WHITE PAPER

A System for Closed-Loop Irrigation: Corn



By Jeff Tucker

AgriNET · Tuctronics · Walla Walla, Washington

Contents

Abstract	3
Introduction	3
Corn Experiment: Evapotranspiration and Crop Coefficients	4
Irrigation Control Algorithm	5
Field Preparation	7
Flow Rate Control	11
Resource Mitigation	12
Corn Field Moisture Probe Chart for the Zone Used in the Algorithm	13
Accuracy of the Two Weather Stations	13
Corn Field Irrigation Calculations	14
Importance of Vapor Pressure Readings	17
Soil Rate of Change Analysis	18
Back End Services	20
Correlation of Irrigation Need with IR Leaf Temperature	21
Corn Quantity Assessment	24
Corn Quality Assessment	25
Corn Experiment Conclusion	26
Works Referenced	29

Copyright © 2019 Jeff Tucker. All rights reserved.

Abstract

This white paper describes a closed-loop regulation feedback system based on moisture level. It was used to control algorithms for watering a corn field and a lemon tree (see our other white paper). This experiment demonstrates that it is possible to meet a high standard for yield and production by using moisture sensors to maintain moisture level at a particular soil depth. The ideal moisture level was calculated for a growth period from the flood drought method described in this paper, in order to find the extreme of said characteristics. Specifically, we calculated the soil's water holding capacity and the point at which a plant had been watered to a temporary state of wilt.

This system allows a grower to conserve water while also producing the best possible crop.

Introduction

Consumers want their food to appear perfect and pristine, free from insect damage or discoloration. Consumers also want their food to be safe: free of pesticides, herbicides, and polluted water. These two desires are in direct contradiction of each other; the only way to achieve pristine, perfect crops is to use these chemicals. The alternative is organic food. Unfortunately, there is a very serious problem with the production of organic food in the United States; fish parts are used as fertilizer in many cases, and they contain heavy metals like mercury; when organic foods are tested for heavy metals, they are found to contain traces of mercury. High levels of mercury can negatively impact brain development in young children, and in adults, it can cause brain, heart, kidney, lung, or immune system damage. Proof of this can be found in Brian Baker and Diana Tracy's "Heavy Metals in Fertilizers Used in Organic Production."

There is little current regulation governing the heavy metals in organic foods; thus, when one purchases organic food with the hopes of consuming a purer crop, one is possibly doing the opposite and exposing oneself to heavy metals. Minimizing water use to minimize chemical flushing into the water table will become essential in this battle of contradiction for the marketplace.

We have created a system that will prevent loss of quality or quantity, while maintaining the safety and integrity of the crop. The system outlined in this white paper is also intended to minimize the use of water. Conservation of water is an important issue, but specifically, our goal is to minimize chemical flushing, since this practice is the main perpetrator behind fertilization chemicals being pushed below root level and entering into the water table.

It is important to note that rain also pushes these chemicals down into the soil. When creating an irrigation plan, growers need to account for this phenomenon. Our algorithm takes it into consideration, avoiding oversaturation. It works to prevent permanent wilt in crops, conserve water, and refrain from polluting drinking water with fertilization chemicals.

Copyright © 2019 Jeff Tucker. All rights reserved.

Corn Experiment: Evapotranspiration and Crop Coefficients

Introduction to Evapotranspiration

Evapotranspiration is a combination of water, which is transpired by a plant, and the evaporation of that water. It is calculated via the Ref-ET software from the University of Idaho. There are two kinds of reference evapotranspiration. For this experiment, the mowed, irrigated turf grass model (reference ET) was used. Reference ET can be calculated by tracking weather data through weather stations and using the data values in an equation. This system for calculation comes from the Penman-Monteith equation software. Because reference ET depends on the weather, its value will change over time.

The equation for reference ET involves vapor pressure, surface radiation, heat flux of the soil, air temperature, and wind speed. Because some of these values may not be directly measured by weather stations, other measured values can be used to calculate them. Daily solar radiation, air temperature, and humidity can be used for this purpose, because they have known relationships to the values required by the equation.

Introduction to Crop Coefficients

Crop Coefficient Curves are used to calculate crop-specific water requirements from Reference Evapotranspiration. This information can optimize irrigation and plant uniformity. There is a wealth of research suggesting the benefit of calculating water requirements; however, Crop Coefficient Curves have compromises. Primarily, these CC curves are site-specific to the research plot where they were created. In addition, the number of points provided is usually sparse. The points usually define a curve that does not have the detail required for a smooth transition of water amount through the maturity of the plant. Abrupt changes in water amount are the usual result of using CC curves with a low number of points per season. The variety of the crop used to create the CC is usually different from the variety being grown. CC curves do not exist for every variety; a CC curve is usually only for a general classification of a crop. Crop coefficient creation from moisture-controlled irrigation is the goal of our research.

Copyright © 2019 Jeff Tucker. All rights reserved.

Planting to Harvest	CC1	CC2	CC3	Planting to Harvest	CC
1	0.07	0.07	0.07	1	0.07
1	0.07	0.07	0.22	1.2	0.11
2	0.07	0.22	0.22	1.4	0.14
2	0.22	0.22	0.44	1.6	0.17
3	0.22	0.44	0.44	1.8	0.20
3	0.44	0.44	1.10	2	0.22
4	0.44	1.10	1.10	2.2	0.24
4	1.10	1.10	0.83	2.4	0.26
5	1.10	0.83	0.83	2.6	0.29
5	0.83	0.83	0.44	2.8	0.35
6	0.83	0.44	0.44	3	0.44
6	0.44	0.44	0.44	3.2	0.57
				3.4	0.73
				3.6	0.88
				3.8	1.02
				4	1.10
				4.2	1.12
				4.4	1.09
				4.6	1.02
				4.8	0.93
				5	0.83
				5.2	0.74
				5.4	0.66
				5.6	0.59
				5.8	0.52
				6	0.44

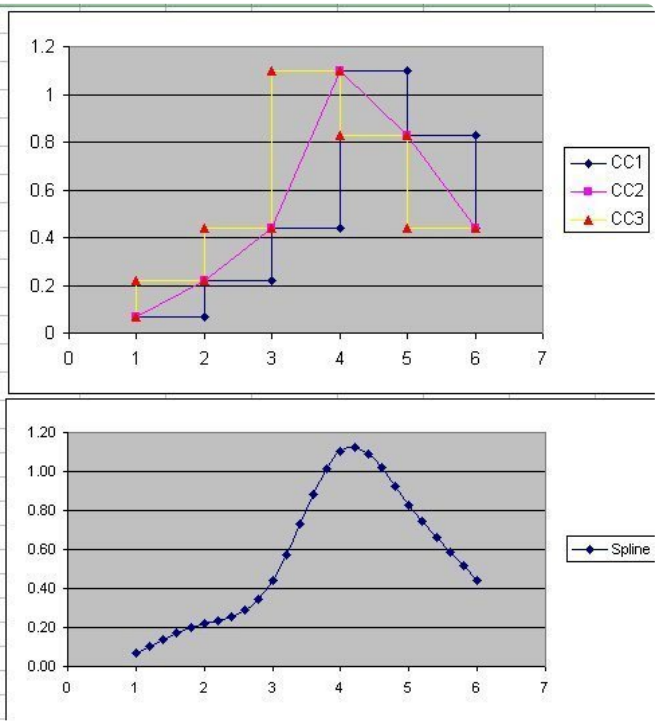


Figure 1. Crop coefficient values by growth stage and the resulting crop coefficient curves.

Irrigation Control Algorithm

The Irrigation Control Algorithm requires the following parameters:

Copyright © 2019 Jeff Tucker. All rights reserved.

