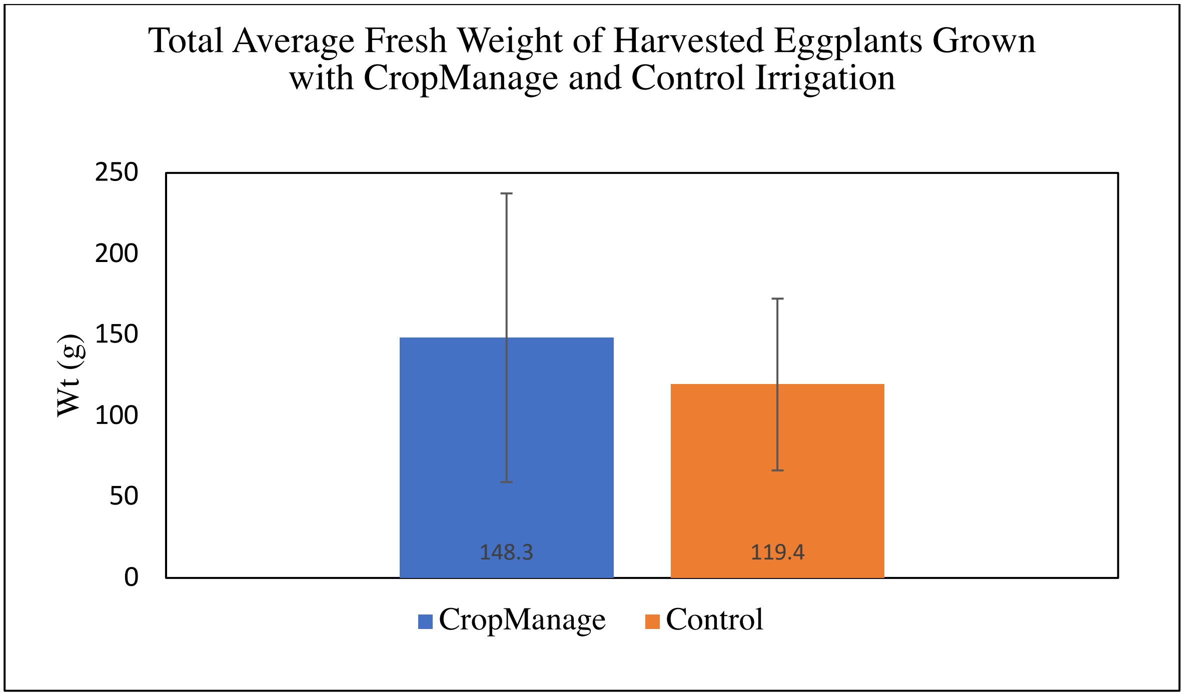


Figure 34A. Total average fresh weight (g) of eggplants grown with CropManage and control irrigation at the UOG Triton farm. Whiskers represent the standard deviation of all measured weights for each irrigation treatment plot

