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Final Report: Agricultural water conservation through an automated system for monitoring soil moisture and controlling irrigation using low-cost microcontrollers

Texas Water Development Board Contract 1713582116

Prepared for:

Texas Water Development Board

Prepared by:

Mengmeng Gu, Ph.D.

September 2021

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Executive summary

Texas has 218 container nursery plant producers with 46,750 acres, which use 776,321,000 gallons of water. And other open field horticultural crops use19,641,391,000 gallons of water (USDA census of agriculture, https://www.nass.usda.gov/Data_and_Statistics/index.php). Most waters were groundwater from wells. Most of the irrigation is turned on and off at a specific time of the day with a timer-based controller. To evaluate and demonstrate the water-saving of the sensor-based technology, this project presented and compared the sensor-based and traditional timer-based to improve water use efficiency, conserve water in nurseries, and improve container-grown plant quality in the Gulf Coast. Four irrigation treatments were set up with four rows, and one soil moisture sensor was placed in a pot in the middle of each row. A timer or the sensor-based controller controlled the irrigation of each row. Wax ligustrum and 'Clara' Indian hawthorn were selected test plants. The irrigation system worked well both on sensor-based and timer-based irrigation. The irrigation system can be triggered when the sensor's soil moisture reading reaches the set point. The sensor readings can be updated and communicated with the software properly. Growers can monitor the soil moisture anytime anywhere through the website or mobile phone APP, saving labor costs. The plants grew well in all the treatments. The canopy width, plant height, and growth index are not significantly different between the sensor-based and timer-based treatments, except that the fresh shoot weight of zone 2 (18%-23%) was considerably higher than others.

There were significant in-group variances, which could be caused by ununiform irrigation and clogging. The reason could be the frequent clog of drippers. It is essential to install a filter system to avoid clogging of the dripper to achieve better performance of sensor-based irrigation.

1 Introduction

Texas has 218 container nursery plant producers, accounting for a $ 162,244,186 sales value in 2019. Due to the limited volume of the container, plants production in containers requires frequent irrigation to maintain optimal crop growth and quality. In 2018, 27,147,463,000 gallons of water were irrigated for 46,750 acres of nursery and other horticultural crops grown in the open field of Texas, of which 19,641,391,000 gallons were groundwater from wells; and 776,321,000 gallons of water for nursery and other horticultural crops under protection (USDA census of agriculture, https://www.nass.usda.gov/Data_and_Statistics/index.php). Most of the irrigation is turned on and off at a specific time of the day with a timer-based controller.

It is reported that daily water applications to dogwood and red maple trees were reduced by 63% and 33% when using sensor networks and automatic irrigation control systems, without affecting the growth of either species (Belayneh et al., 2013).

Plants have been reported to grow faster and healthier. Sensor-based irrigation in cut snapdragon production increased profits by 65% per year by improving quality and reducing production time per crop, allowing an additional 2.5 crops per year to be produced (Saavoss et al., 2016). Because under the conventional timer-controlled irrigation, growers tend to err on the wet, and not the dry, side to ensure plants get plenty of water, plants' root conditions swing between flooding and regular, which inhibits plants root and shoot growth. Sensor-based automated irrigation aims to provide just the right amount of water to plants to avoid drought or flooding. Healthy plants will have fewer insect or disease (especially root disease) incidences and thus reduce chemical input and environmental and human exposure to chemicals. Healthier plants from nurseries generally perform better in landscapes too.

In addition to water conservation, sensor network control saved significant time in daily irrigation management, which converted to an annual net savings of $5263 and a payback period of 2.7 years in container production of dogwood and red maple (Belayneh et al., 2013). Growers have been reported to sell plants faster and spend less labor and resources. Reduced labor hours associated with irrigation management allowed for the reallocation of that labor toward other production and shipping-related activities, especially during peak production periods. Nurseries use slower release fertilizers or soluble fertilizers applied with irrigation water; excessive irrigation readily leaches nutrients from soilless substrates. Precise irrigation water applications prevent unwanted leaching and runoff, thus improving the water and fertilizer use efficiency. It is estimated that the adoption of sensor-based irrigation by half of existing U.S. ornamental operations could save enough water from supplying over 400,000 households, cutting greenhouse gas emissions by the equivalent of 7500 cars, and lower nitrogen runoff by 300–600 Mg (Majsztrik et al., 2013).

This project aimed to develop and promote a new irrigation strategy (sensor-based, instead of timer-based) to improve water use efficiency, conserve water in nurseries and improve the quality of container-grown plants in the Gulf Coast area.

2 Project implementation

This project has three tasks: Task 1 purchases equipment and develops demonstration fields; Task 2 assesses the effectiveness of automated irrigation systems; and Task 3 promotes and disseminates results.

We originally had quotes from Meter Group for a sensor-based irrigation monitor and control system before submitting the proposal. Still, they discontinued the product after we received the award notice from Texas Water Development Board. After extensive literature research, the Ranch system (RS) RM210 irrigation controller was selected, purchased, and installed as the irrigation controller for the research plot at Rancho Encino Farm (Task 1).

Figure 1. The project location at Rancho Encino, Bay City, Texas

Rancho Encino is a large wholesale tree farm explicitly developed to serve landscape architects, contractors, re-wholesalers, and retailers. The location is southwest of Houston (Figure 1). There are many other large nurseries in that area, and Rancho Encino is selected for this project as a typical nursery in Texas.

The irrigation control system Ranch system (RS) RM210 is Mesh Telemetry Base Station, including six analog/digital inputs, RS232, RS485/SDI12 (Figure 2).

Figure 2. The host controller of Ranch system (RS) RM210.

The RM210 maintains constant connectivity to the Ranch Systems online software (Figure 3) and regularly collects data from associated mesh telemetry nodes (RS300 nodes) in the same general area. It also acts as a controller for control actions programmed in the server software, executing irrigation programs, and transmitting start/stop commands to equipment attached to nodes.

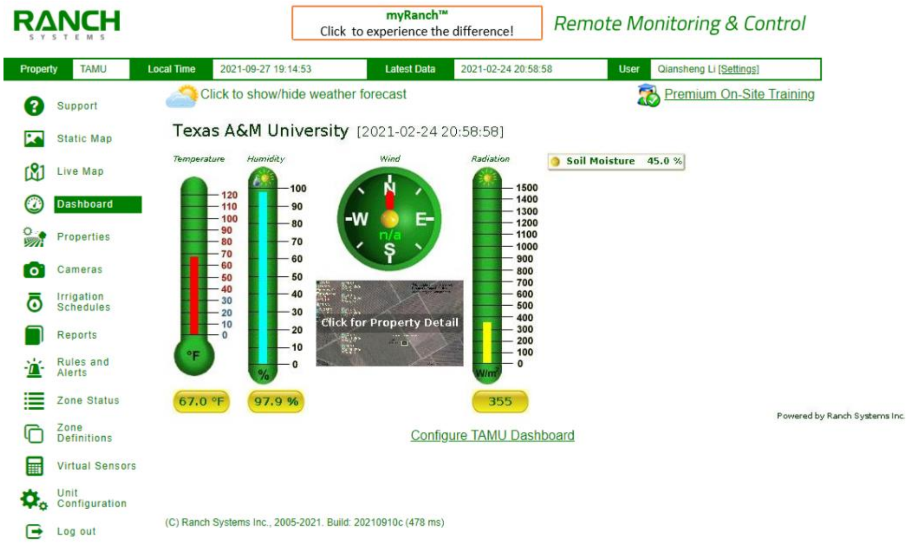


Figure 3. The online software interface of Ranch Systems.

The trial plot at Rancho Encino Farm was arranged as Figure 4.

Four irrigation treatments were set up with four rows, and one soil moisture sensor was placed in a pot in the middle of each row. Irrigation of each row was controlled by a timer or the sensor-based controller: 1) timer-based control (zone 4, sensor DP4)— water was turned on for 10 min each day in summer (June 16-October 23), or 10 min every other day. 2) sensor-based — water was turned on for 10 min when the moisture sensor reading decreased to 15% (zone 1, sensor DP3), 18% (zone 2, sensor DP6), 21% (zone 3, sensor DP2), respectively. Water was turned off when the moisture sensor reading increased to 20% (zone 1), 23% (zone 2), 26% (zone 3), respectively. The lowest levels (15%, 18%, and 21%) of sensor-based irrigation were based on intensive testing conducted on the Texas A&M University campus before the on-farm research component (Progress Report 10/15/2018-01/15/2019; Progress Report 10/15/2019-01/15/2020).