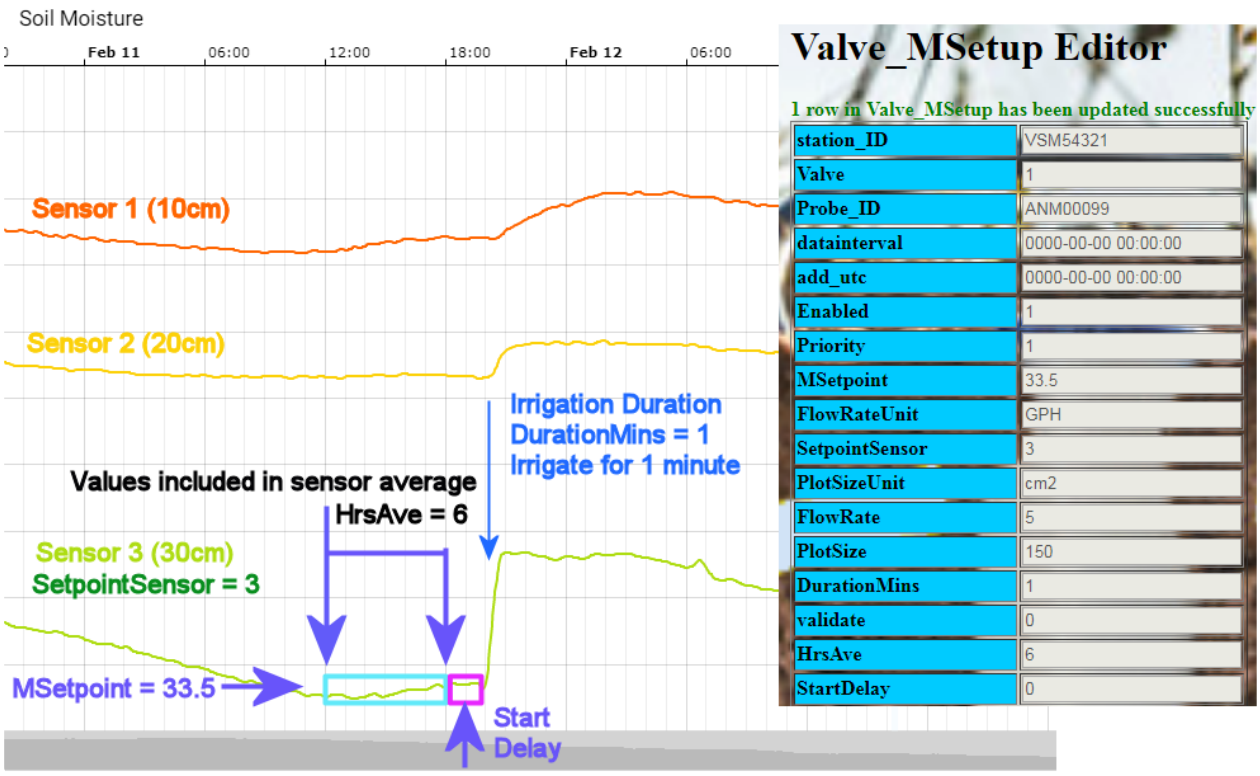


Figure 2. Irrigation control parameters in the AgriNET valve setup editor: the setpoint sensor, moisture setpoint, averaging period, irrigation duration and start delay, shown against the soil moisture readings.

Pivots: Since the only variable with a pivot is rotation speed, there is an inherent efficiency problem. To be energy efficient, the pivot must apply the required water in as few rotations as possible. But this speed calculation is limited because of the need for the water to be applied at a rate slower than the soil drainage rate. If multiple rotations are required to achieve this delivery speed versus amount, electrical efficiency suffers because the pivot must carry a full pipe load of water multiple times.

Drip irrigation: Frequency and duration can be controlled per zone. Drip is highly ideal for closed-loop irrigation.

Other irrigation methods are beyond the scope of this research.

How Parameters Are Chosen for the Corn-Specific Irrigation Control Algorithm

The same control algorithm used in the Lemon Tree experiment (Tucker, 2019) will be used to control the irrigation in zone 3 of the AgriNET cornfield.

Traditionally, managing a soil medium for the sake of maximizing crop production is done through the use of water sensors and a graph. All soil mediums are different. All installations are different, but they all have similarities. One of the first things considered is the rate of infiltration. At some point, water will move down through the profile. We can monitor that movement and control the filling of that profile. One can

Copyright © 2019 Jeff Tucker. All rights reserved.

observe the water uptake of the plants being grown and only fill the profile with water just below that level. As the plant grows and the root system develops, water consumption will increase, and water will need to move lower in the profile. At all times, one must be careful not to over-water and over-saturate the soil.

Gravity is a constant, and it is the greatest force moving water down through the soil profile. Gravity causing water to fill the lower depths, however, is not ideal. Gravity pulls just as hard at the lower depths; we have only pushed the water and nutrients out of the most active root zone. Most irrigation systems are designed to keep up with the demand needs of the plant during peak growth, but our irrigation system works on multiple levels, taking into consideration not only the plant's needs, but also the wellbeing of the water table beneath the plant, as well as conservation of water.

All soil mediums are different, and all installations are different. The numbers used in the management of any profile can vary. The movement of the water is the important factor, not the number. The number is only relative to the movement, either increasing or decreasing (P. Mike Jeffers, 2002).

Field Preparation

Equipment Necessary

- AgriNET Telemetry for all monitoring instruments and valves
- 3 zone control valves (12 volt, 2 wire latching, LTE cellular radio for communications)
- 4 Sentek Drill & Drop moisture sensors
- Well pump water delivery system
- PSI regulation system: AgriNET eValve digital pressure sensor based PSI control
- 2 weather stations: Spectrum WatchDog ET station and Meter Group ATMOS 41 solid state
- 10 ft × 10 ft well-irrigated, mowed turf grass for the ET reference weather station location
- 2 ambient and infrared temperature thermopiles with telemetry
- Solar panels, batteries, mounting poles
- Toro drip tape, 2″ layflat mainline, spaghetti tubing, Clearlocs from Clearwater Supply
- 150 micron and 75 micron sequential filters
- Light spring tooth, rototilled to 6″. Planted with a standard John Deere Flex Planter model 70 depth wheel of x inches.

Copyright © 2019 Jeff Tucker. All rights reserved.

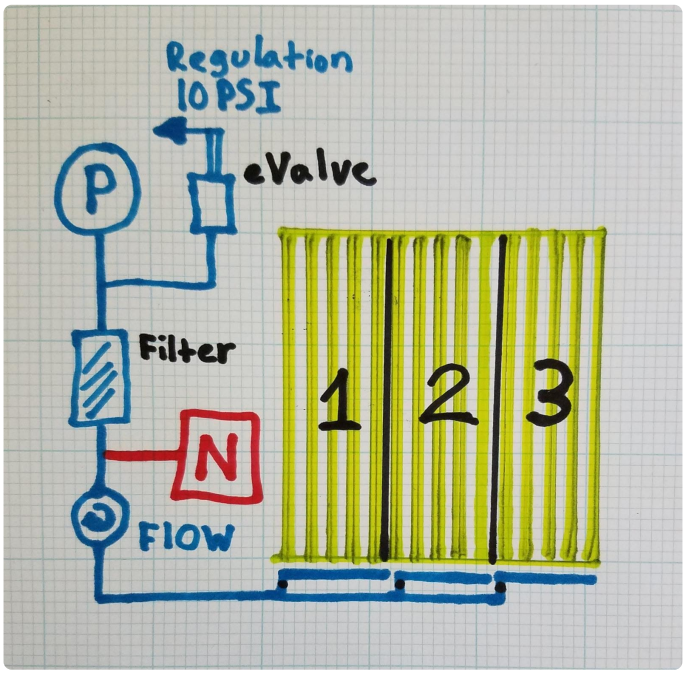


Figure 3. Water delivery: pump, filter, nutrient injection, flow meter and AgriNET eValve pressure regulation at 10 PSI, feeding drip zones 1, 2 and 3.

Dryland Control Plot

Two rows of dryland, non-irrigated corn running 8 feet were planted and monitored with the same Sentek soil moisture monitoring probes as used in the irrigated cornfield and the lemon tree experiment. This was the control and comparison for no irrigation. The chart below is from this plot.

