THE IMPACT OF IRRIGATION SCHEDULING ON WATER USE EFFICIENCY OF CORN AND SOYBEAN PRODUCTION IN HUMID CLIMATES: LESSON LEARNED FROM ON-FARM DEMONSTRATION

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ABSTRACT

This study explores water use efficiency (WUE) in southwest Michigan's humid climate, focusing on improving irrigation management practices. Several different levels of irrigation were examined as experimental treatments to better understand their impact on crop productivity. Despite testing an array of different experimental irrigation treatments, we found no statistical differences but noted unequal averages and data spreads. These trends suggest more samples, under typical climatic conditions, are needed to distinguish which irrigation approaches enhance WUE. We also contrasted producers' methods with experimental treatments, highlighting the challenges of optimizing WUE in the region's climate and soil conditions even with past experience in irrigation management. Additionally, part of this research explores sensor calibration under fixed soil moisture near field capacity. Calibration formulas for the Pinotech Soilwatch-10, Metergroup 10-HS and Metergroup Teros-12 were found and analyzed. This study's findings provide practical insights for producers and was conducted as a demonstration study for the benefit of producers, with the intention of providing a baseline for improving their irrigation management practices. emphasizing the need for flexible, quantitative, and scientific irrigation strategies to optimize agricultural crop production in southwest Michigan's environment. By bridging theory with real-world applications, this research contributes to responsible water management, aiming to enhance irrigation water use efficiency in the region.

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Chapter 1. Introduction

Water is considered to be the most critical natural resource by most experts and is needed for countless processes ranging from photosynthesis to resource refinement. Although only 2.5 percent of the acreage in the United States and one percent of the acreage in Michigan is irrigated cropland, agriculture is the leading consumer of fresh water (USDA, 2017.) In 2015, over 40 percent of the United States' freshwater withdrawals were utilized for irrigation (USDA, 2017). This proportion of the United States total water withdrawal equates to 118 billion gallons of water per day or forty-three trillion gallons per year (USDA, 2017).

Despite this, irrigated cropland accounts for only 14.6 percent of cropland and produces over 54 percent of the nation's crop sales (USDA, 2022). This percentage of the nation's crop sales correlates to over 100 billion dollars in sales from 2017 (USDA NASS, 2017). Additionally, most produce and ornamentals require irrigation to be economically grown in the Midwest. Regardless of a given crops water needs, demand for water, food, fuel, and materials continues to rise. In light of the ever-growing global population and the potential impacts of climate change, maximizing crop yield while conserving water is becoming more critical each year.

Both water and crops are critical resources with ever increasing demand. The primary goal of this research is to improve the productivity and efficiency of farming irrigated crops. Ideally, this is accomplished by optimizing the volume of irrigation water applied to a given crop with the crop's yield. To evaluate overall irrigation efficiency, irrigation application volume, soil moisture, and yield were monitored. Furthermore, Sensor-based irrigation scheduling methods were evaluated to better understand the relationship between irrigation, water use, and productivity. While finding the optimal irrigation application in terms of water use and yield sounds straight forward, it is dependent on the performance of the sensors used. Thus, part of this study is devoted to calibrating the sensors being used. In summary, the overarching goal of this research is to improve irrigation management with the hopes of benefiting producers and reducing water usage simultaneously.

1.1 Hypotheses

This research was conducted for the benefit of local producers as a demonstrative study with the hopes of increasing technological adoption, increasing water use efficiency and conserving water.

- Irrigation scheduling combined with soil moisture monitoring can improve irrigation water use efficiency, increasing crop yield per volume of irrigation applied as compared to traditional methods. If irrigation is scheduled by computation based on soil and crop characteristics, water use efficiency should be higher than similar areas managed using traditional irrigation management methods.
- Application timing and volume as calculated based on soil and crop type optimize irrigation water use efficiency. If estimated timing and volume are used to manage agricultural irrigation, water use efficiency will be higher on average than increased and decreased irrigation volumes and frequencies.
- Temperature influences soil moisture sensor reading throughout the growing season. If sensors are calibrated to compensate for alterations in temperature, error can be reduced to improve data for better management of irrigation.

1.2 Objectives

The above hypotheses and research questions lead to the following project objectives.

- Demonstrate the effectiveness of irrigation scheduling in maximizing water use efficiency.
- Demonstrate the effectiveness of soil moisture monitoring to maintain soil moisture for crop production.
- Compare the effects of varying soil temperature on different soil moisture sensors
- Estimate calibration values for each soil moisture sensor used.

Chapter 2. Literature Review on Improving Agricultural Irrigation Management

2.1 Introduction

Irrigation is critical to agriculture for the production of food, materials, and even fuels (USDA, 2017). In Michigan, throughout the United States, and in many places around the world, Irrigation has the ability to extend growing seasons and expand the variety of crops that can be grown in a given area (USDA, 2017 & FAO, 2022). With increasing concern of environmental impact and increasingly limited freshwater supplies, irrigation is often scrutinized for its water demands. All of these factors increase the demand for research, innovation and technological adoption within the agricultural sector.

2.1.1 Background of Water Withdraw for Irrigation

The first well recorded design of a pump used to supply water for irrigation was designed by Archimedes around 200 BC (Waters and Aggidis, 2015). While this invention was simply a screw pump initially designed to remove bilge water from ships, the same technology permitted farmers to lift water from wells effectively. While this expanded the agricultural area that could be irrigated immensely. Although, it is not likely that water use efficiency was considered beyond the drying out the well, this was likely the first time a civilization had control of irrigation beyond using gravity to move water to furrows or hand watering. Arguably, this was one of the first times in which irrigation applications could have been managed to improve yield on a large scale with significant consideration for ground water usage. It was not until the mid-20th century, when modern irrigation equipment came on the market, that water use efficiency really began to emerge. This advancement started with basic sprinklers and waterlines and grew to the first self-propelled center pivot irrigation system which was invented by Frank Zybach and used water driven mechanisms to move the system about a field (Howell, 2000).

As better irrigation equipment became readily available to farmers, more irrigation systems were installed. Since irrigation has been known to be one if not the most water consumptive practice in Michigan and around the globe, concerns for water conservation have arisen. Several laws, including the Clean Water Act were established in the mid to late 20th century. These laws initiated the movement to improve water quality and conservation. In 1981, the right to farm act was passed protecting farmers access to water for irrigation under most circumstances. While in Michigan there are now more elaborate regulations protecting stream flow and groundwater availability. Michigan's Generally Accepted Agricultural and Management Practices also known as GAAMPs recommends the following (MDARD, 2021):

1. Selecting an appropriate source of irrigation water.
2. Accurate determination of irrigation applications.
3. Evaluating system uniformity.
4. Maintaining good working condition of the system.
5. Accurate measurements of the supply pressure at the distribution system's manifold.
6. Minimize application drift and off target application.
7. Ensuring that the application rate does not greatly exceed the infiltration rate.
8. Adding noise control to engine driven units.

With time irrigation technology advanced yielding high efficiency sprinkler systems along with surface and sub surface drip irrigation. Eventually, systems became increasingly automated and gave farmers more control over their irrigation application volume and timing. All the while, agricultural water use became an increasingly troublesome concern. With water quality and availability catastrophes and food shortages in our recent past, the need to maximize crop production while conserving water is clear.

2.1.2 Advances in Irrigation Technology

In light of inventions such as the center pivot, drip irrigation and sprinkler irrigation, growers now have increasingly adaptable irrigation equipment at their disposal. Depending on the grower's crop selection and characteristics of the land they intend to farm, growers can tailor their irrigation methods to meet their needs. For example, center pivot irrigation accounts for the vast majority of the systems irrigating corn and soybeans grown in Michigan and throughout the United States. This is in part due to the nature of the disease and pests that can affect these crops, but perhaps more logically due to the economics behind this style of irrigation system. On average, one can expect to pay around Ninety thousand dollars for a three-tower center pivot, as compared to over two hundred thousand for the equivalent amount of drip tape to cover the same acreage (Lamm et al., 2020). This balances out to an initial cost of about seven hundred dollars per acre for center pivot irrigation as opposed to one thousand three hundred dollars for the equivalent acreage of drip tape (Lamm et al., 2020). This example only covers the installation costs of these systems, maintenance, and operating costs both have significant impacts on the economics of each type of irrigation. While center pivots are known to retain around fifty percent of their original value after fifteen years (Lamm et al., 2020). Due to the strength and ultraviolet resistance of the drip tape, drip irrigation systems are often degraded beyond repair at this point. Accounting for the impacts of tillage, clogged emitters, effects of contact with the soil it's easy to see that this high efficiency system does have some drawbacks. Since drip irrigation is typically done in rows of drip line, failures in the line can lead to flooding in one area and drought like conditions in another. Drip lines may be buried and thus inaccessible for repair or simply go unnoticed below the crop's canopy prolonging the duration of the failure. This is not to say that center pivots don't malfunction or require maintenance: clogged sprinklers, electrical issues, well pump failure and flat tires are all common in the lifespan of a center pivot and can be costly.

Cost is far from the only concern when considering irrigation technology. While center pivot irrigation has been used for longer and is better suited to high acreage row crops, its less suited to fruit crops and certain types of produce. While some crops can tolerate overhead irrigation via sprinkler or center pivot, others are prone to foliar disease, fungi, parasites, and rots which can be tied to wetting the surface of the leaves or fruit. Due to this fact, drip irrigation is often utilized in these scenarios to reduce the risk of disease. Drip irrigation also has the benefit of minimizing evaporation since irrigation water is applied directly to the soils surface or even to the root zone in the case of sub surface drip irrigation. Having emitters that bleed water slowly into the soil profile allows for the least potential evaporative losses of any system on the market (USGS Water Science School, 2018). These systems can be designed to apply water at a rate that the soil can absorb without causing runoff. Furthermore, plant spacing can be aligned to match the spacing of the emitters on the drip tape, this prevents applying water to areas where the crop cannot easily access and make use of it. Individual lines of drip tape can be turned on via systems of valves allowing for a high degree of control on each irrigation application.

The advances in water distribution technology alone have made a significant improvement on irrigation water use efficiency over the past few decades. While getting an even distribution across a field has been a goal for many irrigation companies for years, we can now expect properly maintained systems to achieve better than eighty five percent irrigation uniformity (Laffan et al. 2015). This parameter can be evaluated by placing containers of known size alongside the length of the irrigation system and running the system over at a set application rate. By measuring the volume of irrigation water in each container, uniformity can be assessed, and adjustments made to the sprinkler package. Ideally, irrigation uniformity is maximized so that the entire area receives the same volume of water. Depending on the location where the correction is made on the system, correcting a sprinkler can have substantial impact on water savings or yield since one sprinkler may cover a large radius as the system rotates around the field. Thus, improving irrigation system uniformity can greatly improve the precision of an irrigation system's applications, adding up to substantial water savings.

Aside from the mechanical advancements that have occurred over the past seventy years, the advent of computer technology has greatly enhanced both system control and our ability to monitor field conditions. Perhaps the most notable advancement in irrigation systems control are variable rate application systems and the ability to program the system to irrigate remotely. Within a single field the soil type and slope can vary substantially. This can create areas with different maximum rates of infiltration. Exceeding this rate can cause runoff whilst still underirrigating the crop. Reducing the application rate and only applying the volume which the soil can feasibly hold in the root zone can eliminate this issue, however, can theoretically reduce the efficiency of other areas with better infiltration rates and water holding capacities. By programing the system to make site specific applications water waste is reduced while maintaining optimal conditions for plant health.

The introduction of computers to agriculture also greatly benefited growers' ability to monitor and understand field conditions. Without computer aided monitoring systems, one would have to periodically check mechanical readings from instruments like lysimeters and take several samples to understand the fields current conditions as compared to the maximum water holding capacity and wilting point. Several companies including Campbell Scientific, Watermark, and

Meter group sell data logging systems capable of measuring field conditions in real time and sending them to the grower. In conjunction with current meteorological projections, these Monitoring systems provide the data needed to maximize water use efficiency. In some cases, utilizing soil moisture monitoring and weather forecasts has been proven to improve water use efficiency by as much as 30% as compared with a traditional irrigation scheme (Liao, 2021). With each passing year more methods of assessing available water become viable, parameters that can be assessed include evapotranspiration, drainage, turgor pressure, sap flow and so on. Measuring different combinations of these aspects using the current sensors available and basing one's irrigation techniques on the parameters assessed has shown increases in water use efficiency, reduction in irrigation volume, and reductions in plant stress leading to improved yield (Bwambale, 2022).

2.1.3 Impact of Improper and Unnecessary Irrigation

The goal of using irrigation is to maintain soil moisture when the natural environment does not meet the needs of the crop. To state this in a quantitative manner, the soil moisture in a crop's root zone should be maintained between a crop specific threshold and one hundred percent of the soil's water holding capacity. Just as with underirrigating, overirrigating can have negative impacts on the health of the crop as well as the surrounding environment.