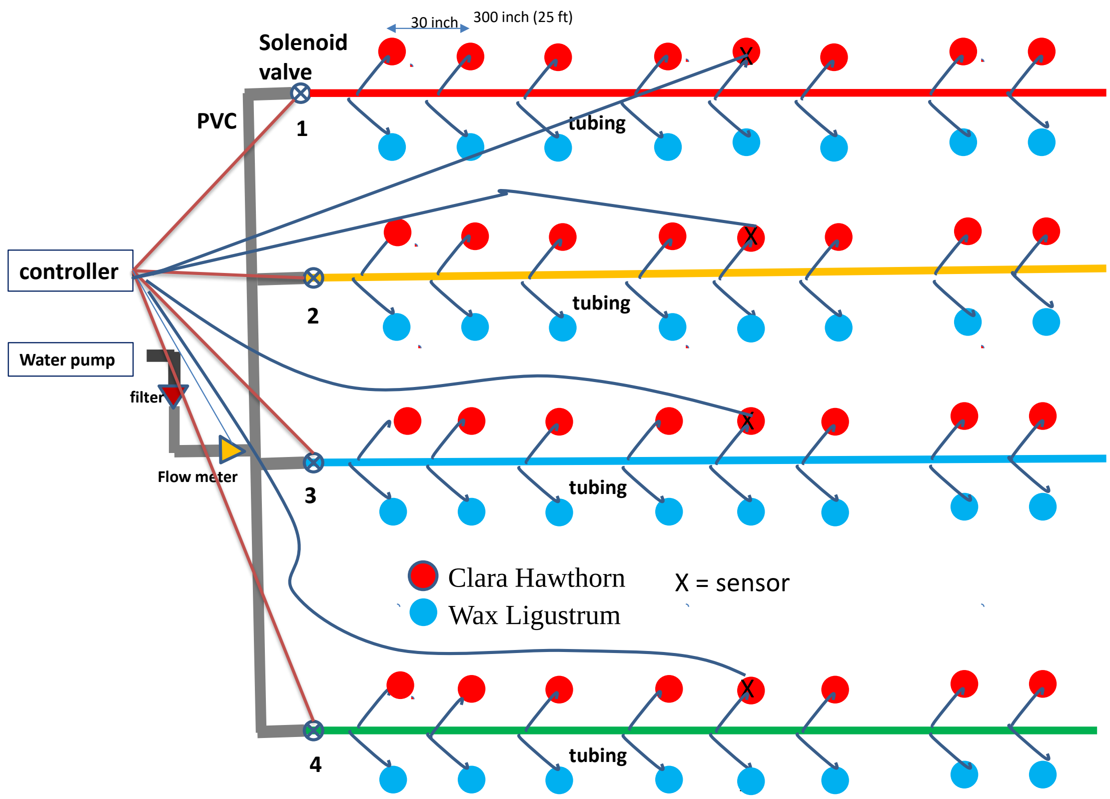


Figure 4. **Plot arrangement with two plant species ('Clara' Indian hawthorn and wax ligustrum) and four zones: (1) control (zone 4, sensor DP4)— timer-based irrigation for 10 min each day in summer (June 16-October 23), or 10 min every other day. 2) sensor-based — 15% (zone 1, sensor DP3), 18% (zone 2, sensor DP6), 21% (zone 3, sensor DP2). 'X' indicates the pot where the soil moisture sensor was placed.**

Wax ligustrum and 'Clara' Indian hawthorn were selected as the test plant materials based on their popularity in nursery production and landscapes and the availability of liners at the beginning of the experiment. Eight liners of wax ligustrum and 'Clara' Indian hawthorn were planted in each row in three-gallon pots filled with bark-based potting mix in July 2019. Each pot was applied with 15-gram control release fertilizer in spring and autumn.

On 1st December 2020, plant height, canopy width was measured, then the shoots were pruned 10 cm above the soil surface. The fresh shoot weight of each plant was weighed and recorded. The means of plant height, canopy width, plant growth index, and fresh weight of each treatment (zone) were calculated and statistically analyzed by SPSS Statistics Software (IBM SPSS Statistics for Windows, Version 19.0. IBM Corp., Armonk, NY, USA).

3 Results

3.1 Air temperature, soil temperature, and relative humidity (1/1/2020~12/31/2020)

The air temperature of 2020 was monitored continuously by RS controller internal temperature sensor. The lowest temperature was 32 °F in winter; the highest was 105°F in summer (Figure 5). The lowest soil temperature was 36 °F in winter; the highest soil temperature was 95°F in summer (Figure 6). The relative humidity mostly ranged from 60% to 100% but dropped to 20% occasionally (Figure 7).

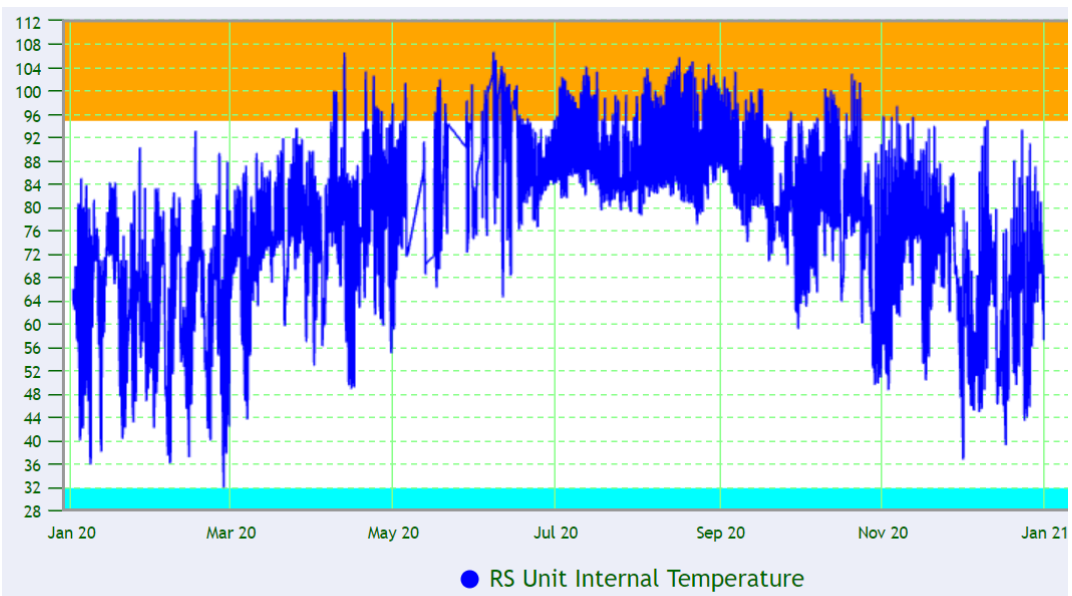


Figure 5. Air temperature monitored with RS unit internal temperature sensor from 1/1/2020 to 12/31/2020.

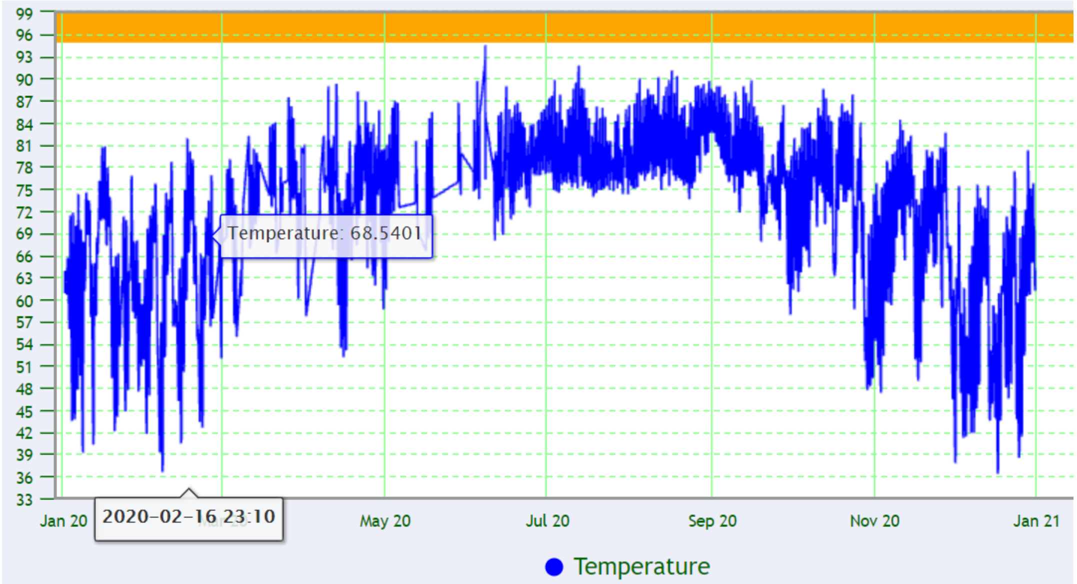


Figure 6. Soil temperature monitored from 1/1/2020 to 12/31/2020.