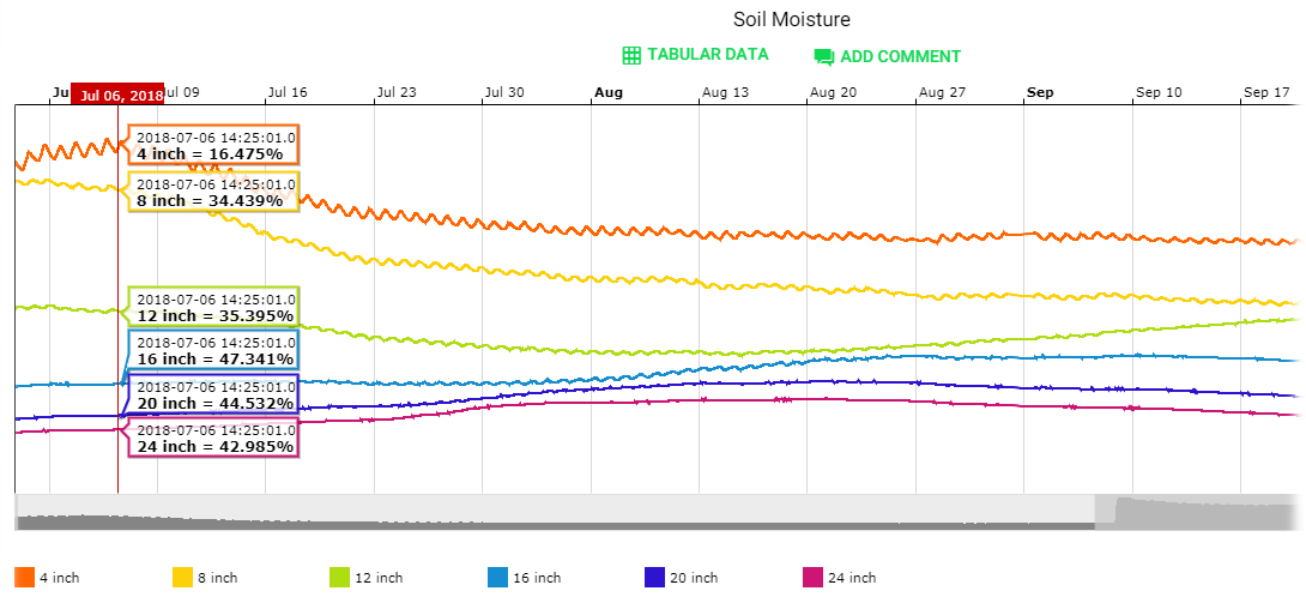


Figure 4. Soil moisture at each depth in the dryland (non-irrigated) control plot.

Copyright © 2019 Jeff Tucker. All rights reserved.

Field Layout

The corn field is 180 feet × 180 feet (54.86 meters). The corn was planted in 2 rows 30 inches (76 centimeters) apart in 6 inch (15 cm) wide beds with 6 inch wide plantless alleys in between each bed.

We had 15 beds of corn. Each bed had two rows of corn, with three runs of drip tape. A central tape and two lateral tapes were used. The drip tape and the corn are all 15 inches (38 cm) apart from each other. There is a corn plant every 6.25 in (15 cm). There is an average of 2.8 ears per plant. Our survival rate was 98%. Each bed is 6 ft by 180 ft (1.8 meters by 54.86 meters).

The irrigation tape emitter spacing was one foot with a flow rate of 0.22 gallons (.83 liter) per minute per 100 ft (30.5 m). 5 mil tape was used. Three drip tapes per bed were used, offset 15 in (38 cm) from the corn rows. See Figure 5.

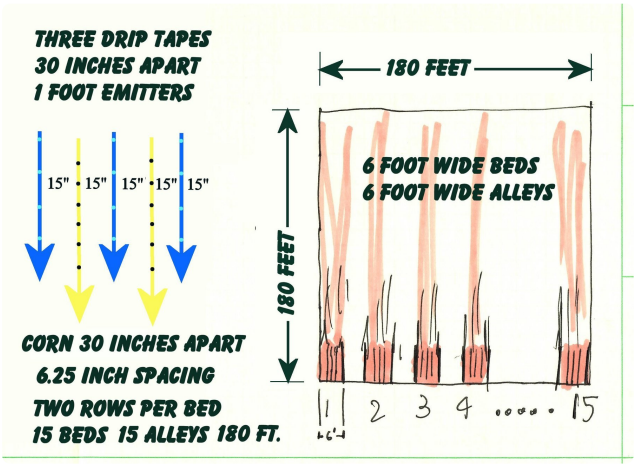


Figure 5. Field layout: three drip tapes 30 inches apart with 1 foot emitters; corn rows 30 inches apart at 6.25 inch spacing; two rows per bed; 15 beds and 15 alleys, 180 feet long.



Figure 6. The corn field with an AgriNET telemetry station.

Copyright © 2019 Jeff Tucker. All rights reserved.



Figure 7. Corn rows with drip tape.



Figure 8. Sprouting irrigation over the seed rows.

One 6 hour irrigation was used directly over both seed rows in the bed with two tapes prior to the triple drip tape installation to sprout the seeds.

We used 4 lbs 2 oz of seed. The photograph of the corn rows (Figure 7) is from 85 days before the corn was ready for harvest.



Figure 9. Label from the corn seed bag (SE Yellow Bodacious R/M) and the treated seed.

Copyright © 2019 Jeff Tucker. All rights reserved.

Flow Rate Control

The accuracy of the flow rate was achieved by using clean water, an AgriNET eValve regulation system for constant PSI, and two levels of filtration. Flow meter validation was used to verify the regulation system.

Weather validation was achieved by using 2 different weather stations. One was a traditional Spectrum WatchDog; the second was a Meter Group ATMOS station. ET stations must be on mowed, irrigated turf to be accurate for reference ET. Our corn crop also shows good uniformity in the photo.

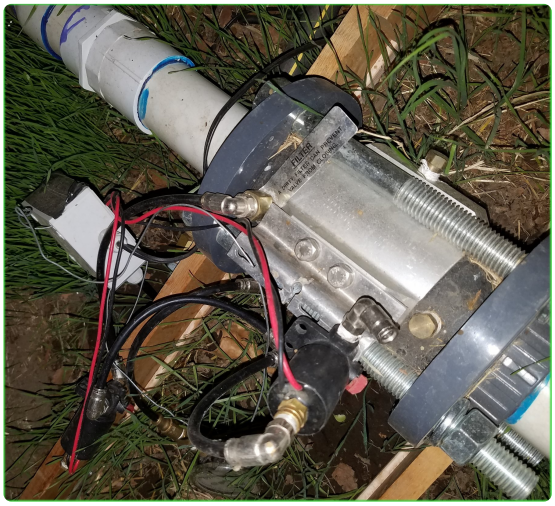


Figure 10. Flow meter and pressure regulation hardware.



Figure 11. Weather station on mowed, irrigated turf beside the corn.

Copyright © 2019 Jeff Tucker. All rights reserved.

Resource Mitigation

The original system has a resource mitigation subsystem that decides the amount of available water distributed according to priority to the needed irrigations for that day. The priority is determined by the proximity of current average moisture to the wilt point moisture. Cornfield zones that are closer to triggering irrigation according to their target moisture average will have higher priority, and therefore will be scheduled before trees or zones having an average moisture level that is farther away and above the target.

In other words, the system decides the order in which the plants will be irrigated, and the priority is simply determined by the threat of wilt. The threat of wilt is quantified by how close the current average moisture is to the irrigation target for that particular lemon tree.

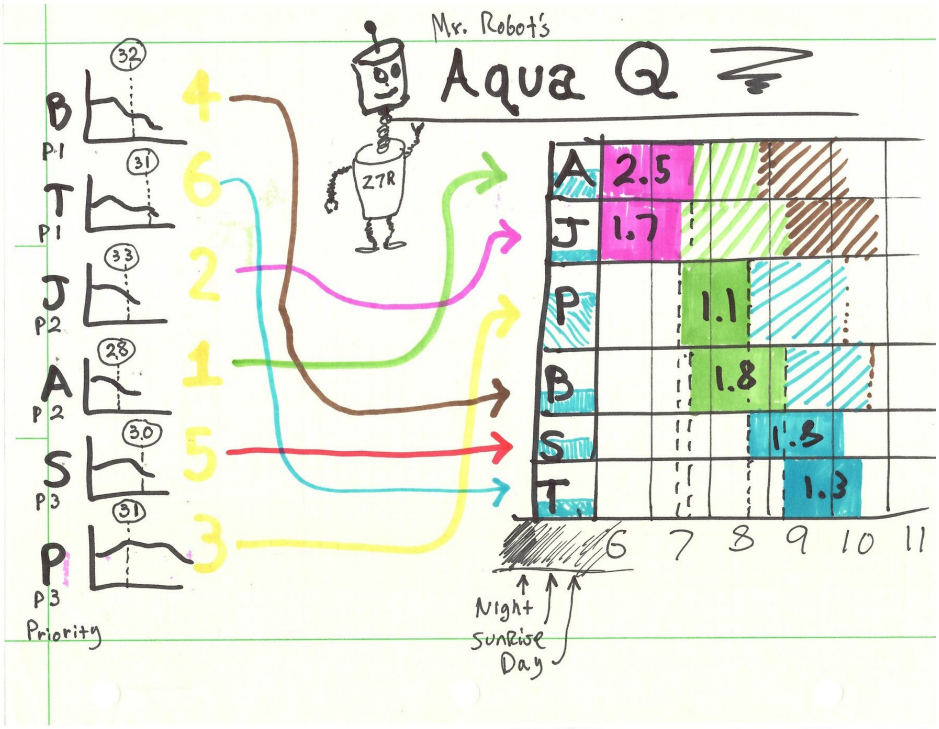


Figure 12. Resource mitigation concept: zones are ranked by how close they are to their wilt threshold, and the available water is scheduled in priority order.