The most obvious impact of over-irrigation is that it wastes water. As previously stated, irrigation is the largest water consuming activity in the United States (USDA, 2017). This is not to say that all growers who irrigate wastewater, but rather that great care should be taken in using water for irrigation. In a scenario where overirrigation occurs, there are only three pathways for the water to undergo, all of which risk water becoming less accessible or degrading in quality. The basic water balance displays all three of these pathways:

EQN. #1. Infiltration - Evapotranspiration - Increase in storage = Drainage

(D.L. Nofziger, 2003)

In theory, infiltration and drainage both have the potential to replenish local water supplies, however if the water remains exposed and evaporates, the water is lost into the atmosphere. Even when excess irrigation drains back into the local water supplies, there are losses to evaporation. Additionally, soil nutrients and organic matter, carried in runoff (a component of drainage), have the potential to degrade the quality of surrounding natural water bodies. Lastly, infiltration is the water returning to underlying aquifers. While this retains the water, it has the potential to move nutrients out of the root zone and contaminate the aquifer.

Aside from the misuse of water, overirrigation has the potential to increase disease risk. In order for a pathogen to infect a crop, the host plant, pathogen, and proper environmental conditions must all be present (Salamanca, 2014). In many cases, the pathogens which infest a particular crop may already be present in the soil and debris. Many of these pathogens are moisture dependent and need only an extended period of high moisture to infect the plant. In addition to promoting the establishment of a given foliar disease by increasing leaf wetting duration, the impact of water droplets can disperse propagules, spreading the disease (Dixon, 2015). The addition of unnecessary irrigation has the potential to make the difference between the pathogen remaining dormant and infesting the crop.

Lastly, overirrigation has the potential to cause leaching of nutrients in the soil to areas below the root zone where the crop cannot make use of it. Over six million tons of Nitrogen were applied to the United States corn fields in 2018, while 208,000 tons of nitrogen were applied in soybeans (USDA ERS, 2019). While most of the nitrogen was utilized by the crop or fixed in the soil, a percentage of the nitrogen applied to the field is at risk of being leached. While nitrogen can be applied in several different forms, the prominent form that can be leached out of the root zone is Nitrate ($NO3^-$) (Killpack & Buchholz, 2022). While other nutrients like phosphate do have the potential to be leached, they are considered to be less of a threat as they are fixed in the soil under most conditions (Wyatt et al., 2019).

Even under theoretically perfect irrigation management, nutrients can be leached due to high volume rainfall events. Once leached, the Nitrate that once was in the soil profile moves downward until it reaches groundwater, from this point it contaminates the groundwater and reduces the water quality of all wells that draw from it. In a similar way, phosphates can be introduced to the local surface water in a dissolved form or in runoff from extreme precipitation events (Wyatt et al., 2019). While an irrigation application should never cause runoff, it is important to note the risk that exceeding the soils infiltration rate and extreme over irrigation pose. Phosphates have the potential to cause excessive algae growth when introduced to aqueous environments, which can lead to eutrophication. A prime example of this is the impact that agricultural fertilizer is suspected to have on Lake Erie. In the 1960's and 1970's Lake Erie was often considered to be a dying or dead lake due to pollution from industrial wastes, sewage, and agricultural runoff (United States Environmental Protection Agency, 2022). However, since the 1990's there has been a noticeable increase in algal growth due to phosphorus from non-point sources which notably include row crop agriculture (Harrigan, 2015).

In 2014, growers in the United States paid on average 571 dollars per ton of urea (45% nitrogen) and 611 dollars per ton for diammonium phosphate (18% nitrogen and 46% phosphorus) (United States Environmental Protection Agency, 2022). Even considering the millions of tons of nitrogen and thousands of tons of phosphorous applied, this value pales in comparison to Lake Erie's 12.9-billion-dollar tourism industry and the value of restoration efforts on the lake (United States Environmental Protection Agency, 2022). Regardless of perspective, preventing leaching and runoff of applied fertilizers is beneficial for both agriculture and the environment from both an environmental and economic standpoint.

2.1.4 Irrigation Scheduling

Models for soil moisture and plant water usage range in complexity from basic water balances involving generalized crop water use, evaporative losses, and precipitation, to complex sets of equations that account for growth stage, rooting depth and other crop and soil characteristics. These types of models do not evaluate irrigation efficiency, but instead attempt to improve application volume and timing. In most cases the water applied as irrigation is actually subject to a factor that accounts for losses in the application. For example, based on a crop coefficient, daily water use can be found on a crop water use curve. By establishing the soils water holding capacity in the root zone and setting a minimum threshold, one can use this daily water use to find how long the water in the soil profile will sustain the crop. Volume can then be calculated by simply subtracting the current available water in the profile from the profile's maximum capacity (Harrison, 2005). While most would agree that leaving some water holding capacity to act as a buffer is advisable, this method is basic and yet still effective. Using these more basic parameters in conjunction with a local weather forecast is commonly referred to as checkbook scheduling. Some models have built off of this and include maximum infiltration rates to prevent runoff (Werner, 1993). The limits one selects for a field's minimum soil moisture can be determined by the maximum and minimum crop water stress index. This is a variable that shifts with crop and growth stage. This threshold serves as a baseline for determining when to irrigate and can greatly influence a crop's water use efficiency (Payero and Irmak, 2006).

In light of new technologies capable of attaining data and computing sets of equations, many models have been created with the intention of optimizing irrigation applications. For the most part, these more advanced models are based off of the same water balance, but they break down each component into data that can be collected or estimated in the field.

The most basic method of collecting data to create an irrigation schedule is to manually evaluate field conditions. This can be done with little more than a shovel, a ruler, and a notebook. The United States Department of Agriculture, Natural Resource Conservation Service provides the following guidelines:

USDA NRCS “Feel and Appearance Method” (USDA, 1998)

1. Collect samples of the soil at 1-foot increments throughout the root zone, for each depth perform the following
2. Attempt to create a “ball” with the soil by griping it in your hand a few times.
3. Attempt to make a ribbon with the soil by feeding it between your index finger and thumb.
4. Find the soil’s texture by assessing its ability to ribbon, firmness and surface roughness of ball, glistening appearance, and soil color. This step may also rely on how well the ball of soil remains intact after a few light bounces in one’s hand.
5. Estimate the available water percentage and depletion below field capacity by comparing observations with the photographs and charts supplied in the USDA NRCS Feel and Appearance Methods

These methods are reported to produce estimates which may be up to 95% accurate with experience and skill in carrying out the procedure (USDA NRCS, 1998). The end product of these methods is a sum of the depletion from each sampled are in the root zone, which is in theory the amount of irrigation that would need to be applied on that day to bring the soil profile back up to full capacity. The counterpart to this value is the amount of available water left in the soil profile. This method does not include a projection for creating a schedule but rather is focused on the current soil conditions. While these methods do take some skill to perfect, they are very cost effective and simple in nature.

To improve further on making better use of each irrigation application, one must account for the climatic conditions in the field and be able to accurately forecast them in the near future. Accounting for the climatic conditions of the field allows for the modeling of all inputs and removals of water from the system. This type of "model" is referred to as a weather-based schedule and provides the basis to help improve the timing of each irrigation application. Knowing how much water is in the soil profile is still just as important with this type of method as in the previous. However, weather-based scheduling goes a step further allowing one to work with the water that nature gives and takes to maintain enough water to keep plants in good condition.

Assuming one has cellular signal or some kind of internet connection, data can be sent in real time from dataloggers and directly applied to these equations that make up the model as opposed to manually collecting the data. Alternatively, one can download data from their local weather station. While data collected outside of the area being managed is subject to some level of variation, local data can still be of great use in making estimates for irrigation management. The MSU Irrigation Scheduler has the benefit of accounting for many parameters like crop, rooting depth, soil type, growing degree days, precipitation, crop stage, and soil moisture to optimize irrigation applications. This Irrigation scheduling program is based in excel and is free to access and utilize. This Irrigation scheduling program essentially models the field conditions using several sets of equations in excel along with the fields data and data from the closest MAWN weather station. Once the field's current conditions are established, this program estimates the irrigation required in the next week based off of automated weather forecasts focusing on changes due to evapotranspiration and precipitation. This method of modeling allows us to set soil moisture thresholds to keep a consistent irrigation application between different areas. By adjusting the threshold and irrigation application volume using this program, we intend to find the irrigation application which will optimize crop yield and irrigation water use.

Aquacrop is another model that can be used to improve irrigation water use efficiency. Similar to MSU's Irrigation scheduler, Aqua crop accounts for several environmental and crop specific variables. However, instead of focusing solely on the immediate irrigation scheduling for a field, Aquacrop projects the effects that the environment and management of a crop have on its productivity (Food and Agriculture Organization of the United Nations, 2022). While this does have some merit, it should be widely known that we do not have the capability to project weather patterns that impose positive or negative impacts on crop productivity over the course of an entire growing season with a high level of confidence. Thus, the precision of any model attempting to make this type of long-term projection is inherently limited at this time. While this program does allow one to project the growing season or retroactively view the growing season to find the stress points of the crop, it does not schedule irrigation as effectively over short intervals. Thus, Aquacrop is rarely used in this project.

The final type of scheduling method used to model the irrigation needs of a field is Sensor Based Irrigation Scheduling. This method utilizes readings from sensors to assess the available water in the soil profile in close to real time. In theory this method would allow one to irrigate exactly when the soil moisture falls below an acceptable threshold, even to the point of having a completely automated irrigation system. However, to make the best use of irrigation water, future precipitation and evapotranspiration should be accounted for. To do this one must find local values for the crop's evapotranspiration and subtract them from the amount of available water. A Reputable forecast for local rainfall should be used to time irrigation so that the profile has room to store the precipitation as opposed to allowing it to drain and leach nutrients.

2.1.5 Soil Moisture Estimation by Calculation

In its most basic sense, water use efficiency can be defined as a crop's yield per amount of water received by the field. While this parameter is useful, it lacks the detail to establish exactly how much water was actually used by the crop, how much of the precipitation came from irrigation as opposed to rainfall, and how much of the irrigation water drained below the crops rootzone at the time of the application. Comparing the yield of a similar area of the field that receives no irrigation to an irrigated portion of the field and produces an area's relative yield. Dividing relative yield by the amount of irrigation applied to the irrigated portion of the field creates the fields irrigation water use efficiency. Both of these measurements are based strictly on the irrigation and yield of a field. There are many other aspects of Irrigation efficiency which one may choose to evaluate, including perspectives from physiological, Irrigation science, agronomic, and economic viewpoints (Nair et al., 2013).

Some experts have considered variables that are correlated to irrigation water use and crop yield. Some have chosen to observe the carbon gains of a plant or small plot of a crop as compared with the precipitation that was received. This has been done by observing instantaneous carbon flux of a plant or as biomass accumulation over time (Bacon, 2004, Kramer, 1983). While this parameter is useful for a crop grown for total biomass, like alfalfa or switchgrass, it loses relevance when applied to grain and fruit crops as vegetative growth and reproductive growth vary substantially. The intrinsic water use efficiency of a crop is defined as the ratio of carbon dioxide assimilated into a plant as opposed to the amount of carbon dioxide released by the plant as transpiration (Cordon et al., 2002). Alternatively, this parameter can observe the carbon dioxide exchange of a canopy or single leaf to estimate the crop's yield (Sinclair, et al 1984). Water use efficiency can also be written in terms of a photosynthetic parameter, as in the case of the transpiration ratio which is a physiological constant dependent on the crop over the saturation deficit of the surrounding atmosphere (Monteith, 1986). While all of these parameters at least relate the crops yield and water use, they are not direct comparisons and thus introduce the potential for error. Some methods of irrigation like that of flooding via diverted surface water introduce too many potential factors to come to good conclusions but can be evaluated per component and compound to base decisions off of (Burt et al., 1997).

In a more sophisticated system like drip, sprinkler, or center pivot irrigation, several efficiencies can be observed. Application efficiency refers to the amount of water withdrawn from the environment compared with the amount of water used by the crop (Kruse,1978). This parameter does not account for the water lost to drainage, in air evaporation, or water that is scattered and never reaches the crop. This missing water is accounted for in equations like that of irrigation system efficiency irrigation system efficiency which is the amount of water conveyed and distributed by the irrigation system to a location the plant can utilize it divided by the total irrigation water withdrawal. This can be considered on a per application basis or over the course of a season (Bos and Nugteren, 1990). Similarly, field application ratios evaluate how adequately the crop was watered and can be defined as the amount of irrigation needed by the crop divided by the volume of water which was applied to the crop (International Commission on Irrigation and Drainage, 1978). These parameters adequately evaluate the water application compared with a crop's needs, but they miss the bigger picture including the final product. The crops yield is included in the simplified version of irrigation water use efficiency mentioned earlier. This definition is formally defined as crop water use efficiency, being the total crop yield per unit area divided by the total volume of irrigation applied to the field (Gregory, 2004). While this makes no attempt to account for underlying variables via comparison with a control area, it is effective in making a basic estimation of how well the crop converted water to end product. This equation can be modified to create more precise estimations of different parameters. A prime example of this is the equation for water productivity which includes rainfall to help eliminate the impacts of rainfall variations (Playan and Mateos, 2004).