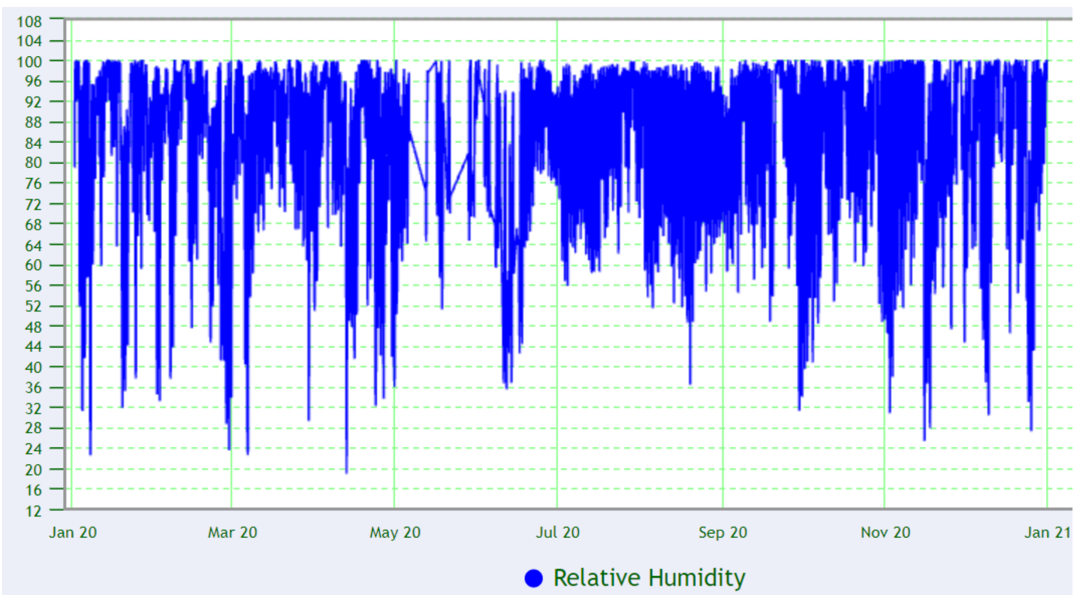


Figure 7. Relative humidity from 1/1/2020 to 12/31/2020.

3.2 soil moisture monitored by sensors in different treatments.

In zone 1, the soil moisture was set up at 15%-20%, which means irrigation will be triggered when the sensor reading drops to 15% and off when the sensor reading increases to 20%. Throughout 2020, the system ran smoothly, except that the electricity failure happened on the rainy days between late May and early July. The soil moisture ranged from 15% to 25% on most days but occasionally jumped to above 30% or even 40% (Figure 8), which could be caused by heavy rains or sensor error.

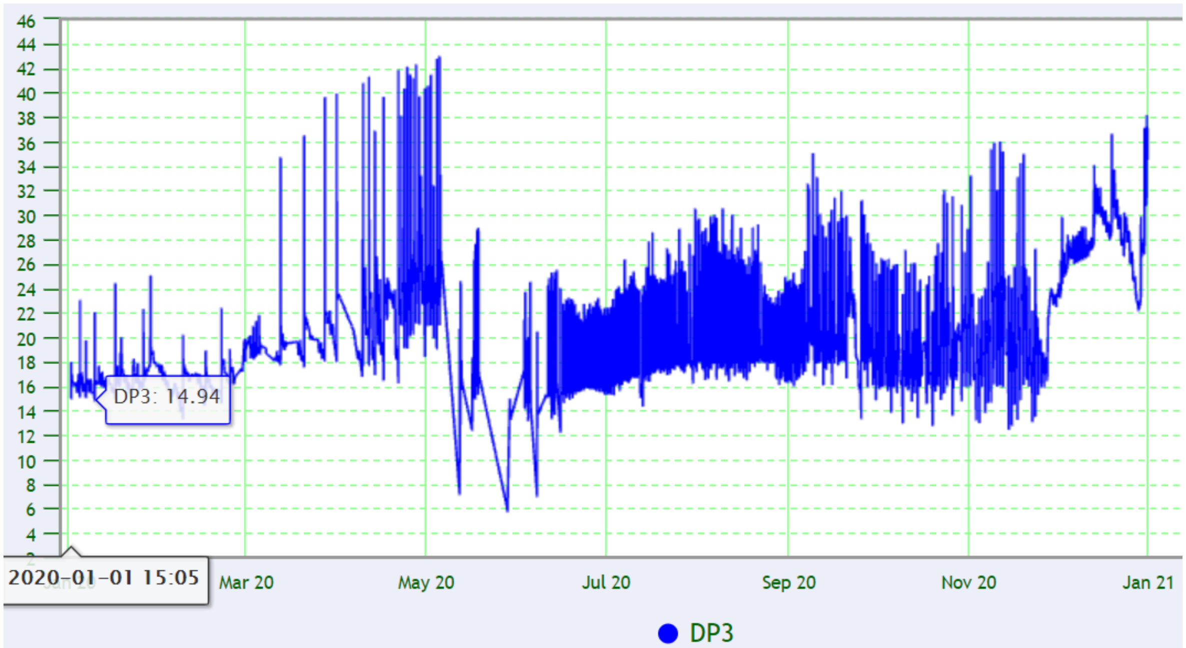


Figure 8. Soil moisture readings in zone 1 from 1/1/2020 to 12/31/2020. Water was turned on when soil moisture decreased to 15% and off when increased to 20%.

In zone 2, the soil moisture was set up at 18%-23%, which means irrigation will be triggered when the sensor reading drops to 18% and off when the sensor reading increases to 23%. Throughout 2020, the system ran smoothly, except that the electricity failure happened on the rainy days between late May and early July. The soil moisture was ranged from 18% to 40% on most days (Figure 9), which were more comprehensive than zone 1.

In zone 3, the soil moisture was set up at 21%-26%, which means irrigation will be triggered when the sensor reading drops to 18% and off when the sensor reading increases to 23%. Throughout 2020, the system ran smoothly, except that the electricity failure happened on the rainy days between late May and early July. The soil moisture was ranged from 18% to 36% on most days (Figure 10). But there were some abnormal readings in September, which reached above 80%.

Zone 4 was set up by timer with 10 minutes per day. The soil moisture readings were above 30% from January to May and above 25% from July to December (Figure 11). The highest reading was about 50%. The lowest soil moisture reading was more elevated than sensor-based readings, possibly because of a long time between irrigation. The minimum irrigation time was 10 minutes for the timer-based system. The soil moisture readings dropped to about 20% in autumn and winter when the irrigation was

It is scheduled every other day.

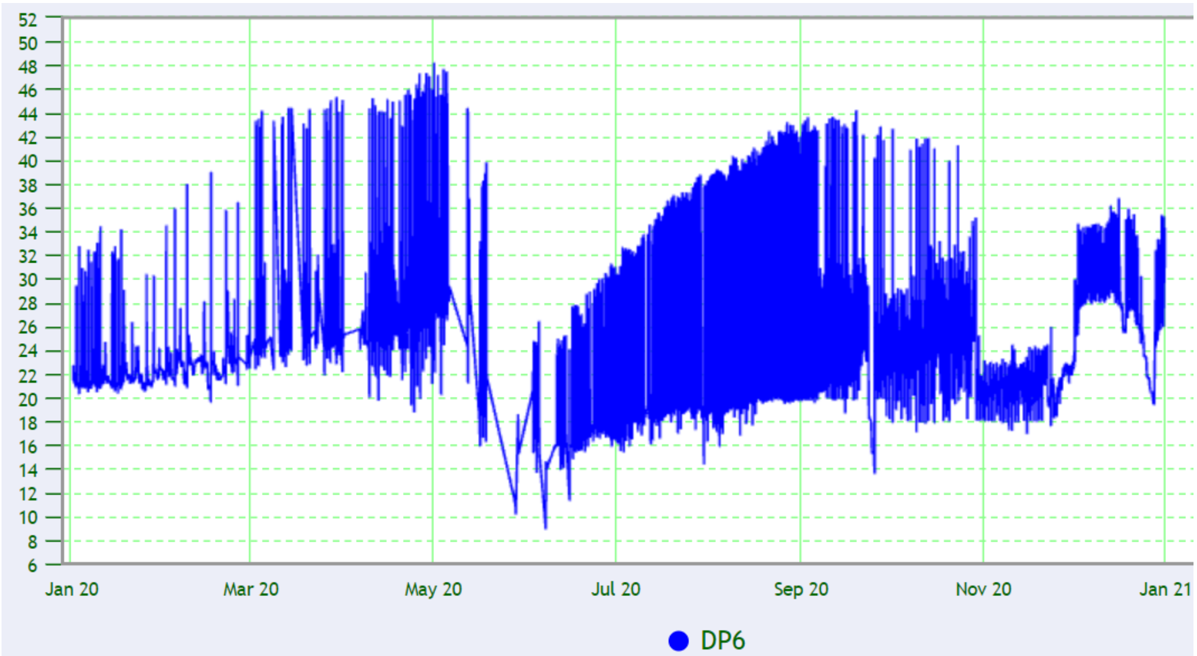


Figure 9. **Soil moisture readings in zone 2 from 1/1/2020 to 12/31/2020. Water was turned on when soil moisture decreased to 18% and off when it increased to 23%.**