Copyright © 2019 Jeff Tucker. All rights reserved.

Corn Field Moisture Probe Chart for the Zone Used in the Algorithm

The light blue line represents the sensor placed at the 16 inch level. This is the sensor used to control the irrigation. The chart shows no water going past the 24 inch (60 cm) sensor. This is essential so no chemical is flushed down into the ground below the corn roots. The vertical blue bars are the irrigations. Usually there were two irrigations of 6 hours each, with a 4 hour delay before the zone was eligible for irrigation again.

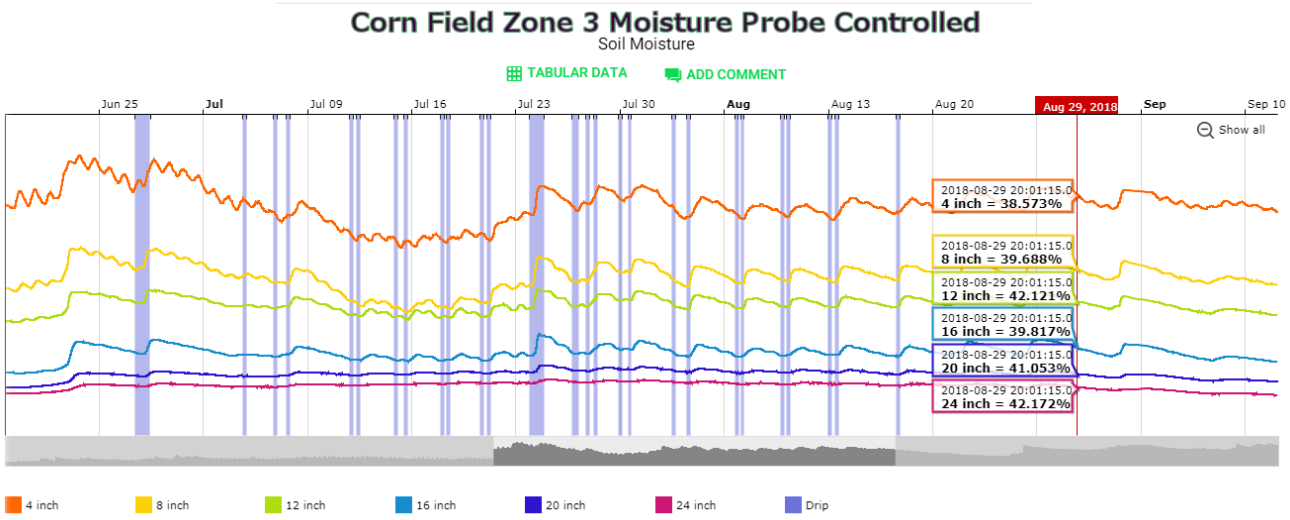


Figure 13. Corn field zone 3, moisture probe controlled. Vertical bars are irrigation events.

Accuracy of the Two Weather Stations

The weather station pair is evaluated by comparing the readings of each to see the degree to which they differ. Graphing of the weather readings shows that the Spectrum and ATMOS stations closely follow each other in both air temperature and humidity readings. Two stations also ensure that our weather data is solid, as our next calculations depend on it. It is essential that reference ET calculations are based on a weather station placed 2 meters above a 10 × 10 ft (3 × 3 m) area of mowed, well-watered grass. Otherwise, if placed over dry soil, a more arid condition will seem to exist and degrade the weather station reference ET calculations.

Copyright © 2019 Jeff Tucker. All rights reserved.

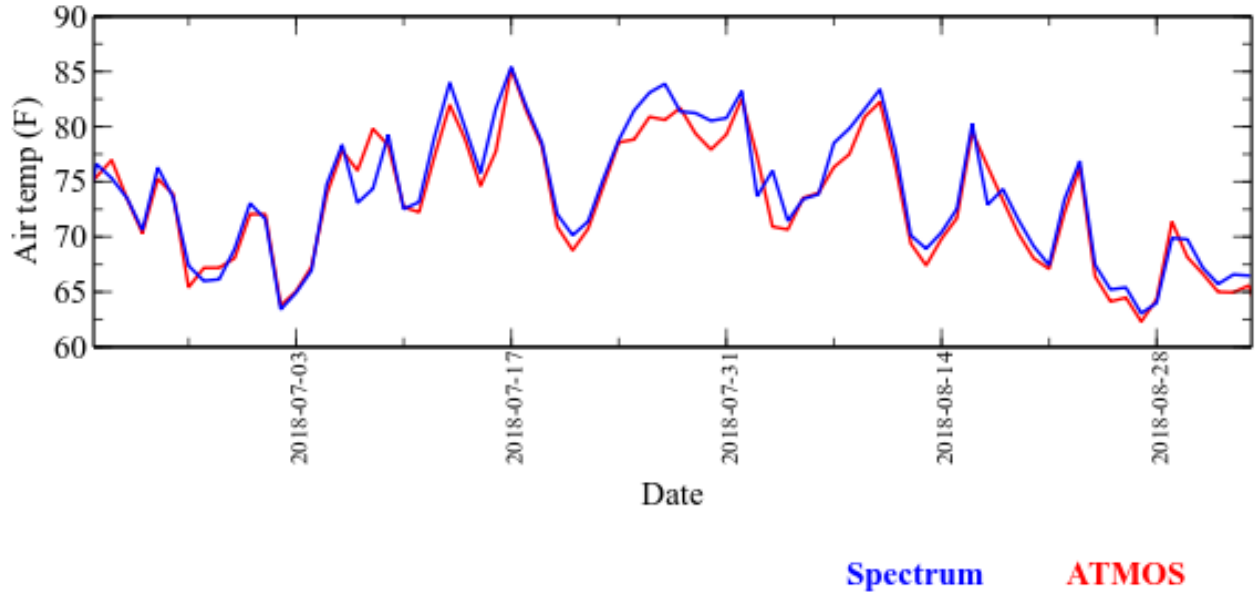


Figure 14. Spectrum and ATMOS air temperature reading comparison.

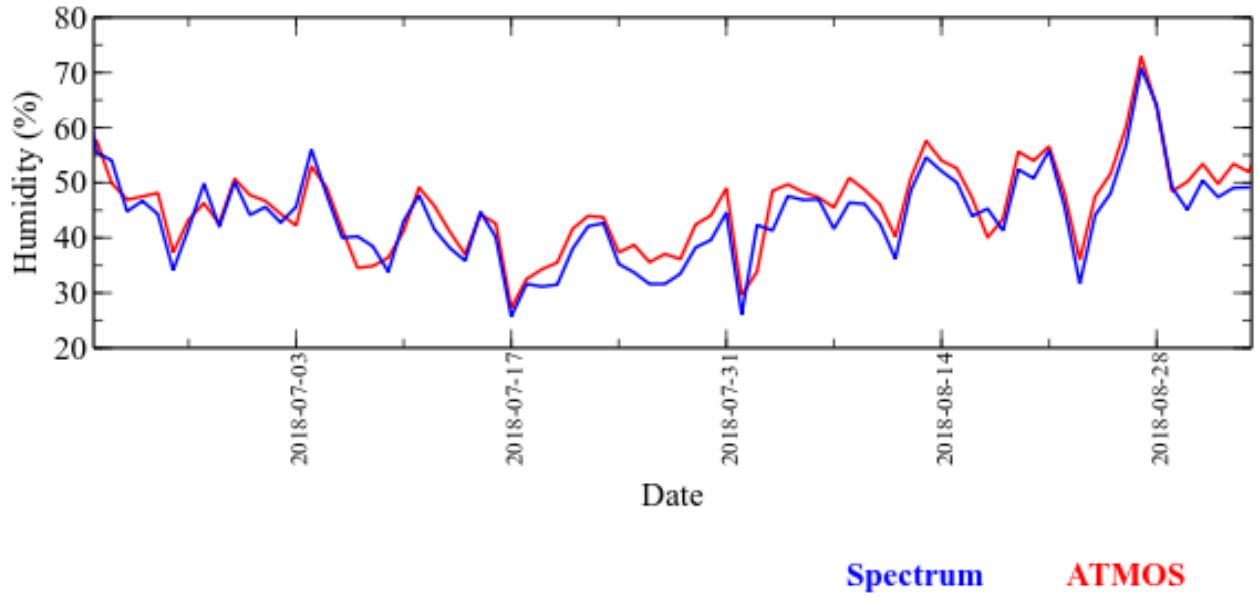


Figure 15. Spectrum and ATMOS humidity reading comparison.