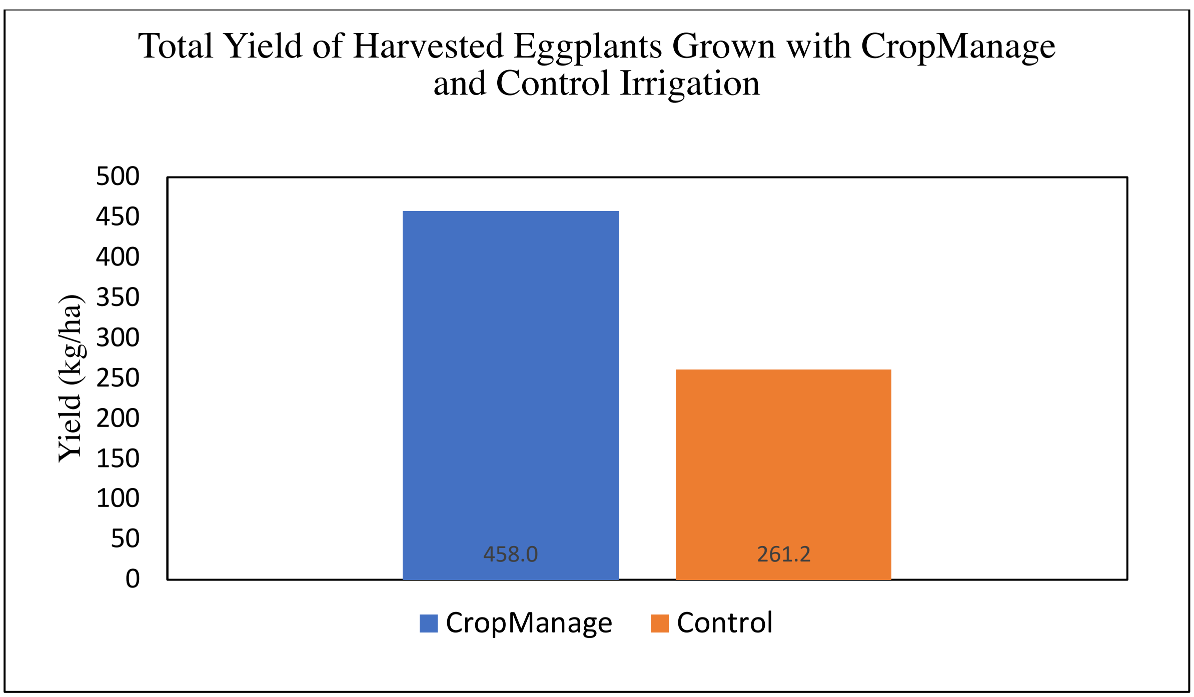


Figure 34B. Total yield (kg/ha) of eggplants grown with CropManage and control irrigation at the UOG Triton farm.

Figure 34A and 34B show the difference between the produce output of eggplants grown with CropManage and control irrigation. Within the six harvest events, a total of 48 produce weight measurements were collected for CropManage (average fresh weight: 148 g ± 89 g), and a total of 34 produce weight measurements were collected for control (average fresh weight: 119 g ± 53 g). Figure 34A shows the total average fresh weight (g) of eggplants for each irrigation setting while Figure 34B shows the total yield (kg/ha). The total crop yield was calculated using the total fresh weight of eggplants grown with both CropManage and control irrigation in their own respective 0.0384-acre plot. Based on the total average fresh weight of CropManage and control eggplants, CropManage produced an average of 28g more eggplants in fresh weight than control eggplants. Based on the total yield of CropManage and control eggplants, CropManage has a great yield than control by 196.78 (kg/ha).

Conclusion and Recommendations

Because CropManage was based upon California regions' agricultural data or modeling algorithms, baseline data (Phase I) specific for Guam are needed and be incorporated in CropManage to generate irrigation recommendations for Guam farmlands. Phase I includes roots, plant canopy cover, and weather measurements. Data collection is ongoing.

During the 2020 data collection (dry season), there was no significant difference with the yield between CropManage and control crops. However, CropManage saved over 13,500 gallons of water. However, there were many complications encountered during Phase I data collection and could affect the models created for Phase II when calculating the crop coefficient (K_C). Although strong Phase I data for eggplants have already been accumulated, Phase I data for other crops such as pepper and tomato may be lacking to produce accurate models. Furthermore, they have not been tested yet in side-by-side trials. The most recent eggplant side-by-side trials show promising results; however, the single trial does not produce conclusive results as to whether CropManage will increase irrigation efficiency during other seasons, with other eggplant varieties, or with other soil types. Phase I data accumulation is needed for all crops of interest to make Phase II models more robust and accurate. Likewise, more side-by-side trials are needed to confer a conclusive statement about CropManage's efficacy when applied in Guam. We also recommend improving crop management technique by correcting issues with pesticide and herbicide applications to improve crop yield. In addition, better quality pressure regulators are be used to avoid irrigation lines leaks or bursts.

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