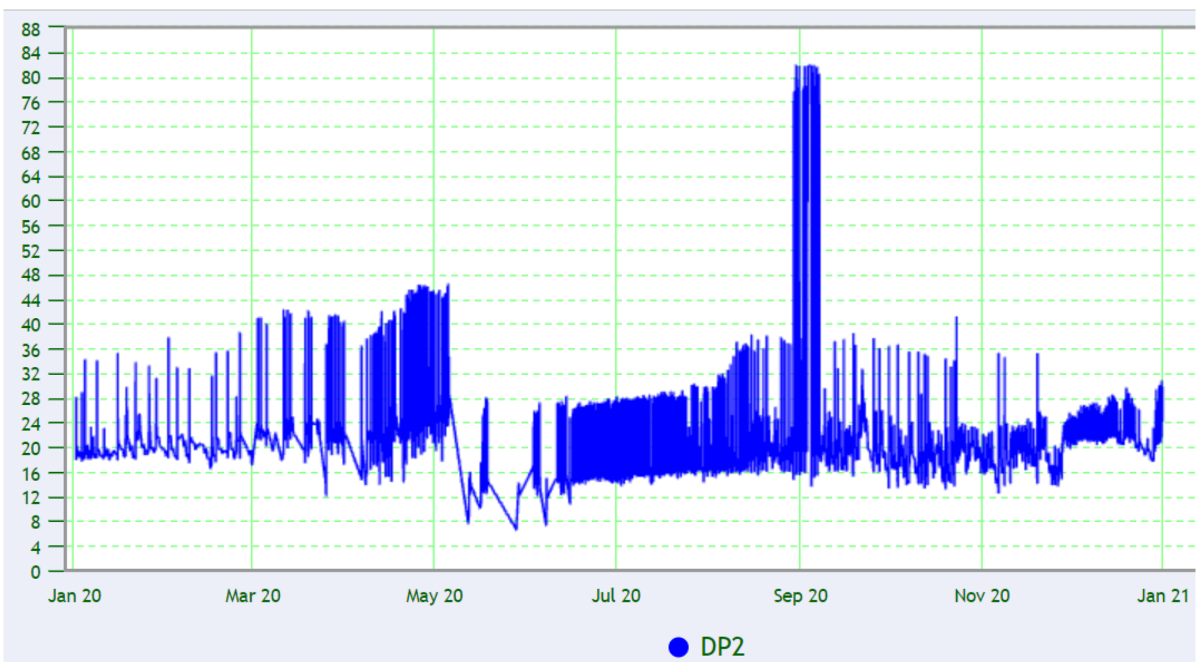


Figure 10. **Soil moisture readings in zone 3 from 1/1/2020 to 12/31/2020. Water was turned on when soil moisture decreased to 21% and off when it increased to 26%.**

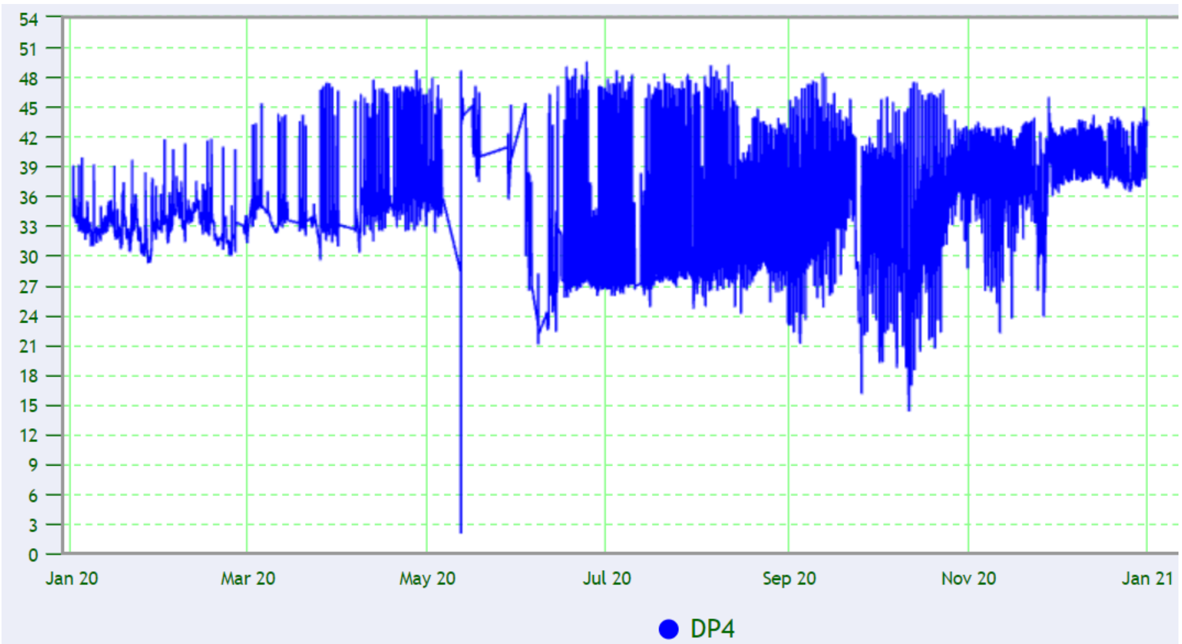


Figure 11. **Soil moisture readings in zone 4 from 1/1/2020 to 12/31/2020. Water was turned on for 10 minutes each day in summer (June 16-October 23) or 10 minutes every other day in this timer-based system.**

3.3 Plant growth

All the plants grow well and meet the requirement for sale before pruning for measurements (Figure 12). The plant canopy width, height, and plant growth index had no significant differences between sensor-based irrigation treatments and timer-based irrigation treatment in either wax ligustrum or 'Clara' Indian hawthorn (Figure 13).

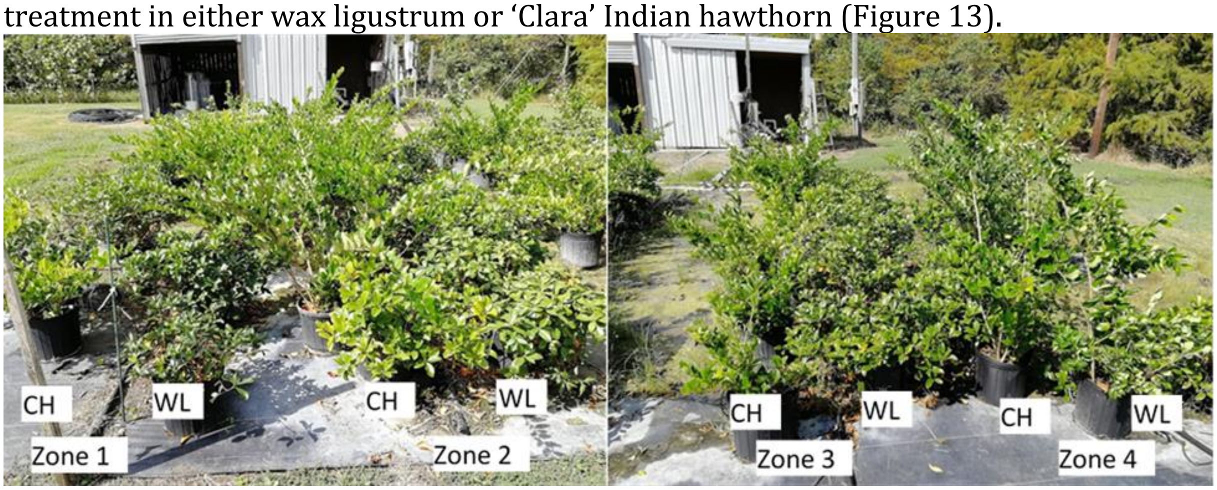


Figure 12. **Plants (CH—'Clara' Indian hawthorn; WL—wax Ligustrum) before pruning for final measurements on December 1, 2020.**