Corn Field Irrigation Calculations

Our plot is 45 ft (13.7 meters) × 180 ft (55 m). We had 15 beds of corn. Each bed had two rows of corn, with three strands of drip tape. The drip tape and the corn are all 15 inches (38 cm) apart from each other. There is a corn plant every 6.25 in (15.87 cm). There is an average of 2.8 ears per plant. Our survival rate was 98%. Each bed is 6 ft by 180 ft (1.8 by 54.86 m).

Copyright © 2019 Jeff Tucker. All rights reserved.

Procedure for Creating a Daily Crop Coefficient

1. **Attain reference ET for all data points.** Input weather data into the Ref-ET software.[1] Ref-ET outputs the reference ET of grass for each weather measurement.

2. **Attain daily reference ET.** Output of reference ET is in inches per hour. To find total daily ET, one hourly value of ET_{ref} must be taken for each hour of the day. Thus, 24 values of reference ET are summed for each day. Values are taken as close to hourly as possible. When there is no data for a given hour, the data is copied from an adjacent hour. When there are multiple hours in a row with no data, data is copied from an adjacent day. Each sum of 24 hourly values is the daily reference ET in inches.

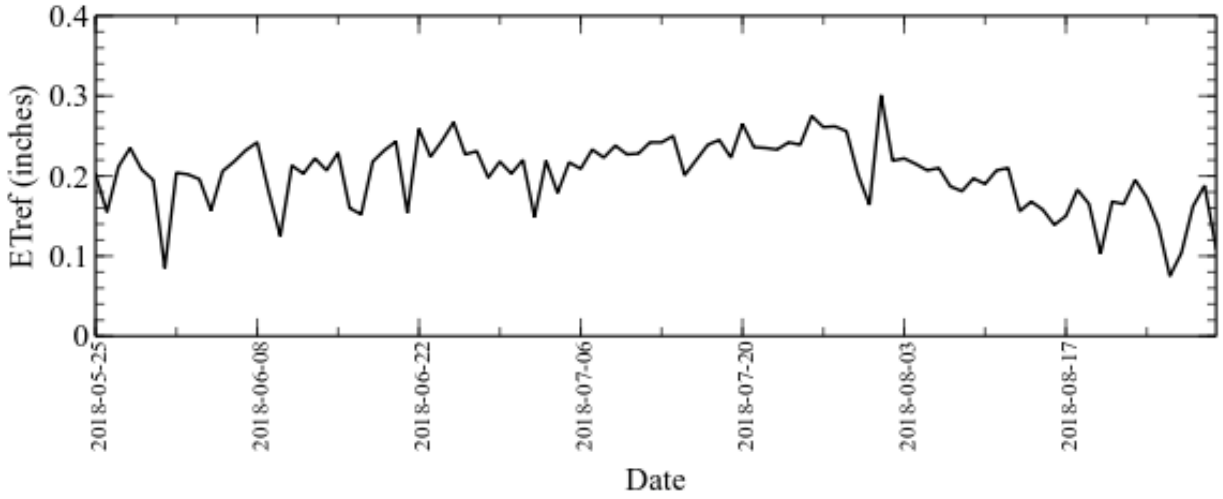


Figure 16. Daily reference ET.

3. **Interpolate irrigation data.** The sporadic watering schedule is smoothed out to create a continuous irrigation curve. A rolling average is taken from a sample of 15 days. For each day, the average irrigation amount is taken from 7 days in the past to 7 days in the future. The smoothed irrigation curve retains the same total water volume as the original data.

1. Reference Evapotranspiration Calculator. Accessed from the University of Idaho webpage: https://www.uidaho.edu/cals/kimberly-research-and-extension-center/research/water-resources/ref-et-software. Authored by Richard G. Allen, Ph.D., University of Idaho, 2018.

Copyright © 2019 Jeff Tucker. All rights reserved.

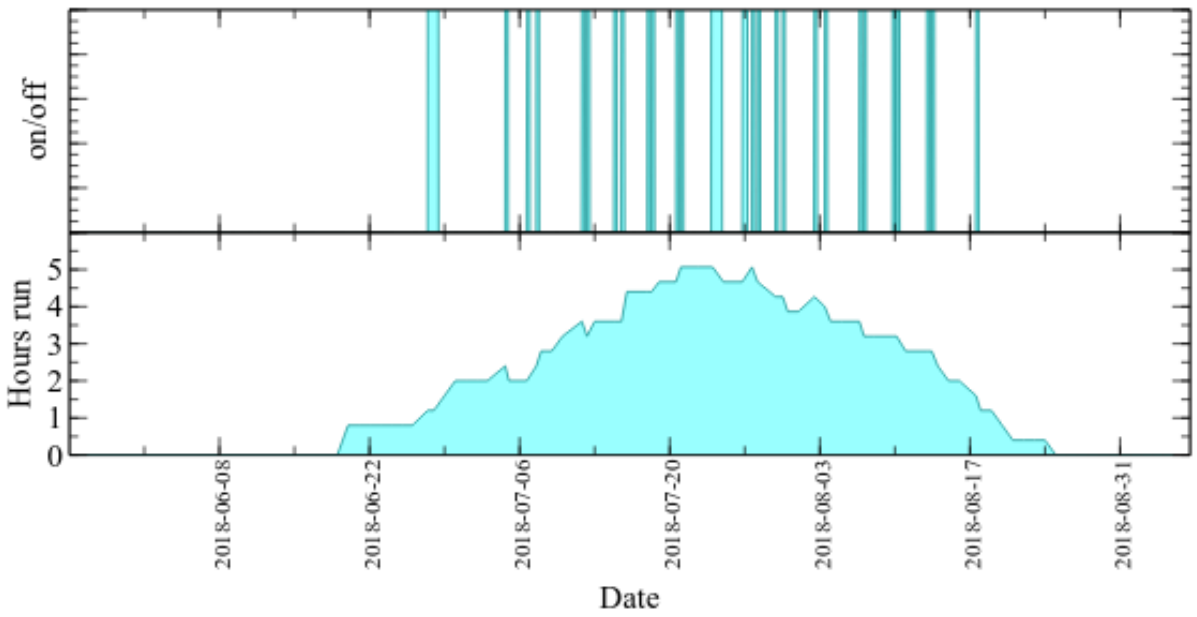


Figure 17. Actual irrigation (top) and average irrigation (bottom).

4. **Convert irrigation units.** The irrigation data is recorded as hours of pumping water. To compare irrigation amounts to reference ET, irrigation must be expressed in inches. The flow rate of the drip tape used is 0.22 gallons (83.39 litres) per minute for every 100 ft (30.48 m).

   > 0.22 gal min^{-1} per 100 ft = 0.0022 gal min^{-1} ft^{-1}
   > 45 × 180 ft drip tape × 0.0022 gal min^{-1} ft^{-1} = 17.82 gal min^{-1}
   > 17.82 gal min^{-1} × 60 min hr^{-1} = **1,069.2 gallons per hour**
   > Plot area: 180 ft × 90 ft = 16,200 ft^2
   > 16,200 ft^2 × (1 acre / 43,560 ft^2) = **0.371900826 acres**
   > 1,069.2 gal hr^{-1} ÷ 0.371900826 acres = **2,874.96 gallons per hour per acre**
   > 2,874.96 gal hr^{-1} $acre^{-1}$ × (1 acre-inch / 27,154 gal) = **0.105876152 inches per hour**

   This rate is multiplied by each daily irrigation time to attain the daily irrigation in inches.

5. **Find the crop coefficient.** For each day, the crop coefficient is obtained by dividing daily irrigation by reference ET.

Copyright © 2019 Jeff Tucker. All rights reserved.