2.1.6 Soil Moisture Sensors

In order to make any use of the forementioned equations or models, one must collect data that is at least closely correlated and more preferably as directly related as possible to the parameters described. There are many different brands and models of data logging systems and sensors available for purchase, such as Watermark, Campbell scientific, and meter group. Alternatively, some companies provide platforms from which one can design and build their own data loggers from.

Regardless of exact brand and model, some of the most pertinent parameters that should be measured in order to make informed irrigation decisions include soil moisture, precipitation, temperature, and relative humidity. With proper placement soil moisture sensors allow one to observe the changes in water available to the plant over time. While this is not a direct method due to the fact that one must estimate part of an entire soil profile based on one or more sensors that use either electrical conductivity or resistance to evaluate the amount of water present in the soil's pores. Assuming one uses a sensor that measures soil moisture via water matric potential like the watermark 200ss, values must be converted to find soil water availability and content. This type of sensor reports readings as a pressure and is typically converted to available water by evaluating the soil's water holding capacity and a threshold corresponding to the crop's wilting point.

The need to calibrate one's sensors based on the soil's dry, wet, and field weight does not change with model of sensor or brand. Despite some companies claims, even if sensors read properly out of the box, one still needs to know the values for water holding capacity and desired available water threshold to make informed decisions on their irrigation applications and potentially irrigation water use efficiency.

Similarly, if one is to use a resistance-based sensor like that of the Metergroup EC-10, Metergroup Terros 12, or Campbell scientific CS 650, the parameter being assessed is actually electrical conductivity. While this is also not a direct measurement of soil water content, it's widely accepted to convert this measurement. Once again, the most direct measurement of soil water content is conducted by oven drying soils and measuring the change in weight.

Several models of soil moisture sensors were utilized for this research to prevent data collection biases and improve relatability with other studies. Models used include Metergroup Terros 12 and HS 10, Soil watch 10 and Campbell Scientific 650 cc. All soil moisture data collected is data from a set time span which is averaged to give us smoother data that better represents the changes in soil moisture over time. The reported data is calibrated based on the soil moisture found by observing the change in mass after oven drying the soil, and temperature correction factors discussed in the last chapter.

In order to evaluate the total amount of water in the rooting zone, the current root depth must be known. While models can estimate this value, digging a soil pit can be beneficial in improving the precision of this estimate. Assuming one has placed multiple sensors at different depths, the rooting zone can be broken up based on sensor location. This allows one to account for differential water content due to changes in soil texture and type. Generally, it is recommended that each layer of soil in the soil profile is sampled by at least one sensor. Additionally, one should place one sensor just below the maximum rooting depth of the crop. As the crop sends down its roots, sensors below their reach can help alert one of potential water losses due to drainage. Soil is inherently variable over space and time, even with sensors at multiple depths, it may be necessary to install several replications to ensure quality of data for the basis of irrigation management (Irmak et al, 2022).

Aside from soil moisture, most sensors involved in irrigation management and scheduling are focused on evapotranspiration with the exception of rain gages. Temperature and relative humidity in combination can be used to evaluate evaporative water losses. The amount of water the plant theoretically holds can be estimated, however is not typically as concerning as the water applied to the system and the removals. Precipitation, be it irrigation or rainfall, is commonly measured using a rain gage with a funnel like collection bucket of known collection area. Water is then directed into a carefully balanced bucket which empties at a set volume, tripping a counting device that is detected by the datalogger. Unfortunately, these devices need to be cleaned frequently and calibrated in order to collect accurate data. Companies making this type of rain gage include Watermark, Campbell scientific, and Davis among others. Metergroup has developed a rain gage that measures rainfall based on light refraction from a laser which water is funneled by. While some revere this as a superior system, few have formally evaluated and reviewed it.

Although not directly related to irrigation water use efficiency, leaf wetness sensors can be a valuable asset in scheduling irrigation. This type of sensor measures the duration that the crop is subject to dew or other forms of precipitation. This is especially useful during wet years when the risk of disease for a given crop is high. By timing irrigation applications to occur when the crop would theoretically already be wet or would dry quickly, total wetting duration can be minimized reducing the risk of many yield impacting fungi, molds, and rots. This can help to improve yields and therefore crop water use efficiency. For example, Tar spot is a foliar disease that has recently became more prevalent in cornfields of the Midwest. Depending on timing and severity, Tar spot can cause yield losses in excess of 20 bushels per acre (Telenco and Creswell, 2019). Like many foliar diseases, Tar spot is dependent on foliar moisture to maintain a proper environment for infection. This means that it can be partially mitigated by minimizing leaf wetting duration. Similarly, white mold can have a substantial impact on soybean yield. Particularly in the damp, low areas of a soybean field with reduced airflow, white mold can thrive beneath a closed canopy. While not as directly tied to leaf wetting duration, moist conditions are suggested to increase its prevalence. In a study involving several fields in South Dakota yield losses were estimated at over 50% (Mfuka et al. 2020). While irrigation is only one of many components involved in disease risk, any factor that can reduce risk may be worth monitoring.

2.2 Conclusion

In conclusion, the need to maximize crop production while conserving water quality availability. Fortunately, growers have better access to technology meant to improve Irrigation water use efficiency and crop productivity than ever before. By utilizing Irrigation scheduling and crop models, water use, and crop production can be optimized.

Unfortunately, there are still several factors that impact crop productivity and irrigation water use efficiency which are not fully understood. Perhaps the most relevant factor is sensor placement, without extensive sampling it is difficult to establish exactly how many sensors are required to accurately portray the soil moisture at a particular depth and location in the field. Soil varies throughout a field, both spatially and temporally (Irmak et al., 2022). It may be necessary to place multiple sensors per depth and location in order to gain the most beneficial Soil moisture data. Poor sensor placement may result in accurate data that misrepresents the soil moisture in the rooting zone. This could easily lead to mismanaging one's irrigation, potentially reducing crop yields, and increasing water usage.

Additionally, there are relatively few formal studies confirming the impacts of a theoretically optimal irrigation application for a site. In theory, optimized irrigation applications via sensor based or weather-based management should maintain proper soil moisture while minimizing irrigation water use, leading to better yield and reduced water use. It is logical that sensor-based scheduling and scheduling methods could optimize the irrigation applications for a small testing plot, however few have done this at the field scale with replications to back up their findings.

Chapter 3. Temperature Spectrum Calibration of Soil Moisture Sensors in Sandy Soil

3.1 Introduction

Soil moisture sensing is a crucial component in agricultural management, environmental monitoring, and hydrological studies. Accurate soil moisture data can significantly impact crop yield predictions, irrigation scheduling, and climate models. However, for these sensors to provide reliable data, they must be properly calibrated. Calibration involves adjusting the sensor readings to align with known reference values, which ensures that the data collected is both accurate and consistent. This process is vital because soil moisture sensors can be affected by various factors such as soil type, temperature, and sensor installation depth. Without proper calibration, the data from these sensors can be misleading, leading to poor decision-making and inefficient resource use.

3.1.1 Soil and Sensor Properties

The calibration of soil moisture sensors is heavily influenced by the intrinsic properties of both the soil and the sensors themselves. Soil properties such as texture, structure, density, and composition play a significant role in how moisture is retained and how it interacts with sensor probes. For instance, clay soils have a high water-holding capacity but slow drainage, whereas sandy soils drain quickly but retain less moisture. These differences necessitate specific calibration curves for different soil types to ensure accurate measurements.

Sensor properties, including their technology (e.g., capacitive, resistive, or time-domain reflectometry), sensitivity, and response time, also affect their calibration. Capacitive sensors measure the dielectric permittivity of the soil, which changes with moisture content, while resistive sensors measure the electrical resistance between two probes, which decreases as soil moisture increases. Time-domain reflectometry (TDR) sensors use the travel time of an electromagnetic pulse to determine soil moisture content. Each type of sensor requires a unique calibration approach to account for these different measurement principles.

In addition to these fundamental properties, environmental factors such as temperature can influence sensor readings. Temperature fluctuations can cause changes in sensor output, necessitating temperature compensation during calibration. Sensor installation depth is another critical factor; sensors installed at different depths can yield varying moisture readings due to the soil's moisture gradient with depth.

3.1.2 Background of Scientific Community Efforts

Over the years, numerous studies have focused on the calibration and validation of soil moisture sensors to improve their accuracy and reliability. Early research primarily involved laboratory calibration, where sensors were tested under controlled conditions to develop calibration curves for different soil types. Laboratory calibration is essential for understanding the fundamental behavior of sensors in ideal conditions, but it does not always translate well to field conditions where soil properties and environmental factors vary significantly.

Field calibration has gained prominence as it accounts for the dynamic nature of soil moisture and environmental variability. Field calibration involves placing sensors in actual field conditions and adjusting their readings based on in-situ measurements. This approach provides a more realistic representation of sensor performance in diverse soil types and environmental conditions. For instance, the work by Walker et al. (2004) demonstrated that calibration procedures must consider soil-specific properties to achieve accurate measurements across different soil textures.

One of the critical factors affecting soil moisture sensor readings is temperature. Temperature fluctuations can cause changes in sensor output, which necessitates temperature compensation during calibration. Sensors often exhibit temperature sensitivity because soil dielectric properties, electrical conductivity, and sensor electronics themselves can vary with temperature. For example, capacitive sensors measure the dielectric permittivity of the soil, which changes with both moisture content and temperature. Similarly, resistive sensors measure the electrical resistance between two probes, which can decrease as soil moisture increases but can also be influenced by temperature changes.

Temperature compensation involves creating calibration models that account for these variations. Researchers have developed various methods to incorporate temperature corrections into soil moisture readings. One common approach is to conduct calibration at multiple temperatures and develop correction factors or equations that adjust the sensor output based on the measured soil temperature. Studies have shown that including temperature corrections can significantly improve the accuracy of soil moisture sensors. For example, Kizito et al. (2008) analyzed the frequency, electrical conductivity, and temperature dependence of a low-cost capacitance soil moisture sensor and developed a calibration method that accounted for temperature variations.

Advanced calibration techniques have also emerged to enhance the accuracy and reliability of soil moisture sensors. Machine learning and data assimilation methods have gained traction in recent years. These approaches leverage large datasets and sophisticated algorithms to improve calibration accuracy. Chaney et al. (2017) utilized machine learning to develop predictive models for soil moisture content, incorporating a wide range of soil and environmental variables. These models can dynamically adjust sensor readings based on current soil and environmental conditions, including temperature.

The integration of remote sensing technologies with ground-based sensors has enhanced the spatial and temporal coverage of soil moisture data. The synergy between satellite observations and in-situ sensors has led to more comprehensive calibration frameworks. For example, the Soil Moisture Active Passive (SMAP) mission combines satellite and ground-based measurements to provide high-resolution soil moisture data. Das et al. (2010) discussed how the SMAP mission developed algorithms to merge radiometer and radar data, improving the accuracy of soil moisture retrievals by incorporating temperature and other environmental corrections.

Despite these advancements, there is still a need for continuous improvement in sensor calibration methods to better compensate for environmental conditions, including temperature variations. Temperature effects can vary widely depending on the sensor type, soil type, and environmental conditions. Therefore, ongoing research is necessary to develop more robust calibration protocols that can be universally applied across different sensor models and field conditions.

3.1.3 Knowledge Gap in Calibrating the Soil Watch 10 Soil Moisture Sensor

The calibration of many specific sensor models has not been formally studied, as is the case for the Soil Watch 10. This sensor, known for its affordability and ease of use, has been adopted by researchers and industry. However, comprehensive calibration studies specific to this model are lacking. Most available calibration data are generalized and do not account for the unique characteristics of the Soil Watch 10, such as its response to different soil textures and environmental conditions.

Addressing this gap requires that calibration protocols, similar to that of other sensors, be applied to the Soil Watch 10. This involves extensive field testing across various soil types and environmental settings to establish reliable calibration curves. Incorporating corrections specific to this sensor model is essential for enhancing its accuracy. While significant strides have been made in the calibration of soil moisture sensors in general, the Soil Watch 10 requires targeted research to fully realize its potential. Accurate calibration is crucial for ensuring that soil moisture data collected by this sensor is dependable and useful for a range of applications, from agriculture to climate science.

3.2 Methods

This study aimed to assess the performance of different soil moisture sensors in a temperature-controlled environment using three soil chambers with fixed soil moisture. The selected sensors included the Pinotech Soilwatch-10, Metergroup TEROS-12, Metergroup-10 HS, and the Watermark Soil Block. Each of these sensors estimates soil moisture using a slightly different method. The experiment was conducted using three replicates within the same environment to evaluate the relative accuracy, precision, and reliability of each model of sensor under varying soil temperatures.