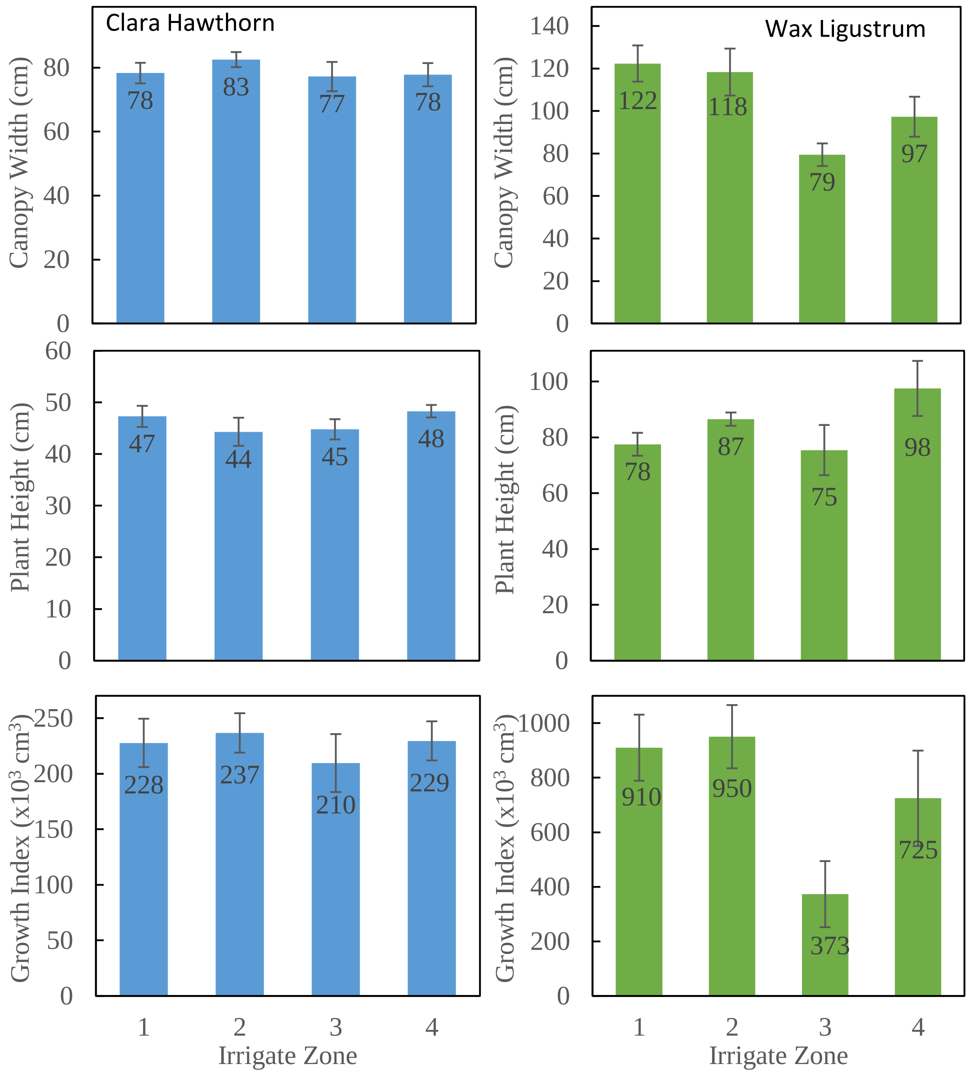


Figure 13. Canopy width, plant height, and growth index of 'Clara' Indian hawthorn and wax ligustrum plants in zone 1, 2, 3, 4 (measured on 1 December 2020.). Canopy width is calculated as (the widest canopy + perpendicular canopy width)/2; plant height is measured from the soil surface to the plant top point; growth index is calculated as GI=π*(canopy width/2) ^2*height, which reflects the volume of the canopy. Data are means of 8 replicates.

Shoot fresh weights of wax ligustrum did not significantly differ among all four treatments. The 'Clara' Indian hawthorn shoot fresh weight in zone 2 (soil moisture setup 18%-23%) was considerably higher than the other treatments, including timer-based irrigation (Figure 14). However, the plant growth performance, including growth index, height, canopy width, did not significantly differ. The heavier weight may have been caused mostly by a larger stem.

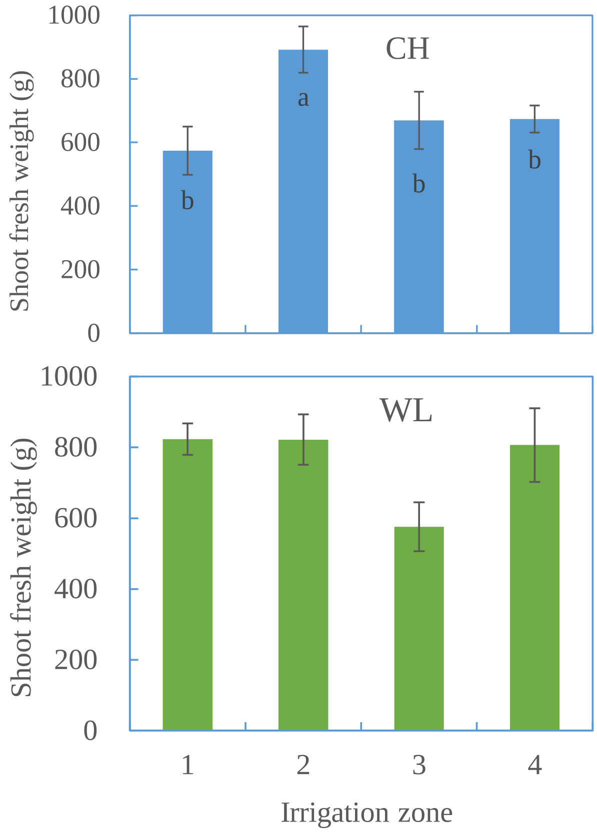


Figure 14. Fresh weight of shoots per pot pruned on 1 December 2020. CH—'Clara' Indian hawthorn; WL—wax Ligustrum.

3.4 Water use and savings

Figure 15 shows when valves were turned on (code '1') or off (code '0') in four irrigation zones in January (A-D), April (E-H), July (I-L), and October (M-P), 2020, representing winter, spring, summer, and fall, respectively. A/E/I/M-- 15%-20%, zone 1; B/F/J/N-- 18%-23%, zone 2; C/G/K/O-- 21%-26%, zone 3; D/H/L/P— timer-based control, zone 4. It is obvious that during summer, valves in sensor-controlled zones (1,2, and 3) were turned on and off much more often than the other three seasons, as plants transpire and absorb water much faster. The lines in sensor-controlled zones (1,2 and 3) were denser than the timer-controlled zone (4) because of the high frequency of on/off as irrigation was triggered when the sensor reading dropped to the pre-set lowest levels (15%, 18%, or 21%) and off when the pre-set highest levels (20%, 23%, or 26%) were reached. In contrast, the timer-controlled zone is turned on for 10 minutes.

There were days when sensor-based valves were on in spring, fall, and winter while the timer-based valve was off. So plants were using water as indicated by sensor-based valves being triggered on. Still, the irrigation was not turned on in the timer-based system, possibly creating plants 'drought' conditions. There were days when sensor-based valves were off while the timer-based valve was on, so plants were not using enough water as indicated by sensor-based valves is not triggered. Still, the irrigation was turned on in a timer-based system, which created somewhat 'flooding' conditions for plants. Neither 'drought' nor 'flooding' optimal plant growth and health.

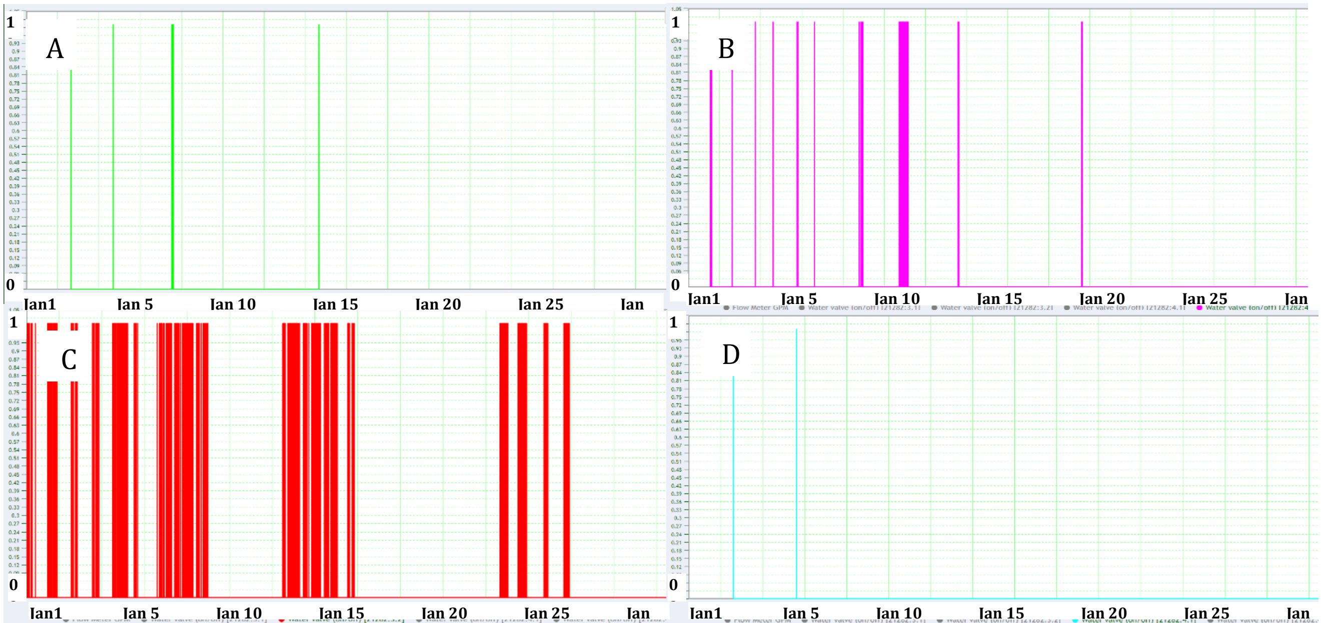


Figure 15. **Valve on/off time of four zones (A-D) in January 2020. A -- 15%-20%, zone 1; B -- 18%-23%, zone 2; C -- 21%-26%, zone 3; D— timer-based control, zone 4.**