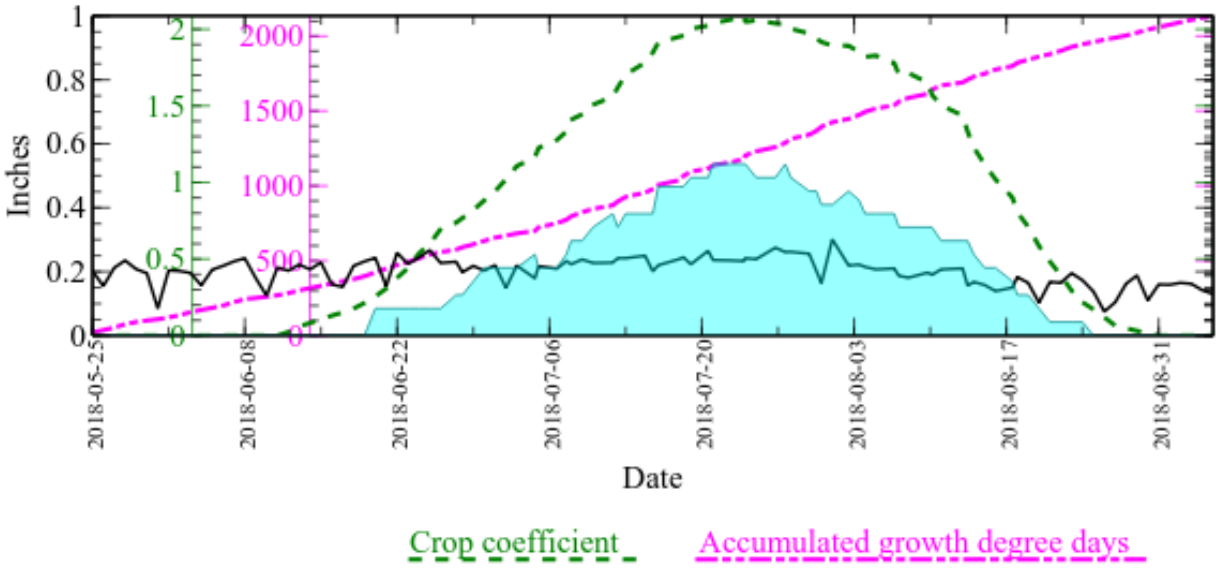


Figure 18. Irrigation compared to reference ET, with the crop coefficient and accumulated growth degree days.

6. **Find accumulated growth degree days.** Until this point, the CC values represent values for days since planting. The CC values of days since planting need to be re-correlated with the AGDU so the maturity of the corn can be a factor in the water amount. The final CC daily table will be the daily coefficient to use per AGDU value on that day. See Figure 18, where the crop coefficient is plotted with AGDU.

Accumulated growth degree days are found through the process described by NDAWN:[2]

- Weather data is limited between 50° F (10° C) and 86° F (30° C) to eliminate growth stress due to temperatures. These are the cold and heat extremes which harm corn growth.
- The average temperature is attained for each day.
- 50° F is then subtracted from each average temperature to attain the **growth degree days**.
- Growth degree days are then added cumulatively to attain the **accumulated growth degree days**.

Importance of Vapor Pressure Readings

ET_0 is calculated with and without vapor pressure data to determine the value of vapor pressure readings in calculating ET. If ET calculations with vapor pressure are similar to ET calculations without vapor pressure, it can be concluded that vapor pressure data is not necessary to calculate ET.

2. North Dakota Agricultural Weather Network. AGDD process accessed via the NDAWN webpage: https://ndawn.ndsu.nodak.edu/help-corn-growing-degree-days.html. North Dakota State University, 2018.

Copyright © 2019 Jeff Tucker. All rights reserved.

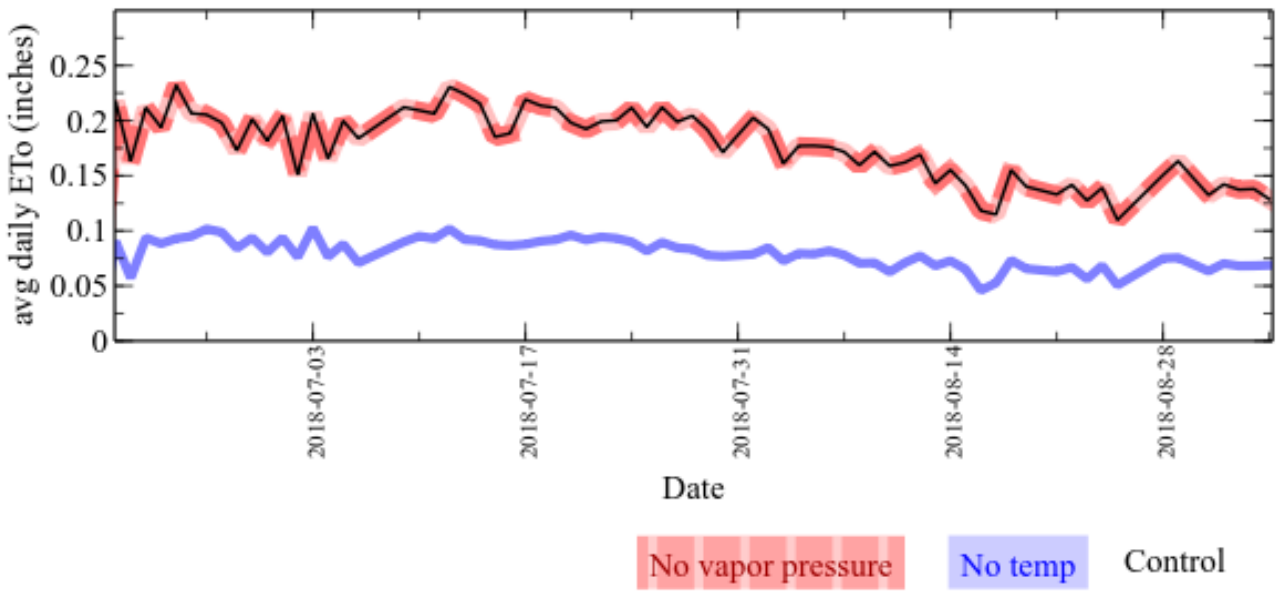


Figure 19. Vapor pressure effect on daily ET (ASCE stPM).

As shown in Figure 19, calculations with vapor pressure removed were 98.4% identical to ET_0 control calculations.[3]

When vapor pressure is absent, it is estimated by using temperature data.[4] ET_0 is evaluated with temperature data removed to show the importance of temperature readings.

Temperature data is seen to be much more important to the ET_0 calculation than vapor pressure data. When temperature data is removed, ET_0 output was only 48.6% identical to control calculations.[5]

Soil Rate of Change Analysis

The purpose of showing the soil moisture rate of change (first derivative) is to determine when the rate was at its maximum. This is possibly the maximum infiltration rate for that level using the water amounts calculated.

3. Uses the ASCE stPM equation for ET_0. Calculations were 98.3% identical when using FAO 56PM.

4. Described in the Ref-ET user's manual, pp. 59–62.

5. Using ASCE stPM. 48.0% identical when using FAO 56PM.

Copyright © 2019 Jeff Tucker. All rights reserved.