The Soilwatch-10 senses soil moisture utilizing the soil's capacitance as the property of measurement. As soil water content increases, the capacitance of the soil surrounding the sensor also increases, allowing for values of capacitance to be analyzed and represent the soil's moisture.

3.2.1 Pinotech Soilwatch-10 Specifications

Soilwatch-10 Specifications (Pinotech, nd)

- Soil Moisture Range: 0% to 100% VWC (Volumetric Water Content)
- Accuracy: Typically, ±3% VWC
- Temperature Measurement Range: -20°C to +60°C

Similarly, The Metergroup-10 HS also uses capacitance to estimate soil moisture. Instead of directly assessing dielectric permittivity, the sensor uses a frequency domain measurement technique. The sensor emits a high-frequency signal into the soil, and the changes in the signal are used to determine the soil's moisture content.

3.2.2 Metergroup-10HS Sensor Specifications

10-HS Sensor specifications (Metergroup, n.d., 10-HS)

- Soil Moisture Range: 0% to 57% volumetric water content (VWC)
- Accuracy: ±3% VWC (typical)
- Dielectric Measurement Frequency: 70 MHz
- Operating Temperature Range: -40°C to +60°C

Lastly, the Metergroup Teros 12 employs a Time Domain Reflectometry (TDR) method. It sends an electromagnetic pulse along a waveguide inserted into the soil. The time it takes for the pulse to travel back is measured, and this time delay is related to the soil dielectric constant, which, in turn, is correlated with soil moisture content.

3.2.3 Metergroup Teros-12 Specifications

Teros 12 sensor specifications (Metergroup, n.d., teros-12)

- Soil Moisture Range: 0% to 100% VWC
- Accuracy: ±1% VWC typical after soil-specific calibration
- Dielectric Measurement Frequency: 70 MHz
- Temperature Measurement Range: -40°C to +60°C
- Electrical Conductivity Range: 0 to 23 dS/m

While the Watermark Soil Block sensors were installed, complications with the dataloggers and the relatively high soil moisture made the data unsuitable.

3.2.4 Soil Chamber Setup

Three identical soil chambers were set up for this experiment. Each soil chamber consisted of a 28.6” x 19.6” x 15” (72.6 cm x 49.8 cm x 38.1 cm) rectangular container made of non-reactive materials to prevent external interference with sensor readings as seen in figure one. The chambers contained a soil profile consisting of primarily sand to simplify the process of maintaining soil moisture and ensure consistent conditions amongst the different chambers. Additionally, sand, having a lower specific heat and density as compared to clay or silt, is favorable for observing temperature and soil moisture fluctuations at a constant soil water content (DeVeries, 1963).

Figure 1. Soil chamber components and construction.

To enhance drainage and capillary water movement, 0.38-inch (9.53 mm) holes were drilled in a grid pattern at approximately a four-inch (10.16 cm) interval as seen in figure 2. A layer of weed guard mesh was placed at the bottom of the container and a second layer was placed immediately above a 2-inch (5.08 cm) layer of pea gravel. These medias allowed for proper drainage and capillary action to fix the soil moisture at a consistent level, near the sand's field capacity. Additionally, these layers eliminate loss of the soil, acting as a porous screen.

Figure 2. Soil chamber with drainage holes.

While the soil chambers were initially irrigated from above to settle the soil (figure 3), the soil moisture was controlled via capillary uptake once the experiment was initiated within the cooler. Moisture regulation was controlled by maintaining the water level at 2 inches (5.08 cm) above the bottom of the soil chamber throughout the duration of the experiment, allowing for capillary action to take place. This was accomplished by placing each chamber inside a water tub and elevating the soil chamber using several 2” (5.08 cm) wooden spacers as seen in figure 4. The spacers were offset from the grid of drainage holes that permitted capillary uptake of the water to prevent obstructions. The water tub was then filled to a depth of 4” (10.16 cm), submerging the bottom of the soil chamber in 2 inches (5.08 cm) of water. This method of maintaining moisture was done to prevent altering the soil’s structure around the sensors and ensure consistent moisture over the duration of the experiment.

Figure 3. Initial surface irrigation of soil chambers.

Four soil moisture sensors were installed in each soil chamber, spaced evenly with a minimum of 6 inches (15.24 cm) between probes in a horizontal orientation seen in figure 4. To further protect the readings of each sensor, the initiation of data collection was offset for each model of sensor. Data was collected hourly since temperature was increased over a manor of days, ensuring sufficient data points for a comprehensive analysis.

Figure 4. Layout of sensor installation.

A large walk-in cooler was used to control the air temperature surrounding the soil chambers, gradually increasing the soil temperature in a controlled manner. The sensors' responses were monitored between 37°F (3 C) and 70°F (21 C) as these are the bounds of typical growing season soil temperatures in Michigan's soils, as observed by several data sets on the Michigan Automated Weather Network (MAWN, 2024). Manipulation of the air temperature was limited by the abilities of the cooler and potential freezing of the water to be drawn into the soil chamber and by the ambient temperature of the building housing the cooler.

3.3 Results

Figure five displays a linear negative response from the Teros 12 sensor to increasing soil temperature in replication one.

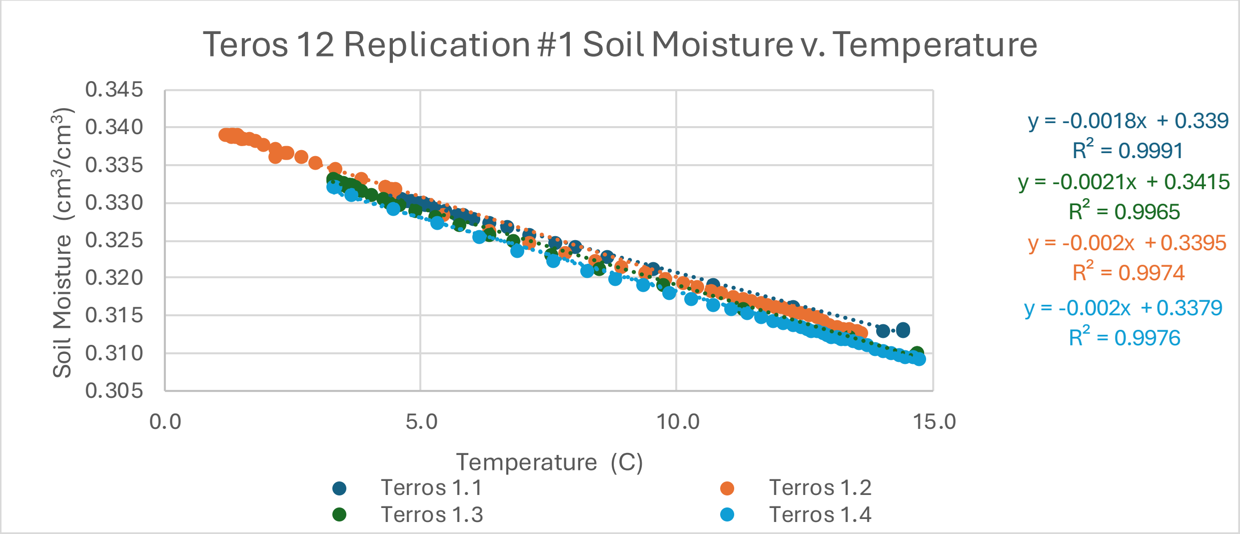

Figure 5. Metergroup Teros 12 replication one plotted as a function of temperature.

Figure six displays a linear negative response from the Teros 12 sensor to increasing soil temperature in replication two.

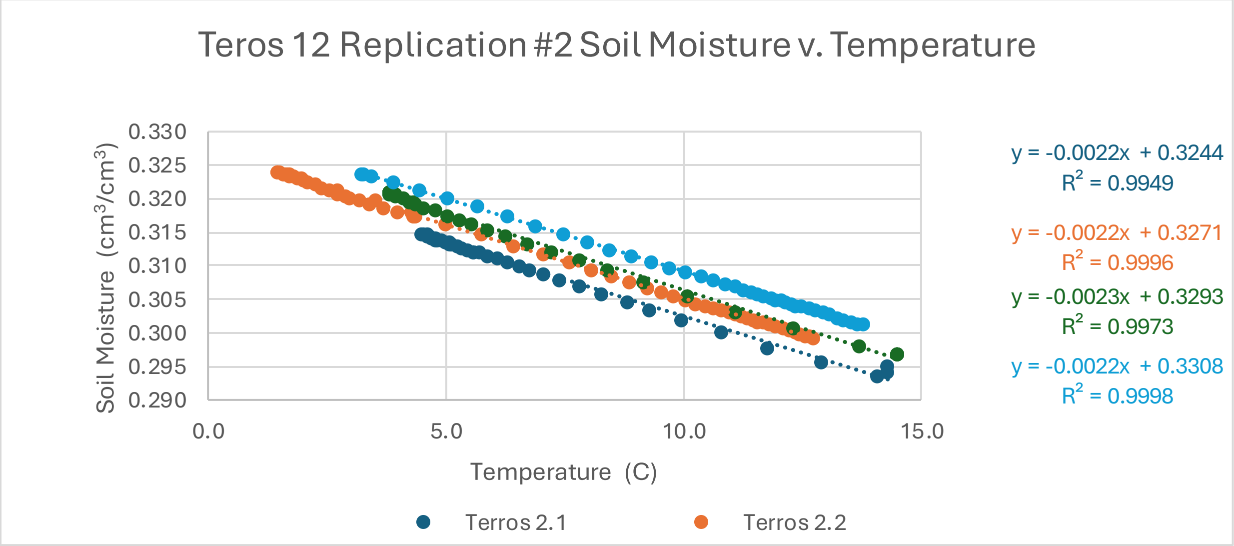

Figure 6. Metergroup Teros 12 replication two plotted as a function of temperature.

Figure seven displays a linear negative response from the Teros 12 sensor to increasing soil temperature in replication three.

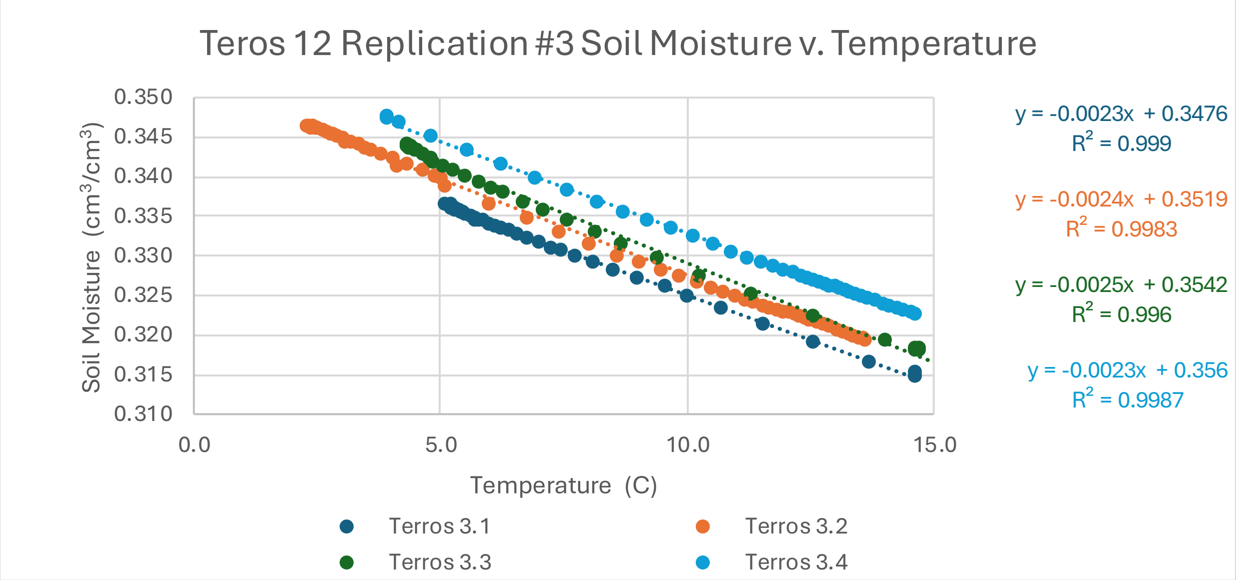

Figure 7. Metergroup Teros 12 replication three plotted as a function of temperature.

Figure eight displays a semi-linear negative response from the Metergroup 10HS sensor to increasing soil temperature in replication one.