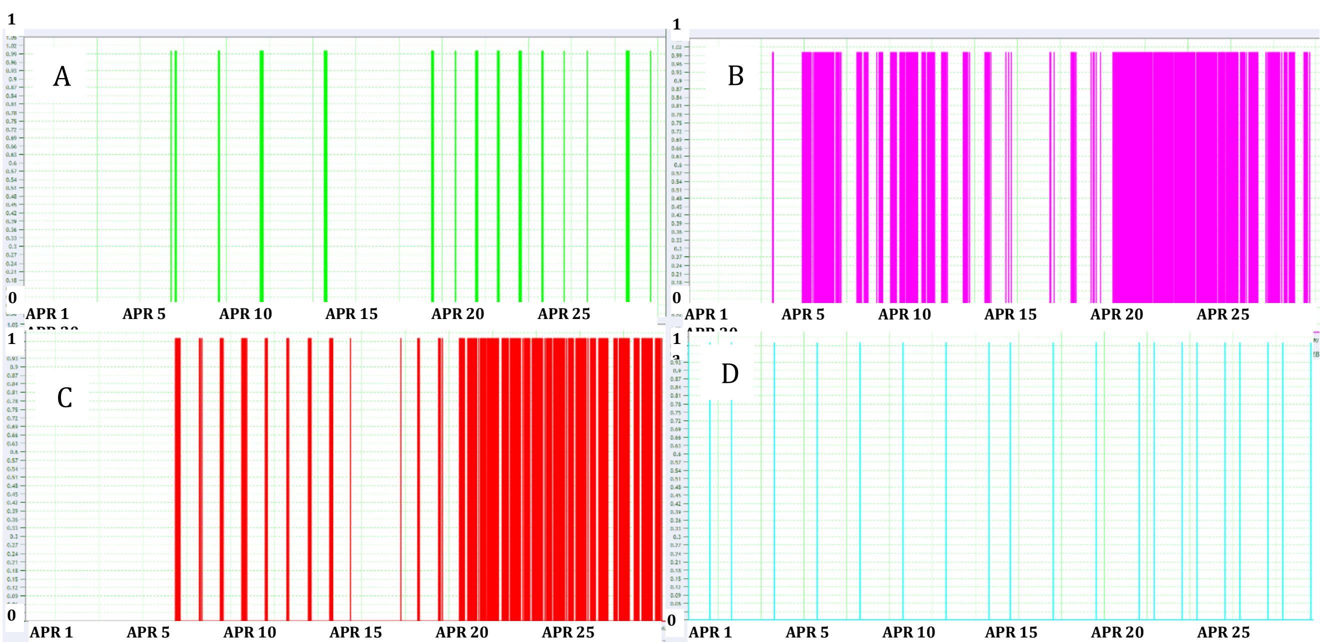


Figure. 16 **Valve on/off time of four zones (A-D) in April 2020. A -- 15%-20%, zone 1; B -- 18%-23%, zone 2; C -- 21%-26%, zone 3; D— timer-based control, zone 4. On the vertical axis, "0" represents valve off, "1" represents valve on.**

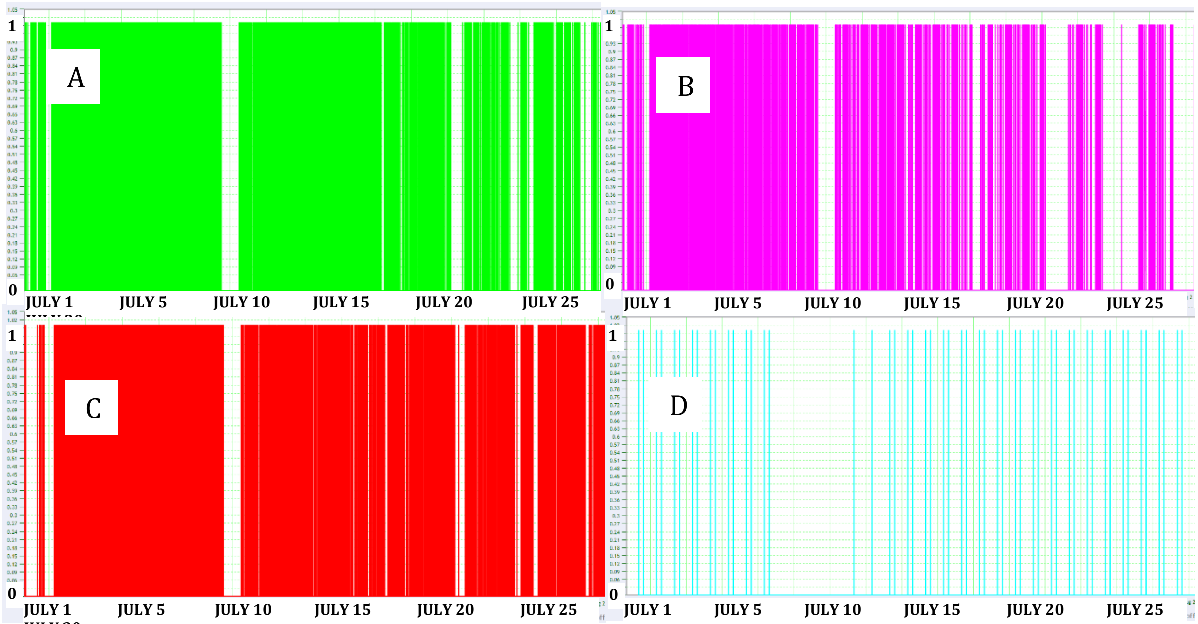


Figure. 17 **Valve on/off time of four zones (A-D) in *July* 2020. A -- 15%-20%, zone 1; B -- 18%-23%, zone 2; C -- 21%-26%, zone 3; D— timer-based control, zone 4. *On the vertical axis, "0" represents valve off, "1" represents valve on.***

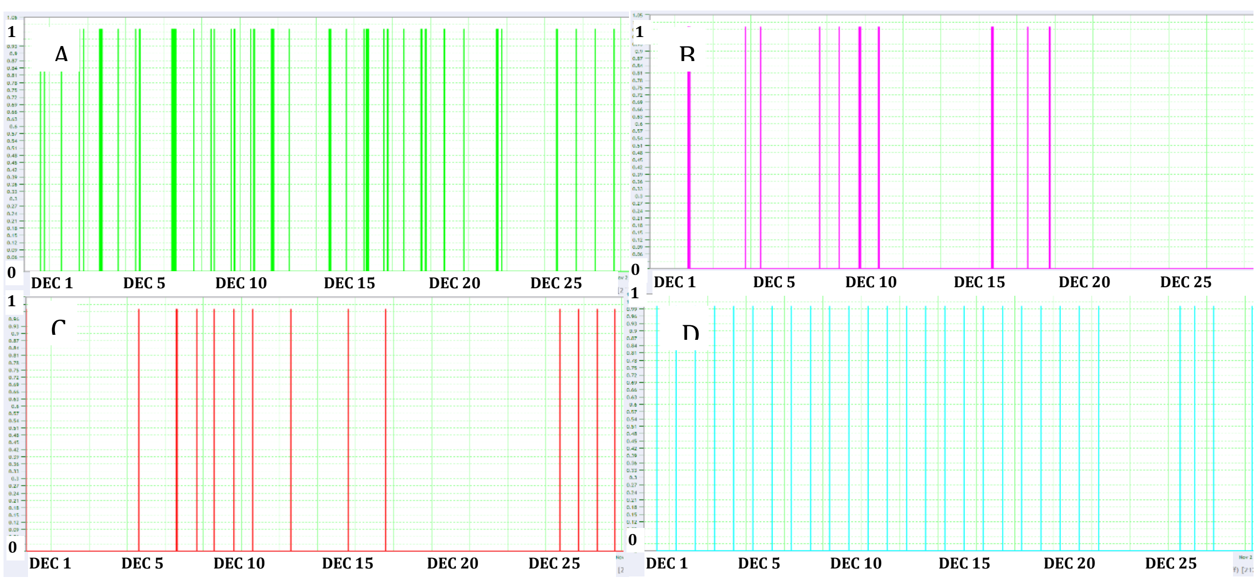


Figure. 18 **Valve on/off time of four zones (A-D) in December 2020. A -- 15%-20%, zone 1; B -- 18%-23%, zone 2; C -- 21%-26%, zone 3; D— timer-based control, zone 4. On the vertical axis, "0" represents valve off, "1" represents valve on.**

Due to the initial mistake of not installing a flow meter at each zone, the total amount of water used or saved was not available immediately from flow meter readings. The controller only provided the whole time when the valves were on, making calculating water use and savings from valve running time impossible. This is a lesson from this project.

4 Conclusion

4.1 For Task 2, assess the effectiveness of automated irrigation systems----- The whole irrigation system worked well both on sensor-based and timer-based irrigation. Timer-based irrigation treatments showed higher lowest moisture reading, which could be caused by over-irrigation as the system require at least 10 minutes irrigation schedule. The irrigation system can be triggered when the sensor's soil moisture reading reaches the set point. However, the readings of moisture sensors were not very stable with occasional drastic fluctuation. The sensor readings can be updated and communicated with the software properly. Growers can monitor the soil moisture anytime, anywhere through the website or APP on a mobile phone. However, the system could not automatically record the water amount irrigated for each treatment, although there was a digital water meter.

4.2 The plants grew well in all the treatments. The canopy width, plant height, and growth index are not significantly different between the sensor-based and timer-based treatments, except that the fresh shoot weight of zone 2 (18%-23%) was considerably higher than others. There were significant in-group variances, which could be caused by ununiform irrigation. The reason could be the frequent clog of drippers. The main water supply did not have a filter system, and there were always some drippers that were clogged during the monthly checking.

4.3 For Task 3, promote and disseminate results -----In 2019, Dr. Gu and the graduate student wrote a preliminary summary of the project titled 'Sensor-based automated irrigation monitoring and control' in the TNLA GREEN May/June issue (page 22-23). The paper copy of the TNLA GREEN magazine reaches over 2,000 members, and the online version is available (https://issuu.com/tnlagreenmagazine/docs/tnla_may_june_19_final_lr_singles). Due to the COVID-19 pandemic, the planned face-to-face field day had to be canceled, and online webinars were arranged. On April 1, 2020, Dr. Gu held a webinar (recording https://youtu.be/kFF3ZoZ_H4k) and briefly described her two projects on using sensor-based irrigation monitoring and control at Magnolia Garden Nursery (funded by Texas Department of Agriculture Specialty Crop Block Grant) and Rancho Encino Farm (funded by Texas Water Development Board). Dr. John Lea-Cox, Professor at the University of Maryland, discussed moisture sensor-based irrigation monitoring and control, saving water, and improving plant health and potential cost benefits. During the webinar on August 6, 2020 (recording https://youtu.be/t7cckpXLOjk), Dr. Gu presented results from the sensor-based irrigation control in nursery production. A total of 135 people attended the two live webinars. The recordings of two webinars have a total of 139 views on YouTube.