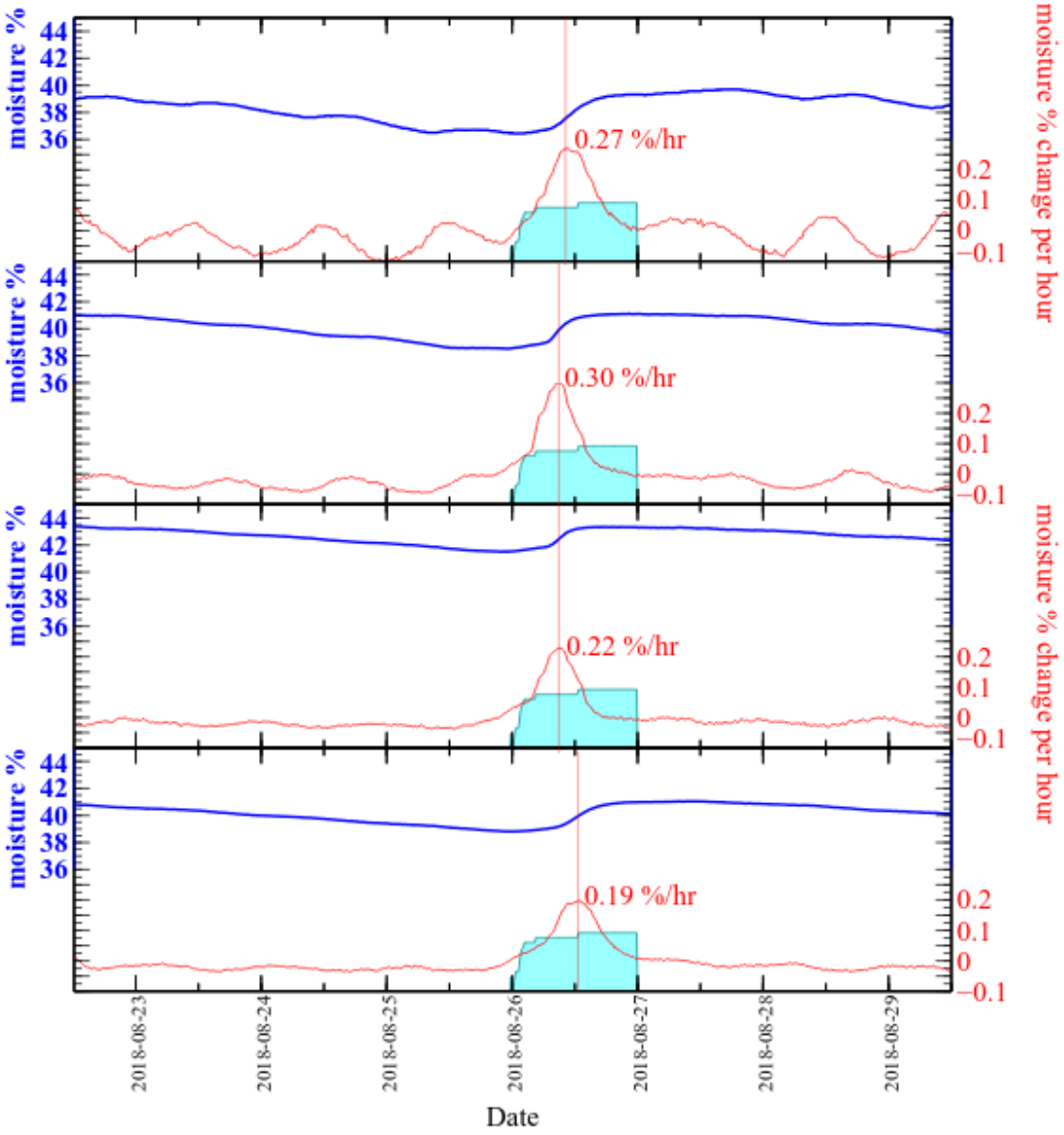


Figure 20. Soil moisture rate of change (first derivative) at 4, 8, 12 and 16 inches.

Figure 20 shows the rate at which soil moisture changes, in percent per hour. The cyan bars on each plot indicate accumulated rainfall. Moisture is read at 4 inches (10 cm), 8 inches (20 cm), 12 inches (30 cm), and 16 inches (40 cm) deep into the soil. The red lines indicate the maximum rate of moisture change for each soil level, also known as the maximum infiltration rate. This helps us see the values of maximum infiltration and the time at which they occur.

Copyright © 2019 Jeff Tucker. All rights reserved.

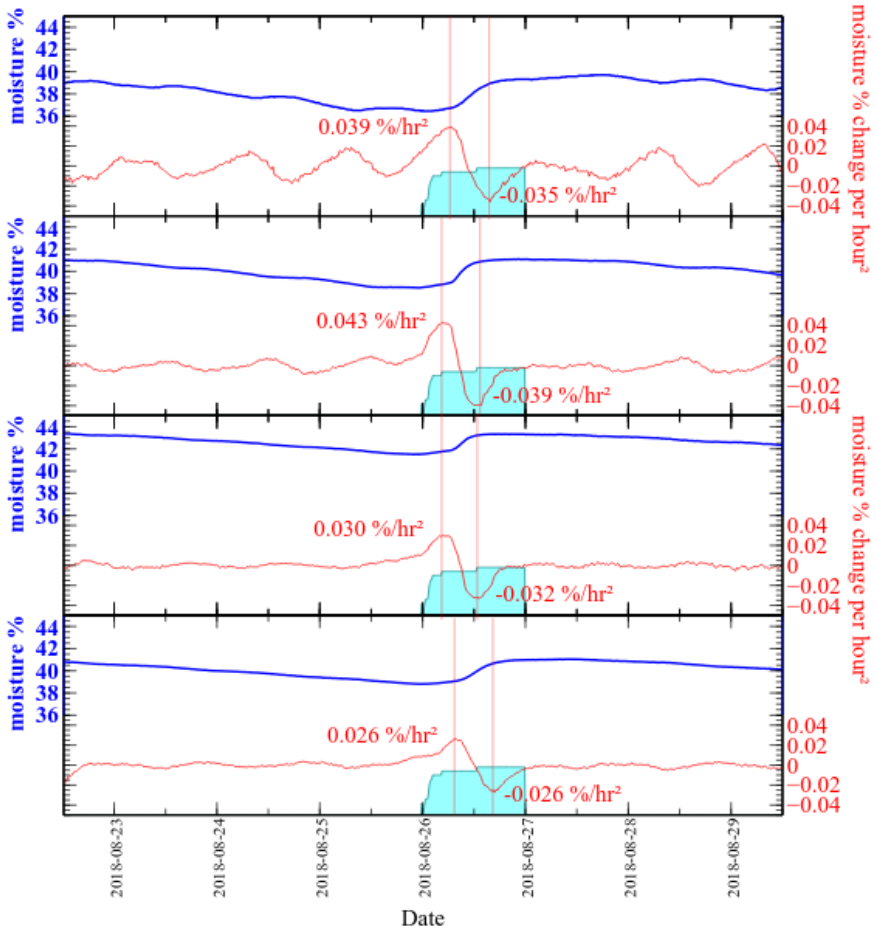


Figure 21. Second derivative of soil moisture.

This is the second derivative of soil moisture, which shows the acceleration maxima and minima for the infiltration rate changes. By identifying the highest and lowest points of the data, we can determine when the soil moisture was changing the fastest, and how fast it was changing at those times. An extreme positive value peak corresponds to the maximum change in the gain of moisture, and an extreme negative value peak corresponds to the fastest decreasing rate of gain of moisture. This data can help determine the ideal pulse time for irrigation by utilizing the rates for a controlled vertical flow.

Back End Services

The corn field sends several transmissions of multi-depth moisture data per hour. The back end server, also known as the Saturn server, looks at the moisture monitoring data from the moisture probe hourly. It compares that value, or series of values, and averages them together according to the parameters set by the irrigation control algorithm.

Copyright © 2019 Jeff Tucker. All rights reserved.

Once per hour, the moisture information is uploaded from the database into the server algorithm for a particular corn field zone. This data is then averaged based on the averaging period parameter in the database for that zone. Each zone has its own set of parameters for the irrigation algorithm. The back end server considers the moisture average for a particular zone against the set of parameters specific to that lemon tree or group of trees.

Every hour, each zone registered in the valve setup database table will be evaluated by the server moisture algorithm. If the valve for that zone is set up as “on demand,” then the valve will open as soon as the condition of moisture level is met for the algorithm for that tree. If the valve is set as “priority based,” then the irrigation will occur according to a schedule created by the resource mitigation system, starting at 6 in the morning.

The valve control system will examine the valve schedule table once a minute for valves that need to be turned on. Essentially, the schedule table includes the valve name, when to turn the valve on, and how long to leave it on. The valve control system running on the AgriNET Saturn server sends a command through a static IP and port. All the field equipment connects regularly as TCP/IP clients. The valve control system is a TCP/IP server that remains connected to all the remote valve control boxes as the valve control system examines the valve schedule every minute. As it finds valves that need to be turned on, it sends a control message to that valve. The valve will respond with a validation. If the valve does not respond, it will trigger a maintenance call to a technician through email SMS, which is simply sending an email to a mobile phone’s SMS service by using a particular email suffix provided by the particular mobile carrier. For example, Verizon SMS can be sent as an email from a computer by using the (phone number)@v3g.com suffix. If the valve unit responds correctly, then the valve control will open the valve and then close that particular valve at the appointed time. In this citrus tree experiment, the valves were opened for a one minute interval, yielding 11.5 oz (340 litres) water per minute.

Correlation of Irrigation Need with IR Leaf Temperature

The purpose of this trial is to answer this question: can the need for irrigation be determined from ambient and infrared leaf temperature?