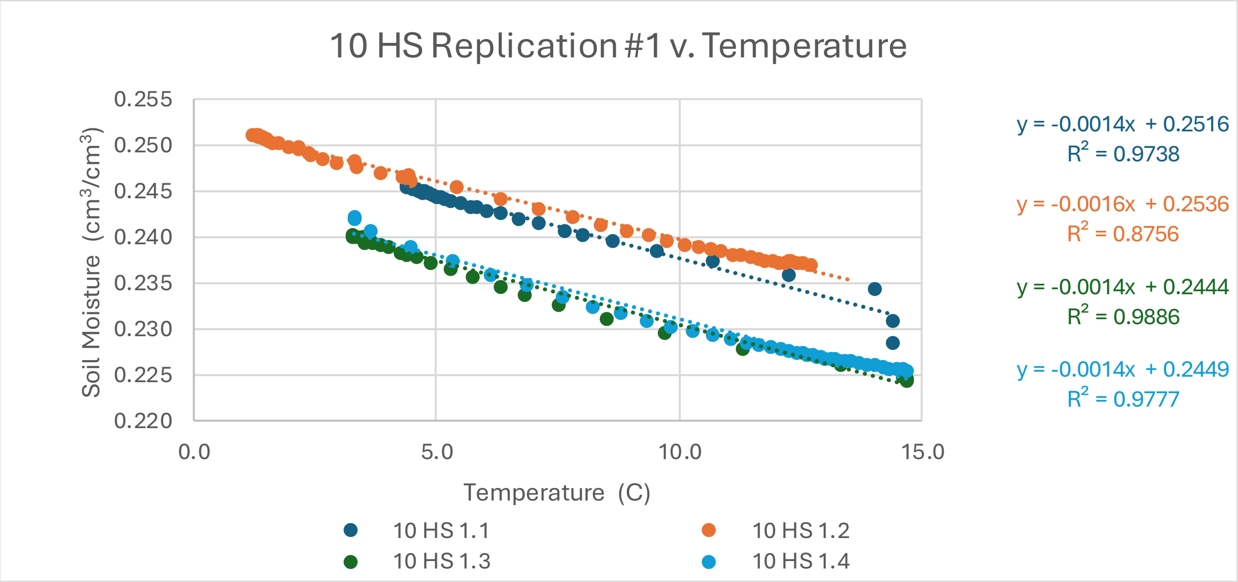

Figure 8. Metergroup 10 HS replication one plotted as a function of temperature.

Figure nine displays a semi-linear negative response from the Metergroup 10HS sensor to increasing soil temperature in replication two.

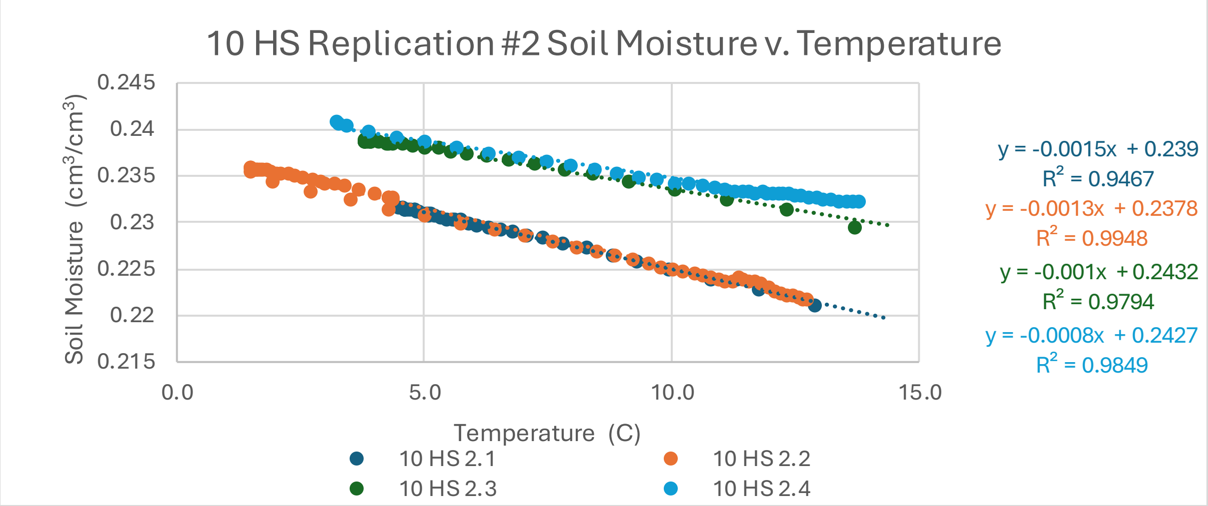

Figure 9. Metergroup 10 HS replication two plotted as a function of temperature.

Figure ten displays a linear negative response from the Metergroup 10HS sensor to increasing soil temperature in replication Three.

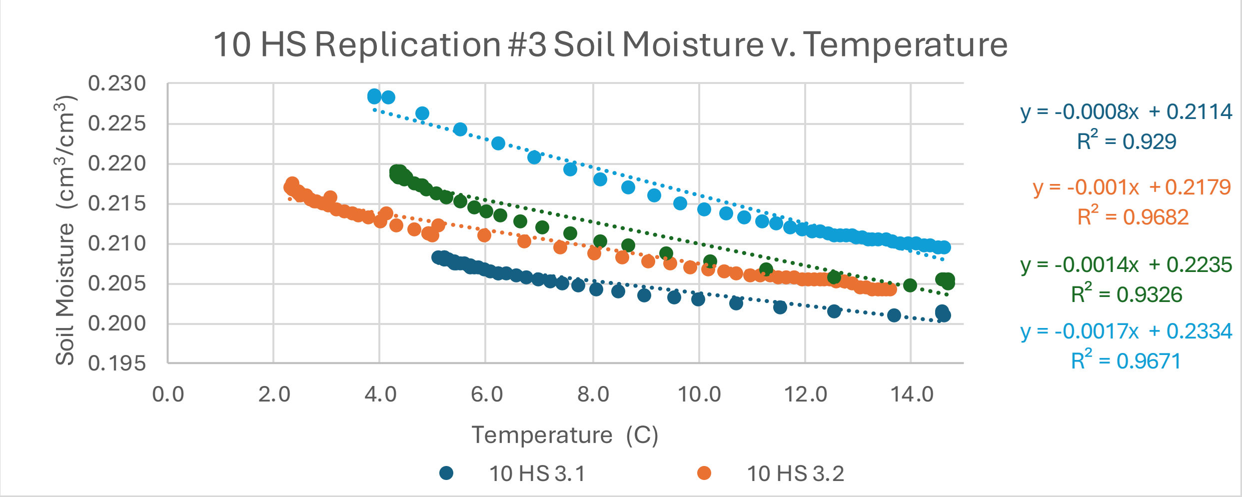

Figure 10. Metergroup 10 HS replication three plotted as a function of temperature.

Figure eleven displays a linear positive response from the Pinotech Soilwatch-12 sensor to increasing soil temperature in replication one.

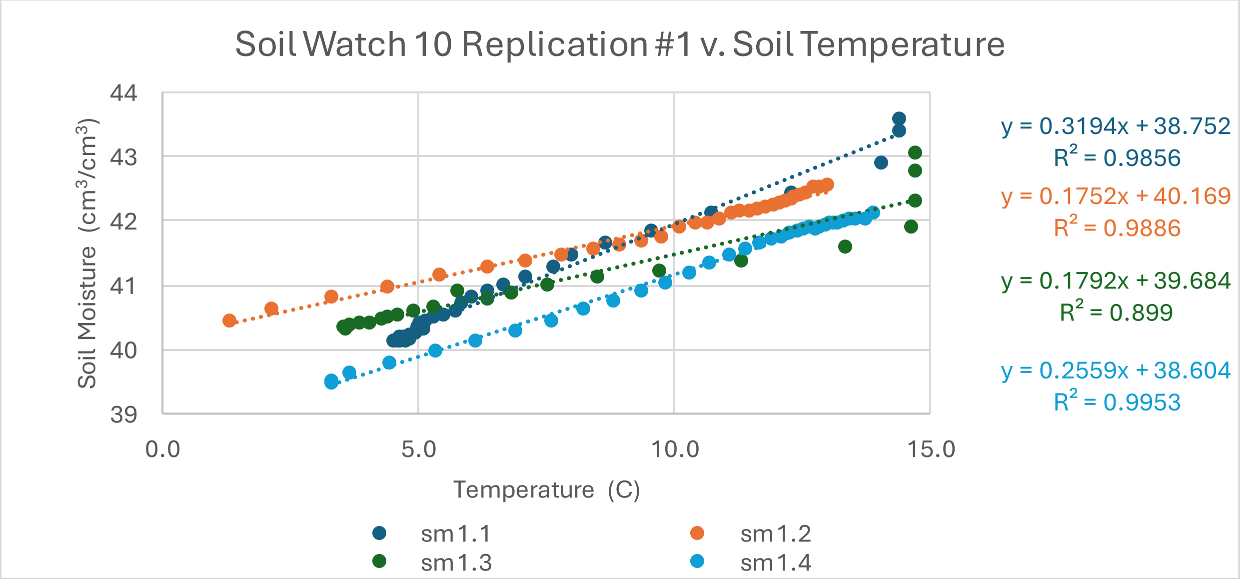

Figure 11. Pinotech Soilwatch 10 in replication one plotted as a function of temperature.

Figure twelve displays a linear positive response from the Pinotech Soilwatch-12 sensor to increasing soil temperature in replication one.

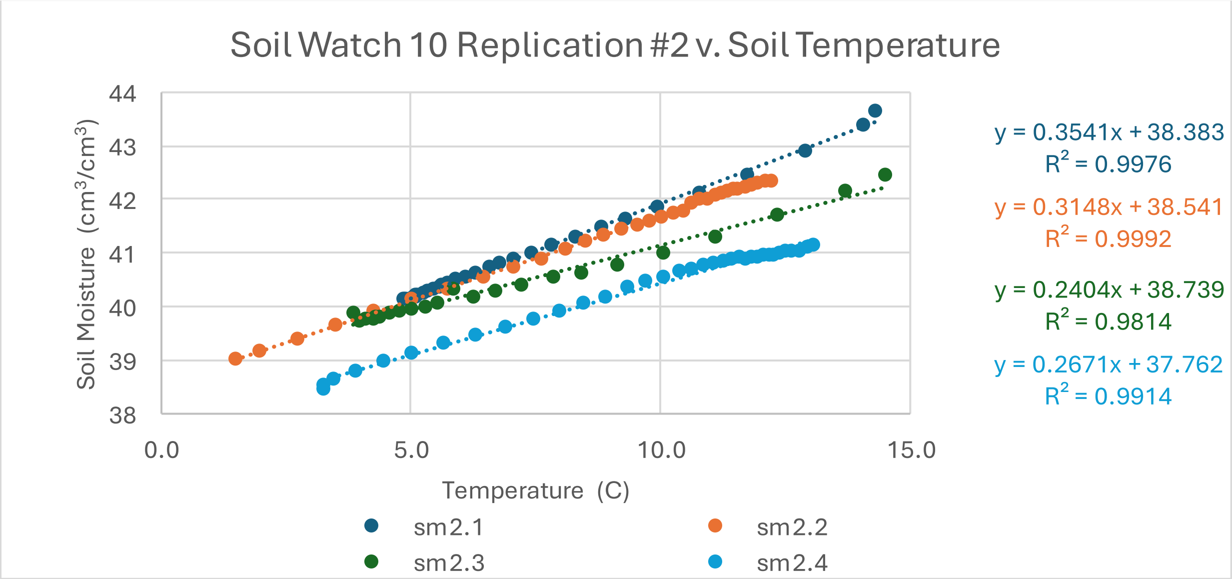

Figure 12. Pinotech Soilwatch 10 replication two plotted as a function of temperature.

Figure thirteen displays a linear positive response from the Pinotech Soilwatch-12 sensor to increasing soil temperature in replication three.

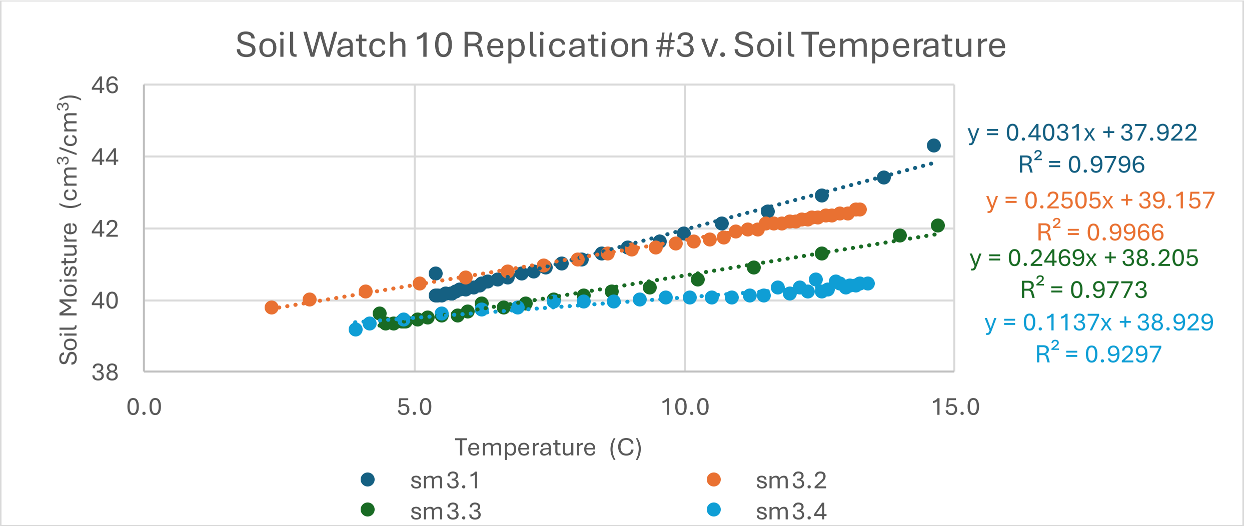

Figure 13. Pinotech Soilwatch 10 replication three plotted as a function of temperature.