5 References

Belayneh, B. E., Lea-Cox, J. D., & Lichtenberg, E. 2013. Costs and benefits of implementing sensor-controlled irrigation in a commercial pot-in-pot container nursery. HortTechnology, 23(6), 760-769.

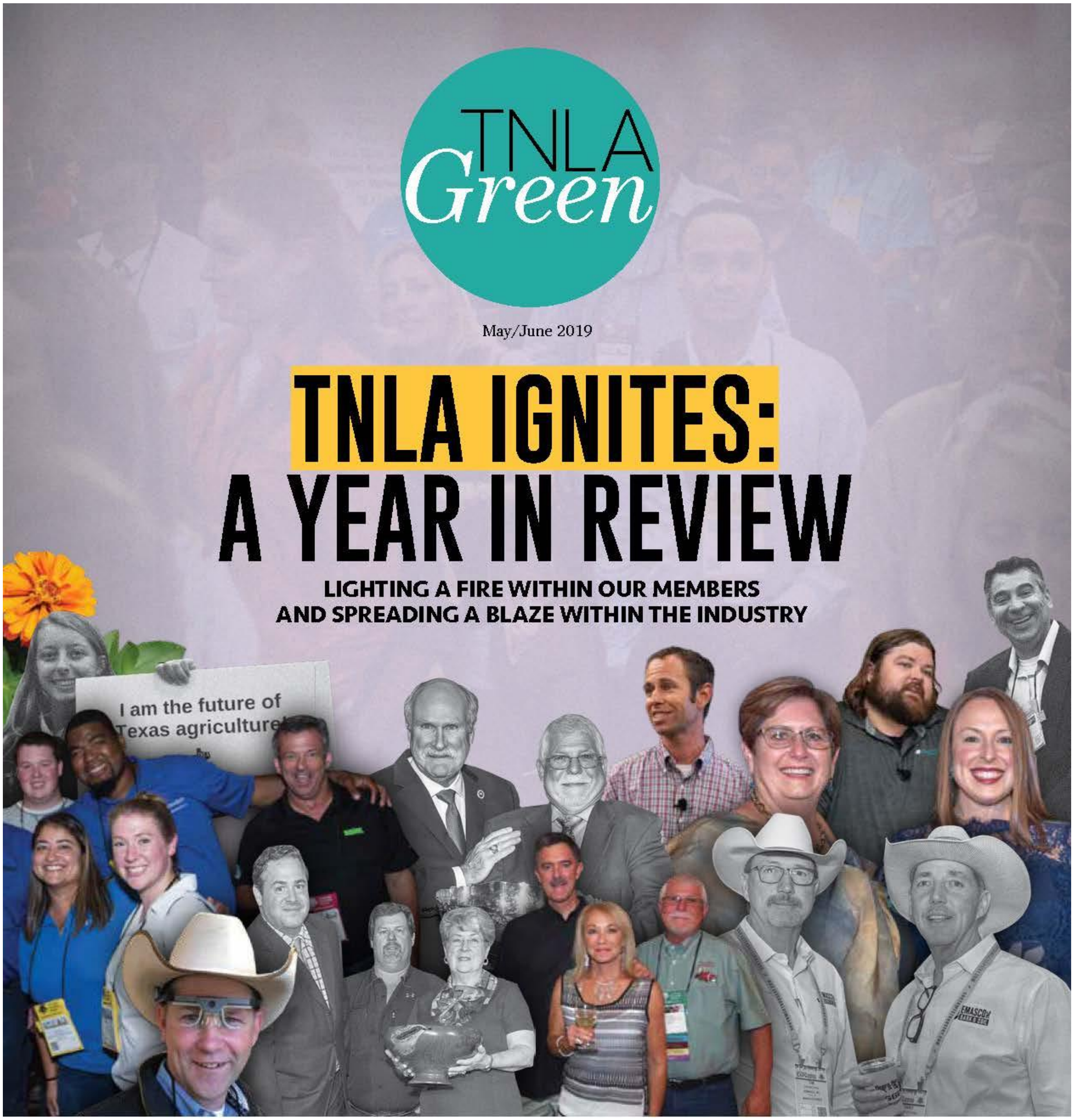
Saavoss, M., Majsztrik, J., Belayneh, B., Lea-Cox, J., & Lichtenberg, E. 2016. Yield, quality and profitability of sensor-controlled irrigation: A snapdragon (Antirrhinum majus L.) production case study. Irrigation Science, 34(5), 409-420.

Lichtenberg, E., Majsztrik, J., & Saavoss, M. 2013. Profitability of sensor-based irrigation in greenhouse and nursery crops. HortTechnology, 23(6), 770-774.

6 Appendix

6.1 Mengmeng Gu and Yuxiu Zhang. Sensor-based automated irrigation monitoring and control. TNLA GREEN, 2019, May/June, 22-23.

6.2 Webinar



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May/June 2019

CONTENTS

GREEN *Vision*

By Mengmeng Gu, Ph.D., & Yuxiu Zhang

Sensor-based Automated Irrigation Monitoring and Control

Figure 2

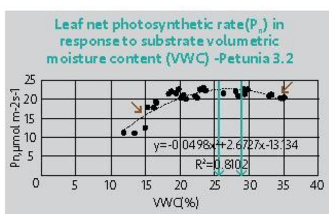
Figure 4

Figure 3

IN MANY PLANT production sites (nurseries or greenhouses), plants are irrigated based on time, most commonly controlled by a timer. The timer is set to switch on and off once or twice (or maybe more often) during the day.

During each irrigation event, plants are often watered before the moisture level in potting mix reaches the permanent wilting point (the minimal amount of moisture in potting mix that plants need to avoid dying from wilting). The water will be on for a pre-set amount of time so that the container moisture reaches container capacity (the maximum amount of water a type of potting mix can hold after irrigation and drainage).

Even a small nursery may easily have over 200 SKUs (stock keeping units) of different plants in different container sizes. For example, the same Texas mountain laurel in 5-gallon,



15-gallon, or 45-gallon containers will be considered 3 SKUs. Different SKUs will more likely have different water needs. For example, Texas mountain laurel in a 45-gallon container may need less frequent watering than those in 5-gallon containers if they're being watered to container capacity each time. Hydrangeas in a 5-gallon container may need to be watered more frequently than Texas mountain laurel in a 5-gallon container. Growers may group plants based on their water needs so that plants are not "drowning" or "dehydrating" in the same irrigation block.

What's the problem here? It is still timer-based, mostly. My graduate student, Yuxiu Zhang, measured the leaf net photosynthetic rate (See Table 1.) in response to substrate (aka potting mix) volumetric moisture content (VMC) of Hurrah White petunias in 5-gallon pots. (See Figure 2.) In this potting mix, did the plant have the highest photosynthetic rate at the highest VMC? (See Table 1.) No, and her prediction model (blue curve in the chart) illustrates that the highest photosynthetic rate is around 27 percent (about three-quarters of the highest VMC).

This 8-percent difference may not be much, and it's about 0.4 gallons of water for this 5-gallon container. But quick math tells me it'll be 168,000 gallons if 1,000 5-gallon containers are watered twice daily from mid-March to Mid-October (0.4 x1,000x 2x210=168,000). By not watering plants to container capacity we could have huge water savings, potentially.

Also worth noting is the photosynthetic rate at 15 percent VMC (red arrow on the left in the chart) is 16 μmol $m^{-2}s^{-1}$, about 70 percent of the highest value. Photosynthetic rate correlates with plant growth. Normally higher photosynthetic rates could translate to faster plant growth. Ideally, we want the photosynthetic rates to stay at the highest level.

In typical timer-based irrigation, substrate VMC gradually drops lower than the ideal level range (the space between green arrows on the chart) and then reaches container capacity when water is turned on. Substrate moisture levels and photosynthetic rate fluctuate.

How can we keep plants at their fastest growth rate while maintaining the highest photosynthetic rate? We need to maintain the ideal moisture level (space between green arrows on the chart). The sensor-based automated irrigation system (See Figure 3.) is designed for just that. Substrate moisture sensors are embedded close to the plant root system in containers (See Figure 2.).

We program the ideal moisture range in the control system, which receives moisture readings from sensors continuously. The control system automatically turns on the solenoid (See Figure 4.) when the moisture level decreases to the lower level of the pre-set moisture range and turns off the solenoid when the moisture level reaches the higher level.

There are many benefits of such sensor-based automated irrigation. By maintaining the ideal substrate moisture range, plants are never thirsty, and we can avoid, or at least minimize, the soggy conditions. Having moist but not wet potting mix could reduce soil-borne disease significantly. This may be important for some finicky plants like gardenia.