Dry corn leaf and irrigated corn leaf infrared data is plotted for possible correlation between the irrigation cycle and irrigated leaf temperature as related to the dry leaf temperature. When the ambient temperature is the same at both the dry and the irrigated monitoring sites, the leaf infrared measurement is at its highest accuracy and precision. During these times of identical ambient temperature, the trial seeks to determine if the irrigated leaf shows a pattern of temperature attributable to an irrigation event. Just as the temperature needs to rise to indicate the possible need for water, the temperature must also be expected to drop after irrigation is applied, or there is no range of leaf temperature suitable for irrigation management via infrared leaf sensor values. The vertical blue bars are the irrigation events.

Copyright © 2019 Jeff Tucker. All rights reserved.

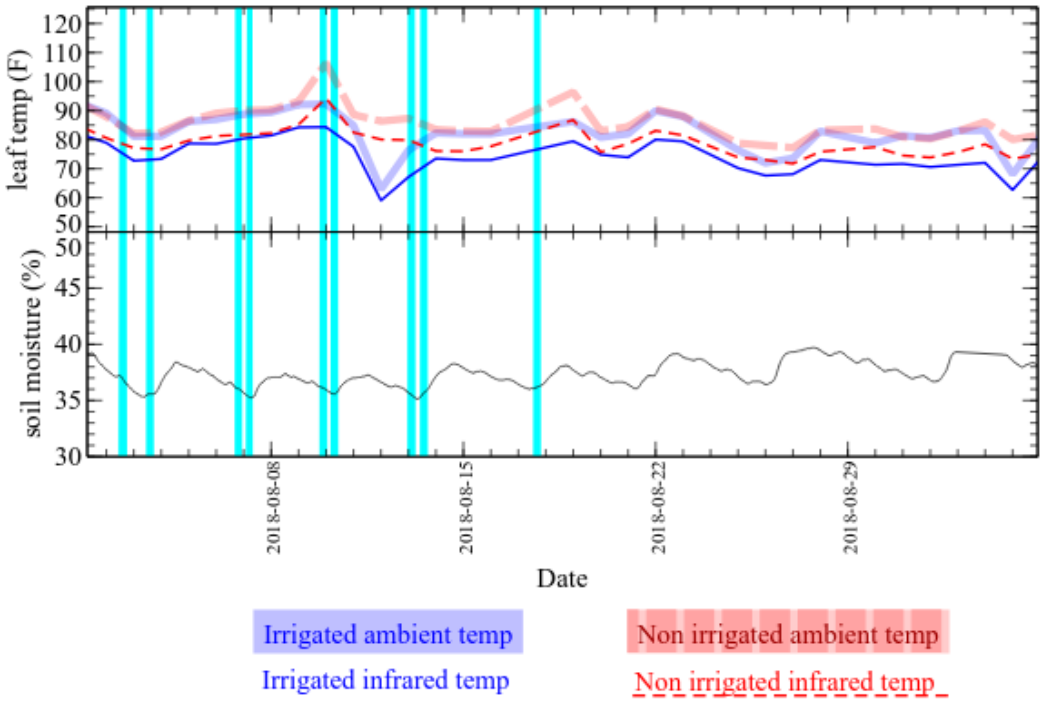


Figure 22. Effect of irrigations on leaf temperature.

Copyright © 2019 Jeff Tucker. All rights reserved.

Figure 22 shows ambient air temperature and infrared leaf temperature for both the irrigated and non-irrigated leaf. This helps us observe how irrigations change leaf temperature from the baseline. Vertical cyan lines indicate the irrigations. The irrigated leaf, represented by the solid blue line, would be expected to react to the irrigations, while the non-irrigated leaf, represented by the solid red line, would not.

As Figure 22 shows, the irrigated leaf temperature closely follows the ambient temperature regardless of irrigation. No significant pattern can be seen between the irrigations and temperature changes, so we can conclude that leaf temperature is not an appropriate indicator for need of irrigation.



Figure 23. Real-time infrared sensor sending data to the AgriNET Saturn server database.

Copyright © 2019 Jeff Tucker. All rights reserved.

Corn Quantity Assessment

346 plants per row	**1,038** plants per bed
1,5576 plants in experiment	**2.2** ears per plant
98% survival rate	**63,051** ears per acre (5,254 dozen)

- The corn was sold commercially at Andy's Market, a very selective local grocery store known for its high produce quality. A quote from the father of Andy's Market Produce Manager: *"This is the best sweet corn I've had in three years."*
- 40 boxes (1,600 lbs) were sold to Andy's Market for $.30 per ear.
- 22 boxes of topped ears were donated to the Christian Aid Center.
- The remainder of the corn was donated to the local high school foreign language department for a charity sale, with the proceeds going to support student travel.

Copyright © 2019 Jeff Tucker. All rights reserved.

Corn Quality Assessment

Seed Watering, Sprout and Root Health Verification



Figure 24. Seedling root development.



Figure 25. Sprouted seed with healthy roots.

Copyright © 2019 Jeff Tucker. All rights reserved.

Uniformity of Kernel Rows



Figure 26. An ear from the irrigated plot.



Figure 27. Husked ears showing uniform kernel rows.

Our corn won first place in the corn category at the Walla Walla County Fair, as well as champion in the horticulture category at the Southeast Washington Fair.



Figure 28. Champion ribbon.

Corn Experiment Conclusion

The purpose of this experiment is the generation of Crop Coefficient curve points for this variety of corn in this soil. In the corn experiment, the corn zones are permitted to require water on demand as soon as the algorithm calculates true for water need. The irrigation can be delivered without delay. There is no resource mitigation required for the corn experiment, as all zones can be irrigated simultaneously with the existing

Copyright © 2019 Jeff Tucker. All rights reserved.

system. Also, the results of the corn experiment are not complicated by a priority variable for competition for water resources, but rather simplified to reflect only the water requirements of the corn itself, and to irrigate the corn on demand in real time, as the algorithm is triggered.

Using the method outlined above, a corn field could be characterized and irrigated from a soil moisture probe and a weather station using the CC curve generated for that location's soil type. Once the CC curve is generated, it can be used with a weather station to calculate site-specific irrigation.

The dryland corn suffered from lack of water and did not yield viable ears. The plants reached only ⅓ the height of the irrigated plants. As soon as initial groundwater was depleted, the dryland corn began to show water stress until the end of the season (see photo below). To validate the corn experiment, the crop coefficient table created must be used with a weather station to produce a field of corn and compare.



Figure 29. Irrigated corn.



Figure 30. Corn plant in the field.



Figure 31. Tasseling corn.

Infrared Leaf Temperature

A correlation between infrared leaf temperature and soil moisture level could not be found. Since the irrigation was driven by soil moisture, this suggests that there was no correlation between infrared leaf temperature and the requirement for irrigation. Infrared leaf temperature did vary, and possible correlations could be found with further data analysis, but generally speaking, an irrigated plant as in this test is at a cooler temperature than a non-irrigated plant, yet does not change sufficiently with the irrigation cycle for any correlation. In this experiment, both an irrigated plant and a non-irrigated plant had their leaves monitored with identical infrared temperature sensing equipment. See the infrared charts above.

Copyright © 2019 Jeff Tucker. All rights reserved.

Future Experiments

In future experiments, some generic qualifying measurements for growth could be the following:

- Biomass root ball size
- Root health
- Leaf size and count
- Leaf water content
- Bud emergence
- Stem size and rate of increase
- Fruit density and count
- Fruit size
- Fruit weight
- Fruit quality as measured by sugar concentration or another parametric value

Copyright © 2019 Jeff Tucker. All rights reserved.

Works Referenced

Allen, Richard G. *Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements.* FAO Irrigation and Drainage Paper 56. (1998). Accessed via http://www.fao.org/3/X0490E/x0490e00.htm

Allen, Richard G. *Ref-ET Software.* Accessed by request via https://www.uidaho.edu/cals/kimberly-research-and-extension-center/research/water-resources/ref-et-software

Baker, Brian, and Diana Tracy. "Heavy Metals in Fertilizers Used in Organic Production." (2004, February 14). Accessed via ResearchGate.com.

Jeffers, P. Mike. "Proposal for Automated Irrigation System to the Hutterian Brethren." (2002). Simplot Archives, Simplot Office in Bruce, Washington.

Tucker, Jeff. "A System for Closed Loop Irrigation: Citrus." (2019). Accessible via ResearchGate.com.

Copyright © 2019 Jeff Tucker. All rights reserved.