Data from the slopes of the linear trendlines for each sensor and replication is summarized into table one. Using the assumption that soil moisture was held constant at near field capacity and there was negligible disturbance, the trends in the data can be attributed solely to the effect of temperature on the soil moisture sensors' readings. Variation, standard deviation and confidence intervals are also included in the table for comparison between sensors.

Table 1. Temperature correction factor analysis

Sensor Factor	**Terros 12**			**10 HS**			**Soilwatch 10**		
	Bucket #1	Bucket #2	Bucket #3	Bucket #1	Bucket #2	Bucket #3	Bucket #1	Bucket #2	Bucket #3
Trial 1	-0.0018	-0.002	-0.002	-0.0014	-0.0015	-0.0008	0.3194	0.3541	0.403
Trial 2	-0.0021	-0.002	-0.002	-0.0016	-0.0013	-0.001	0.1752	0.3148	0.251
Trial 3	-0.002	-0.002	-0.003	-0.0014	-0.001	-0.0017	0.1792	0.2404	0.247
Trial 4	-0.002	-0.002	-0.002	-0.0014	-0.0008	-0.0014	0.2559	0.2671	0.114
Bucket Average	-0.002	-0.002	-0.002	-0.0015	-0.0012	-0.0012	0.2324	0.2941	0.2536

Table 1. (cont’d)

Bucket Variation	2E-08	2E-09	9E-09	1E-08	1E-07	2E-07	0.0047	0.0025	0.0140
Bucket Standard Deviation	0.0001	5E-05	1E-04	0.0001	0.0003	0.0004	0.0689	0.0505	0.1183
Overall Average	-0.0022			-0.0013			0.260		
Overall Variation	0.000000037			0.000000091			0.00652		
Overall Standard Deviation	0.00019			0.00030			0.0807		
95% Confidence value	0.00012			0.00022			0.0713		
Lower Confidence Interval	-0.0023			-0.0015			0.1887		
Upper Confidence Interval	-0.0021			-0.0011			0.3313		

3.3 Discussion

In General, all sensors included in the results were influenced by altering soil temperature. Unsurprisingly, this includes those that claim to already have temperature calibration capabilities included in their programing (Metergroup, n.d.). Most companies strongly recommend diligent testing and calibration prior to installation for data collection purposes to avoid this form of error. This further emphasizes the benefits of sensors with integrated temperature data collection or the use of separate temperature sensors to provide values for calibration.

The differences in polarity of slope between the Metergroup and Pinotech sensors are perhaps the most obvious difference in the data. While the results from the Metergroup 10-HS and Teros-12 are both negative and seemingly small (figures 5 - 10), the Pinotech Soilwatch-10 has a much larger slope that is positive seen in figures 11, 12, and 13. This does not automatically indicate a more accurate sensor or even a lesser need for calibration. Since the systems operate based on different principles and have different programing, their readings report differently. This is a good reason to estimate available water using soil moisture data as opposed to directly basing decisions off of soil moisture (Dong et al. 2020). While the readings of the Soilwatch-10 fluctuate more, its range is centered on a scale that is orders of magnitude larger. Since the core principle to this study was to hold soil moisture as constant as possible, it’s not possible to observe each model of sensor’s range nor its sensitivity. This blocks the ability of the study to directly determine each model’s performance and isolates the error due to changes in temperature.

In table one, numeric data can be seen for further analysis and comparison. Despite the data not being reported identically, their data can still be loosely compared. The soil watch sensors have a much higher slope which correlates to the resulting temperature calibration factor. This is not necessarily an issue as its linear and easily compensated for. However, in comparison to the Metergroup sensors, the Soilwatch-10 sensor’s variability (0.00652) and standard deviation (0.0807) are higher indicating less stable readings and less consistency between sensors. Sensor to sensor variability and sensor stability can also be improved using filtering and in-field calibration methods (De Vos, 2021). However, differences in sensor performance can be observed in the variation and size of each sensor model's confidence interval on the correction factor for temperature calibration in comparison to each sensor's range of readings and average slope. Observing average correction factor value, which is the average slope of each model's trendlines, in comparison to the average variation, the Metergroup sensors are more consistent on average. That said, the Soilwatch-10 can be purchased for under 20 U.S. Dollars (Pinotech, n.d.), whereas the Metergroup sensors tend to cost several times more (Metergroup, n.d.). Soil within the context of agricultural fields can be highly variable, requiring several sampling locations to accurately assess the soil moisture and irrigation needs of a single field (Zotarelli & Pharanhos, 2016). All sensors improve more than 1% of the value of their readings using the calibration factors in table one along with their average intercept value to correct for temperature drift. Although this value may seem insignificant, one percent volumetric soil moisture accounts for a larger proportion of plant available water. This inflated version of the sensor's reading gives a more easily understood view of soil moisture for irrigation and could make a difference in application timing, potentially increasing the efficiency of an application.

3.4 Conclusion

In summary, temperature effects on soil moisture sensor readings differently depending on the sensor's method of parameter estimation. For the Soilwatch-10, temperature is positively related to sensor readings with a calibration factor of 0.260 and an offset of 38.7. The 10-HS and Teros-12 had a negative correction factor of 0.0013 and 0.0022 as well as an offset of 0.0237 and 0.340 respectively. Using these formulas to calibrate each model of sensor enhances the accuracy of their readings and can have real world benefits when the data is used to make informed decisions.

Chapter 4. On Farm Demonstration of Improving Water Use Efficiency using In-Situ Soil Moisture Monitoring

4.1 Introduction

Irrigation is a crucial practice to increase crop yields, diversify crop varieties, and mitigate the risks from climate variability and water scarcity (USDA, 2012). Irrigated farms in the U.S. represent a minority in terms of land use and agricultural production but contribute a substantially higher proportion of the country's agricultural output, highlighting the importance of irrigation in sustaining agricultural productivity and livelihoods (Food and Agriculture Organization, 2002). In the Great Lakes region, the demand for irrigation is increasing since it serves as a vital tool for enhancing crop production and ensuring agricultural resilience (Cheu, S., & Gammans, M., 2023). Despite being a water-rich region, the Great Lakes states face challenges related to seasonal water availability and variability, particularly during critical growing periods.

Irrigation helps mitigate these challenges by supplementing natural precipitation and providing consistent water supply to crops, thereby maintaining soil moisture levels crucial for plant growth and productivity. In Michigan specifically, where only a small percentage of land is irrigated, the value of irrigated crops exceeds this proportion due to the cultivation of high-value crops under irrigation (Michigan Department of Agriculture and Rural Development, 2020). Government and university-level research institutions recognize the importance of irrigation in sustaining Michigan's agricultural economy and supporting the production of key crops like vegetables, potatoes, and Specialty crops (Michigan Department of Agriculture and Rural Development, 2020). A previous study shows that potato yields can be decreased by 50% without an irrigation in Michigan (Dong et al., 2023)

Moreover, irrigation increases the resilience of Michigan's agricultural sector by reducing reliance on unpredictable rainfall patterns and adequate soil moisture despite fluctuating environmental conditions. Rainfall data over the last twenty years displays how sporadic rainfall during the growing season can be from year to year (Figure 14). This variation in annual rainfall implies a need for irrigation to ensure a viable cropping season, especially in years with low rainfall volume or inconsistent timing of rainfall events. Amid concerns for water conservation, agricultural irrigation is crucial for global food security and economic stability. It is agreed that recent trends in climatic conditions have not been favorable for corn or soybean production (IPCC 2014). Many producers rely on irrigation to sustain their crop's water requirements. However, irrigation's water demand faces scrutiny, especially with rising water scarcity concerns.

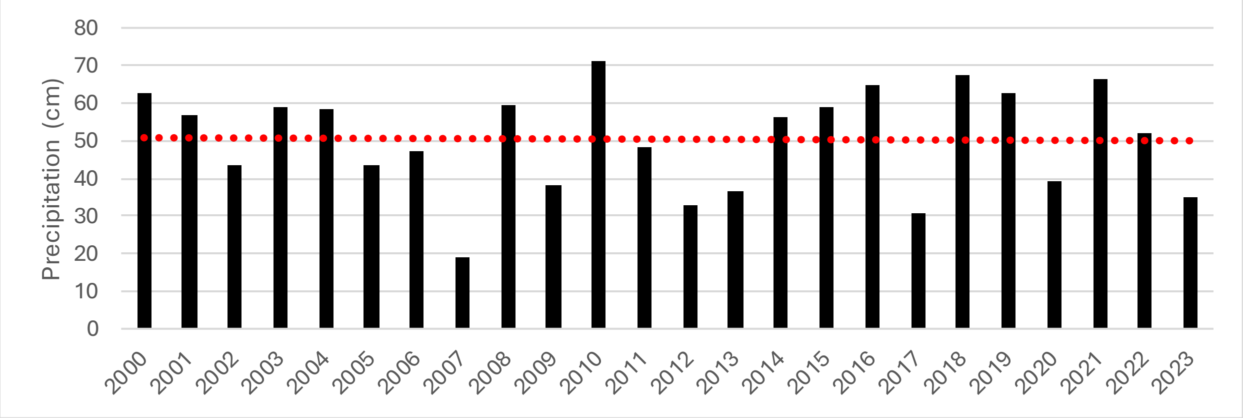

Figure 14. Annual and average (red dashed line) growing season precipitation from Three Rivers, Michigan, from May 1st to September 30th, 2000 to 2023 (National Weather Service, 2024).

Agriculture stands as the leading consumer of freshwater resources in the United States and at the global scale. In 2015, irrigation accounted for over 40 percent of freshwater withdrawals in the U.S., this amounted to a staggering 446 billion liters (118 billion gallons) per day or 163 trillion liters over the course of the year (USDA, 2017). Even in regions with generally abundant sources of surface and ground water, such as the Great Lakes, the importance of conservation efforts is increasingly recognized with increasingly variable climatic conditions and increasing public awareness. The substantial water usage in agricultural irrigation underscores the need for comprehensive water-saving strategies (Grafton et al., 2018; Hanjra & Qureshi, 2010; Postel, 1999). Effective practices, policies and technologies are essential to mitigate water scarcity challenges and ensure sustainable water management practices for future generations. Implementing innovative irrigation techniques and promoting water-efficient farming practices hold potential to significantly reduce agricultural water consumption (Gleick, 2000). Innovative approaches such as precision agriculture and improved irrigation technologies are being explored to enhance resilience and sustainability in the face of climate variability (Hatfield et al., 2011; Lobell et al., 2009). Research efforts are focusing on developing climate-smart agricultural practices tailored to the specific needs of Michigan's diverse agricultural landscape.

Effective irrigation scheduling remains crucial despite the presence of abundant rainfall in southern Michigan’s humid climate. This is because humidity levels affect both the moisture content of soils, and the water needs of crops simultaneously. Humid conditions can lead to increased evapotranspiration rates, where moisture is lost from both the soil and plant surfaces, requiring careful monitoring and management of irrigation (Allen et al., 1998). Proper irrigation scheduling helps prevent waterlogging, erosion of soil, leaching of nutrients, optimizes water use efficiency, and ensures that crops receive an appropriate amount of water at the ideal time to support healthy growth and maximize yields (Taghvaeian et al., 2020). Excess soil moisture can also induce drainage and increase the risk of diseases such as root rot and foliar disease caused by fungal and oomycete infections, underscoring the importance of precise irrigation timing (Irmak et al., 2018). Drainage is a natural and critical process in which excess water moves under the force of gravity, allowing the root zone to return to field capacity and continue drying. However, irrigation applications that induce drainage are both harmful and wasteful as drainage water can remove sediment and nutrients from the soil and deposit them in areas that are negatively impacted by these components which can no longer be used by the crop (Gao et al., 2021). Even in areas where water is abundant and inexpensive, the act of over applying irrigation to the point where large portions of the water is lost to drainage is still costly. The added costs are indirect and may not be observed at the time of the application but are converted to ecological damage from elements and compounds in the leachate and run off, lost nutrients which may have to be replaced with fertilizers, and unnecessary high electrical consumption from pumping water. Furthermore, humid conditions can create challenges in accurately assessing soil moisture levels due to increased evaporation rates and rapidly fluctuating humidity levels (Allen et al., 1998). Understanding the impacts of ET and humidity is crucial for optimizing irrigation scheduling and efficient water use in farming (Tanny et al., 2015).