Plants are healthier and grow faster. Instead of having one to two crops per year, growers may have three to four crops per year. Irrigation water is saved and so is fertilizer, as leaching is minimized. Savings on irrigation water could mean less plumbing and larger production areas without having to pay for a new well. These benefits will likely result in financial benefits, such as savings in labor, materials, and resources.

We have been testing such sensor-based automated irrigation systems in our greenhouse. Once we install the system in a nursery in April, we'll have more field experience to share.

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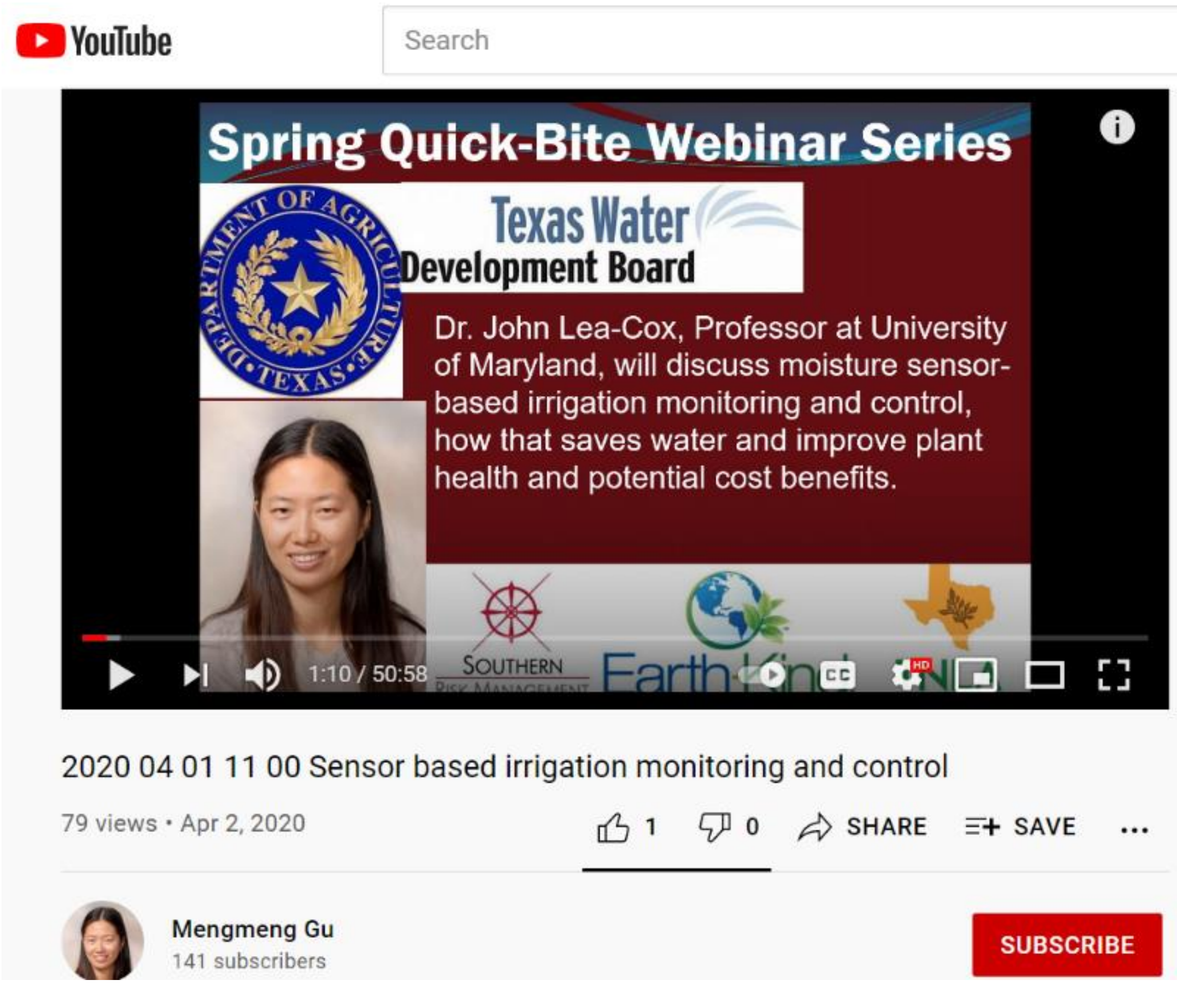
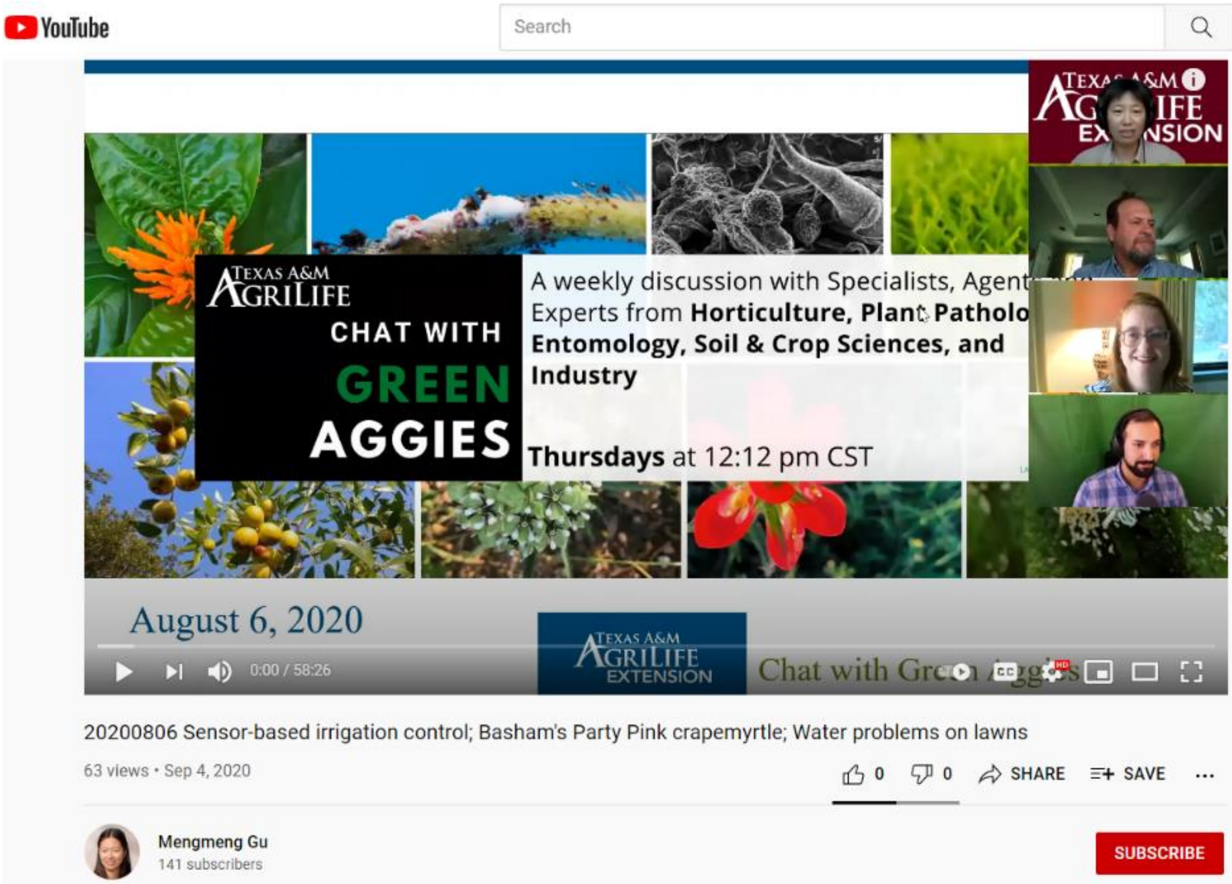


https://www.youtube.com/watch?v=kFF3ZoZ_H4k



https://youtu.be/t7cckpXLOjk

Note on reviewers' comments.

We appreciate all the comments and suggestions to improve our final report. We addressed all the comments and suggestions accordingly to the final report. We also corrected other grammar problems and rephrased some sentences. We modified some figures for better visualization. Please let us know if any additional modifications are needed.

Final Report 1713582116 Review Comments

Overall Content Comments:

• Report should follow TWDB report format should discuss Tasks 1, 2, and 3 and include:

o Introduction

o Summary of project

o Results

o Will forward TWDB reporting guidance for reference

We rewrote and reedited the final report following the TWDB report format.

• The report does not seem to meet the intent of Task 2

o Please discuss on why the results were not found as intended, what problems were encountered, and recommendations on how future research might be improved. Preferably this information would be presented in the Introduction and the Summary sections.

We explained this issue in the report (Page 15).

• The report does seem to meet the intent of Task 3

o Please include outreach and educational components. If there were any activities preformed relating to Task 3, please include them in the report.

We explained on page 15 and included the materials in the appendix.

• Please provide context on why Clara Hawthorne and Wax-leaf Ligustrum plant species were selected for this research.

We explained this on page 5.

• Please provide more context and explanations on the distinction(s) on shoot fresh weight of 'Clara' Indian hawthorn in zone 2 vs other plant's shoot fresh weight.

We rewrote this part.

• Please conduct a peer review or extensive grammatical review of entire report for ensured accuracy.

We asked colleagues for peer review, and did extensively grammatical editing.