Advanced irrigation scheduling techniques such as soil moisture sensing, weather-based scheduling models, and crop water requirement calculations are essential for efficient water management in humid climates (Diaz-Perez et al., 2008). These technologies help farmers make informed decisions about irrigation timing and duration based on real-time environmental conditions and calculated crop water needs. Effective irrigation scheduling not only conserves water but also contributes to sustainable agriculture by reducing energy consumption associated with pumping and distributing water (Irmak et al., 2018). Moreover, it helps mitigate the impacts of climate variability and extreme weather events by ensuring crops have access to adequate moisture during periods of drought or excessive heat (Diaz-Perez et al., 2008). Irrigation scheduling plays a crucial role in optimizing water use efficiency and enhancing crop productivity. It refers to the process of determining when and how much water to apply to crops based on their specific water needs and prevailing environmental conditions. Several methods including soil moisture monitoring, weather forecasting, and remote sensing, can be utilized in irrigation scheduling, each with its advantages and limitations. Weather-based scheduling methods utilize climatic data such as temperature, humidity, wind speed, and solar radiation to estimate crop water requirements. This approach calculates crop evapotranspiration (ET) rates using weather data and adjusts irrigation schedules accordingly. Evapotranspiration (ET) plays a critical role in irrigation management by quantifying the amount of water lost from the soil through evaporation from the soil surface and transpiration by plants. Reference ET (ET_o) serves as a benchmark for estimating crop water requirements and guiding irrigation scheduling decisions. For corn (*Zea mays*) and soybeans (*Glycine max*), reference ET values differ due to variations in crop characteristics and physiological processes. Studies have reported average reference ET values of approximately 7.5 mm/day for corn and around 6.5 mm/day for soybean during the growing season (Allen et al., 1998). These values provide a basis for understanding crop-specific water needs and optimizing irrigation strategies.

The difference in reference ET between corn and soybeans has significant implications for irrigation management, particularly in regions where both crops are grown under similar soil and environmental conditions. Corn's higher reference ET compared to soybean indicates that corn requires more water to support its growth and development stages. This disparity underscores the importance of tailoring irrigation schedules to match crop water demands in order to avoid water stress. This is especially necessary during critical growth periods when water demand and the potential for impact are both increased. Understanding the distinct ET rates between these crops allows farmers to adjust irrigation practices, accordingly, optimizing water use efficiency while potentially reducing irrigation costs and maximizing crop yields under comparable agricultural settings (Payero et al., 2006). By considering current weather conditions and forecasted changes, producers can optimize irrigation timing and volume to match crop water needs relative to the soil type and the soil's water holding capacity to minimize water losses (Allen et al., 1998). Weather-based scheduling is typically effective in humid climates but may require frequent adjustments due to unpredictable weather conditions. Many organizations provide local weather data and forecasts free of charge. However, as with any estimated parameter, some level of error is inevitable. Predicting weather conditions precisely and accurately has been a feat of science for centuries. Although modern technologies and science have greatly improved weather forecasting, application to a specific location is feasible but limited. To further complicate the estimation, weather stations are rarely in close enough proximity to accurately portray the conditions of a given agricultural field. So, some degree of spatial error is also introduced in the estimation of field conditions.

Soil moisture-based scheduling involves monitoring the moisture content of the soil to determine when irrigation is needed. This method relies on sensors placed in the root zone to provide real-time data on soil moisture levels. Producers can use this information to schedule irrigation based on specific thresholds of soil moisture, ensuring that crops receive water when needed without overwatering (Diaz-Perez et al., 2008). One limitation of soil moisture-based scheduling is the need for accurate placement and calibration of sensors, which demands labor and comes at a cost. The placement of the sensors is critical in that each sensor must represent an area within the field and should accurately reflect the conditions of that specific area in order to make management decisions.

Remote sensing-based scheduling leverages satellite imagery and aerial photography to assess crop health and moisture levels across large areas. Remote sensing technologies can provide valuable information on crop water stress, allowing for targeted irrigation management. By analyzing vegetation indices derived from remote sensing data, farmers can identify areas of water stress and adjust irrigation schedules accordingly (Gao, 2009). However, limitations include the cost of acquiring and processing remote sensing data, as well as the need for expertise in interpreting the imagery for irrigation decisions. Overall, irrigation scheduling methods offer valuable tools for farmers to optimize water use and enhance crop performance. Each approach has its strengths and weaknesses, and the choice of method often depends on factors such as crop type, climate, available resources, and technological expertise. Integrating multiple scheduling techniques and leveraging advances in technology can further improve irrigation efficiency and sustainability in agriculture.

Despite the potential benefits in terms of water conservation and crop productivity, many farmers have yet to integrate these technologies into their operations. Several factors contribute to this limited adoption. Firstly, the initial costs associated with implementing irrigation scheduling systems and soil moisture monitoring devices can be prohibitive, especially where profit margins are limited (Huang et al., 2019, Wanyama et al., 2024). Additionally, there is a knowledge gap regarding the practical applications, precision, and benefits of these technologies, leading to skepticism or reluctance to invest (Zhang & Long., 2021). The complexity of data interpretation from soil moisture sensors and the perceived learning curve further deters widespread adoption. In Michigan, despite the state's significant agricultural sector, many farmers continue to rely on traditional irrigation management methods which are less precise due to entrenched practices and limited access to resources promoting new technologies (United States Department of Agriculture, National Agricultural Statistics Service, 2019). While traditional methods of irrigation scheduling can be effective, the need to improve management practices and conserve resources is undeniable. The variable climate of the Midwest, characterized by unpredictable rainfall patterns, underscores the potential advantages of precise irrigation management but also presents challenges in convincing producers to make the shift. Addressing these barriers will require concerted efforts from agricultural institutions, government agencies, and industry stakeholders to provide targeted education, technical assistance, and financial incentives to encourage adoption (Dibbern et al., 2024). Demonstrating the tangible benefits of irrigation scheduling and soil moisture monitoring through pilot programs and case studies can help build confidence among producers and set an example for broader adoption. As awareness grows and technologies become more accessible and affordable, the potential for widespread adoption of these innovative practices in Michigan's agriculture sector holds promise for increased sustainability, productivity, and resilience despite changing environmental conditions.

This study demonstrates the impacts of employing sensor-based irrigation scheduling, aiming to showcase its effectiveness in enhancing crop performance and maximizing irrigation water use efficiency in a humid climate such as Michigan. Many studies have been conducted in arid climates on the topic of water use efficiency, however there is a knowledge gap in improving irrigation water use efficiency, particularly on irrigation scheduling in the area of this study. On-farm demonstrations were conducted in local producers' fields as part of the study, evaluating various irrigation applications to highlight the advantages of sensor technology and irrigation scheduling. To comprehensively assess efficiency, the study incorporates measurements of crop health, soil moisture, temperature, relative humidity, electrical costs, yield and economics while also monitoring plant disease incidence and severity as crucial indicators. The results reveal significant water savings ranging from 25.4 to 50.8 mm in corn and soybean fields, with yields comparable to traditional irrigation strategies in some instances. This not only conserves water but also reduces on-farm energy use, potentially saving up to 26 USD per hectare. Exploration of this critical intersection of agriculture, technology, and water management suggests that the implications of this research extend beyond the fields, contributing to the broader implications on sustainable agricultural practices.

4.2 Methods and Materials

4.2.1 Site Description

For the purposes of this demonstrative study, four locations were selected to test different irrigation management methods. These locations were selected from south-west Michigan as seen in Figure 15, since the majority of irrigated acreage is located within this region of the state (USDA NASS, 2019). These areas possess the largest potential for improvement in water use efficiency using center pivot irrigation. GPS coordinates for field locations, size, cropping regime, and soil type for each site are shown in Table two. In general, the area's soil is well-drained and contains large proportions of sand.

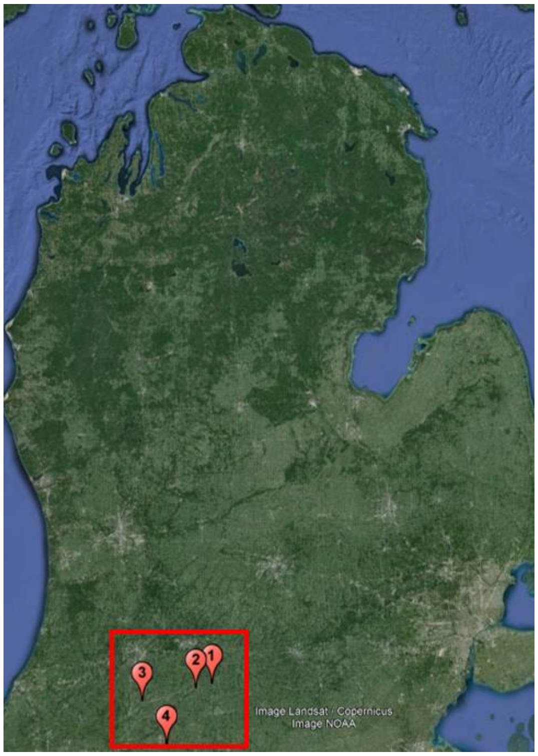

Figure 15. Map of demonstration sites. Site #1: Burlington, Site #2: Union City, Site #3: Mendon, Site #4: Sturgis.

Table 2. Demonstration site locations and features

Location	Area (ha)	2021 Crop	2022 Crop	2023 Crop	Soil Type
Burlington, Michigan	24.3	Corn	Soybean	Corn	Oshtemo / Spinks sandy loam
Union City, Michigan	15.4	Soybean	Corn	Soybean	Oshtemo sandy loam
Parkville, Michigan	12.9	Soybean	Soybean	Soybean	Oshtemo sandy loam
Sturgis, Michigan	12.1	Corn	Soybeans	Corn	Oshtemo sandy loam

Since this study was conducted on fields that were owned by private entities who were gracious enough to allow for manipulation of their irrigation systems, there were some factors which could not be held uniform across all fields. Tillage practices varied by farm and crop as seen in table 3.

Table 3. Tillage practices listed by farm and year

Site	2021	2022	2023
Burlington	Tilled	No Till	Tilled
Parkville	No Till	No Till	No Till
Sturgis	No Till	No Till	No Till
Union City	Tilled	No Till	Tilled

4.2.2 Irrigation Treatments

Each field was divided into five plots to demonstrate irrigation prescriptions (Figure 16). The first of which was the producer’s typical irrigation management practice. While techniques often vary, many producers have experience managing their fields and crops which can be used to manage irrigation more effectively. Having this prescription allowed for comparison of sensor-based and scheduler-based irrigation management practices with the producer's typical management methods. The second experimental treatment was referred to as the "recommended irrigation" treatment throughout this demonstrational study. Irrigation was triggered at threshold of 50% moisture availability depletion (MAD) for both corn and soybean for the recommended experimental treatment. The recommended irrigation treatment, also referred to as optimal irrigation in some places, was established using the last 5 years of rainfall and irrigation data in conjunction with the MSU Irrigation scheduler and soil characteristics. This experimental treatment was designed to be the best estimate of the irrigation requirements of fields in the vicinity of the study. The threshold for MAD was decreased to 30% for the under irrigated experimental treatment (20% less remaining available water) and increased to 70% for the over irrigated experimental treatment (20% more remaining available water). Both the threshold for MAD and irrigation volume per application were adjusted throughout the study based on irrigation simulations from MSU Irrigation Scheduler. As compared to the soybean irrigation application volumes, 6.35 mm of additional irrigation was applied to the prescribed irrigation applications in corn to compensate for the crop's higher reference ET value. Table three shows the details on the threshold for MAD and irrigation volume for each irrigation treatment and each crop. The irrigation volume for corn was larger than soybeans due to the rooting depth. The dry corner of each site was used as a non-irrigated treatment area for comparison of yields with irrigated areas. These dry corners of the field were outside the pivot's area of coverage and were managed the same as the other treatment areas in but had no irrigation applied. In exception to the non-irrigated experimental treatment, all prescriptions were delineated radially around the center point of the irrigation system as seen in Figure 16. Each irrigation management zone was buffered at its borders to allow the system adequate time to adjust application rates. This arrangement helped mitigate irregularities stemming from variations in irrigation systems, soils, and climatic conditions which may have occurred during the assessment of individual experimental treatments. Treatment areas were randomized from year to year and reviewed for irregularities that could influence the results of the study beyond the effects of natural variation.

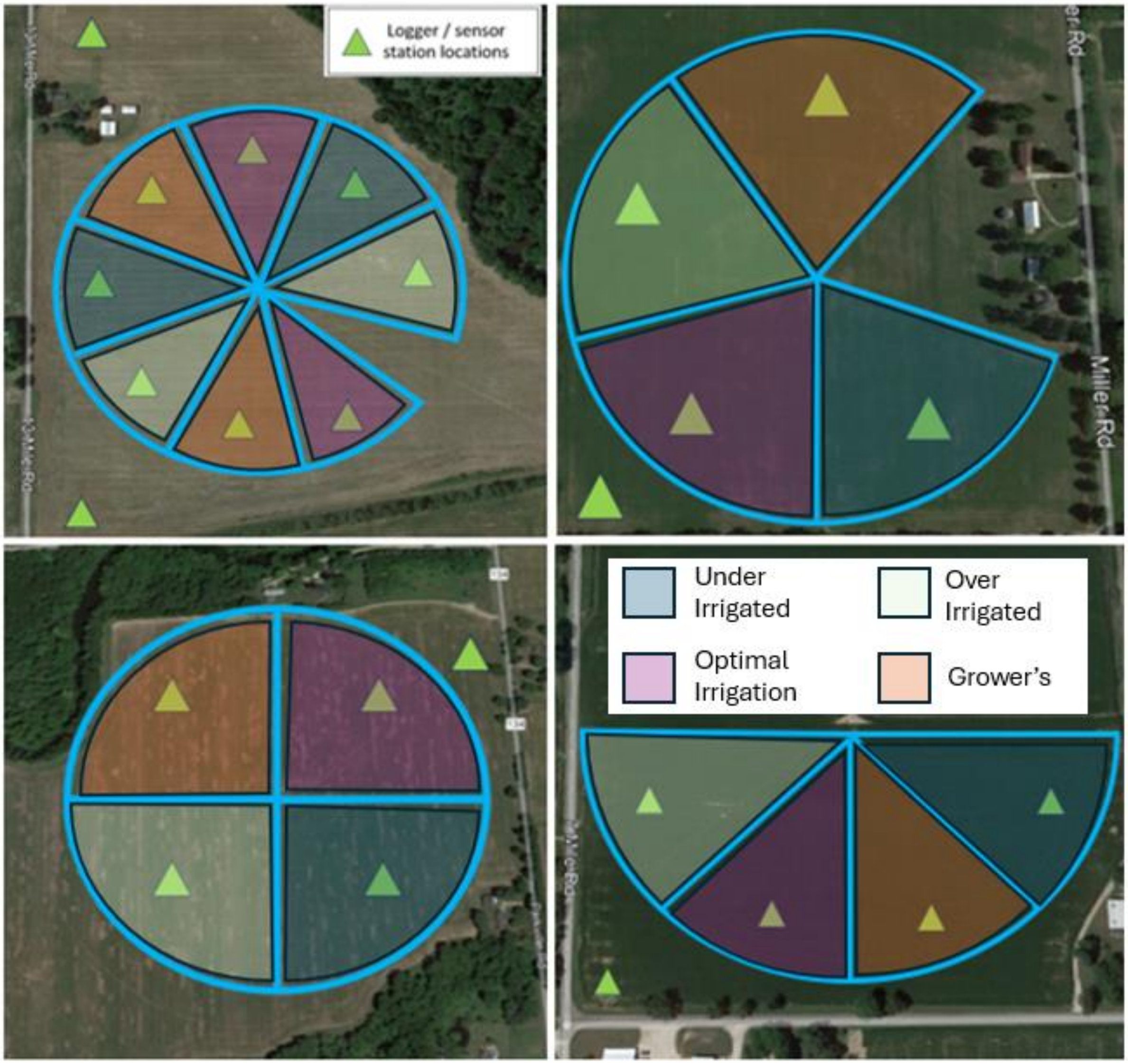

Figure 16. Establishment of treatment plots for each site, Burlington site (top left) Constantine site (top right), Sturgis site (lower left), Union city site (lower right). Green triangles indicating data logging stations with soil moisture sensors. Shaded overlays indicating experimental irrigation treatment as designated in the figure legend. Unirrigated treatment areas are designated by the data logging station outside the center-pivot's radius.

Table 4. Summary of experimental treatments

Prescription Name	**Moisture Availability Deficit**	**Irrigation Amount per Application for Corn**	**Irrigation Amount per Application for Soybeans**
Treatment 1 (Under-Irrigated)	60%	19 mm	13 mm
Treatment 2 (Recommended Irrigation)	50%	25 mm	19 mm
Treatment 3 (Over- Irrigated)	30%	32 mm	25 mm
Treatment 4 (Producer's Management)	NA	NA	NA
Unirrigated	NA	NA	NA

4.2.3 Field Monitoring

Within each irrigation management zone, field conditions were monitored using the Low-Cost Sensor Monitoring System (Hollycross, 2023). This system was developed by Michigan State University Irrigation Lab and was accompanied by at least three Soil Watch 10, manufactured by PinoTech (Zachodniopomorskie, Poland). The Soil Watch 10 sensor is a capacitance-based soil moisture sensor that operates at 75Mhz and has a probe length of 3.8 cm. Table five presents data from sensors placed in 2021, comparing a volumetric sample taken at the time of sensor placement to the sensor’s initial readings. This method of evaluation subjected the samples to evaporative losses due to the time between collection and being weighed and rarely results in a sensor reading being higher than the sample’s volumetric water content. Given the scale of this study and the length of response time to make a complete application compared to shift in soil moisture, the sensors were deemed viable.

Table 5. Sensor performance. Depth listed after location, with the Burlington site having two replications listed as Burlington one through four and Burlington five through eight. These represent treatments one through four (Grower: 1, Recommended: 2, Over-irrigated:3, Under-irrigated:4)

Sample ID	**Theta_V (cm^3/cm^3)**	**Sensor Reading (cm^3/cm^3)**	**Difference (cm^3/cm^3)**
Sturgis 1- 24 in	0.1412	0.132	0.0092
Sturgis 1-15 in	0.1452	0.0962	0.049
Sturgis 1-6in	0.1548	0.132	0.0228
Sturgis 2- 15 in	0.1712	0.108	0.0632
Sturgis 2- 24 in	0.1216	0.121	0.0006
Sturgis 2- 6 in	0.1504	0.112	0.0384
Sturgis 3- 15in	0.1716	0.138	0.0336
Sturgis 3- 24 in	0.16	0.115	0.045
Sturgis 3- 6 in	0.1956	0.14	0.0556
Sturgis 4 - 24 in	0.116	0.0986	0.0174
Sturgis 4- 15 in	0.1328	0.113	0.0198
Sturgis 4- 6 in	0.134	0.101	0.033
Sturgis Dry- 24 in	0.1728	0.1	0.0728
Parkville 1 - 15 in	0.1328	0.159	0.0262
Parkville 1 - 24 in	0.1688	0.126	0.0428
Parkville 1 - 6 in	0.1564	0.132	0.0244
Parkville 2 - 15 in	0.1936	0.0653	0.1283
Parkville 2 - 24 in	0.1632	0.068	0.0952
Parkville 2 - 6 in	0.174	0.0958	0.0782
Parkville 3 - 15 in	0.188	0.0925	0.0955
Parkville 3 - 24 in	0.1708	0.121	0.0498
Parkville 3 - 6 in	0.2092	0.136	0.0732
Parkville 4 - 15 in	0.2044	0.0956	0.1088
Parkville 4 - 24 in	0.1524	0.173	0.0206
Parkville 4 - 6 in	0.1928	0.0932	0.0996
Burlington 2 - 6 in	0.2348	0.2	0.0348
Burlington 3 - 15 in	0.1532	0.168	0.0148
Burlington 3 - 24 in	0.2004	0.143	0.0574
Burlington 5 - 15 in	0.1828	0.165	0.0178
Burlington 5 - 24 in	0.1556	0.141	0.0146
Burlington 5 - 6 in	0.2244	0.164	0.0604
Burlington 6 - 15 in	0.196	0.133	0.063
Burlington 6 - 24 in	0.2004	0.14	0.0604
Burlington 6 - 6 in	0.1972	0.167	0.0302
Burlington 7 - 15 in	0.1988	0.158	0.0408
Burlington 7 - 24 in	0.2356	0.134	0.1016
Burlington 8 - 6 in	0.2536	0.162	0.0916

Table 5. (cont'd)

Burlington Dry - 24 in	0.148	0.16	0.012
Union City Dry - 12 in	0.1756	0.088	0.0876
Union City Dry - 36 in	0.1348	0.099	0.0358
Union City Dry - 6 in	0.2092	0.109	0.1002
Union City 3 - 12"	0.1844	0.153	0.0314
Union City 3 - 24"	0.2364	0.135	0.1014
Union City 3 - 36"	0.1424	0.109	0.0334
Union City 4 - 12"	0.152	0.13	0.022
Union City 4 - 24"	0.1708	0.098	0.0728

Sensors were installed at depths in and below the rooting zone to track water movement during and after each precipitation or irrigation event. Figure 17 displays how sensors were horizontally installed at a variety of depths in close proximity to the crop's roots and not directly under the data logging system. For corn, sensors were placed at depths of 30.5, 61.0, and 91.4 cm. In soybeans, sensors were placed at depths of 15.2, 38.1, and 61.0 cm. LOCOMOS technology was utilized to measure precipitation using a rain gauge, manufactured by Davis Instruments (Hayward, CA, USA). Additionally, PHYTOS 31 leaf wetness sensors, manufactured by METER Group (Pullman, WA, USA) were integrated into the LOCOMOS to monitor the duration of leaf wetting, allowing for the potential correlation with foliar disease pressure. The sensor data were collected on an hourly basis and sent to a cloud website (locomos1.com) through an embedded cell modem.

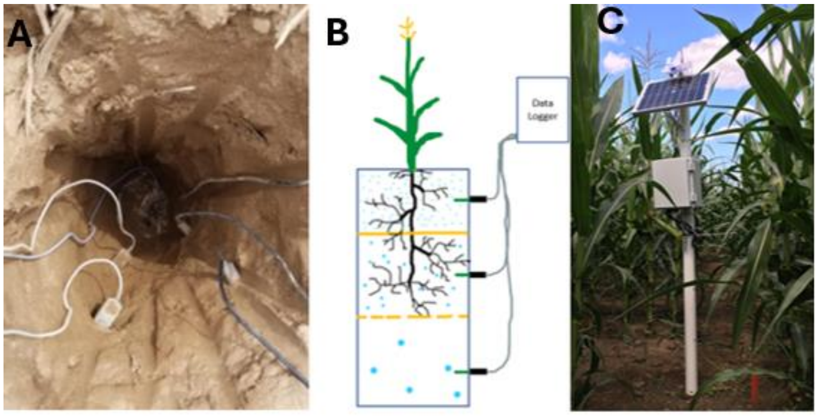

Figure 17. Equipment setup, an example of soil moisture sensors at incremental depths throughout the rooting zone. 4A, Soil pit dug for the installation of the Soil Watch-10 soil moisture sensors. 4B, Diagram of sensor installation with sensors placed throughout and below the root zone to capture the effects of different soil horizons and rooting densities. 4C, LOCOMOS station in a corn field.

4.2.4 Data Analysis

In addition to sensor data, crop development was assessed on a weekly basis, especially during critical phases, enabling a more thorough analysis of yield impacts. Site scouting allowed for monitoring of any quantitative estimates of differences in disease presence. While related to yield, disease presence required quantification of impact for comparison of water use efficiency and yield across different irrigation management areas. Significant differences in disease presence were not found. Thus, data collected on disease presence was not included in this study and the effects of disease were assumed to be comparable between treatments. Furthermore, to compare crop performance, spatial yield data from the combine's yield monitor was collected from each field at harvest. This data was then analyzed on an annual basis for each field, independently, to represent the efficiency of each irrigation management prescription. The average non-irrigated yield was subtracted from the average yield of each management area and divided by the volume of water applied to that particular management area to calculate water use efficiency, following Equation 1 (Irmak, 2011).

$$\text{Irrigation Water Use Efficiency} = \frac{Y_{Irr} - Y_{Dry}}{V_{Irr}} \qquad \text{(Equation \#1)}$$

Where, Y_{Irr} represents the yield of an irrigated area (kg/ha), Y_{Dry} represents the yield of an unirrigated area (kg/ha), and V_{Irr} is the volume of irrigation applied to the irrigated area (mm).

4.2.5 Statistical Analysis Methods

Statistics for this study were calculated using a combination of Microsoft Excel and R Studio. Microsoft Excel was utilized to transfer data over the various stages of this study and hold it for later refinement and analysis. Calculations of significance and power were reserved for R studio version 2023.12.0. Significance was analyzed using a pairwise Tukey's test for significance at an alpha of 0.05. The power test also utilized an alpha of 0.05 and a power of 0.8. Once treatments were tested for significance, boxplots of yield and WUE were created to visualize the data.

4.3 Results

4.3.1 Weather Data

Figure 18 shows weather summary during the growing season in Burlington/Union City, Parkville, and Sturgis, respectively. Data was collected from the National Weather Service starting in May and ending in August each year 2021 through 2023.

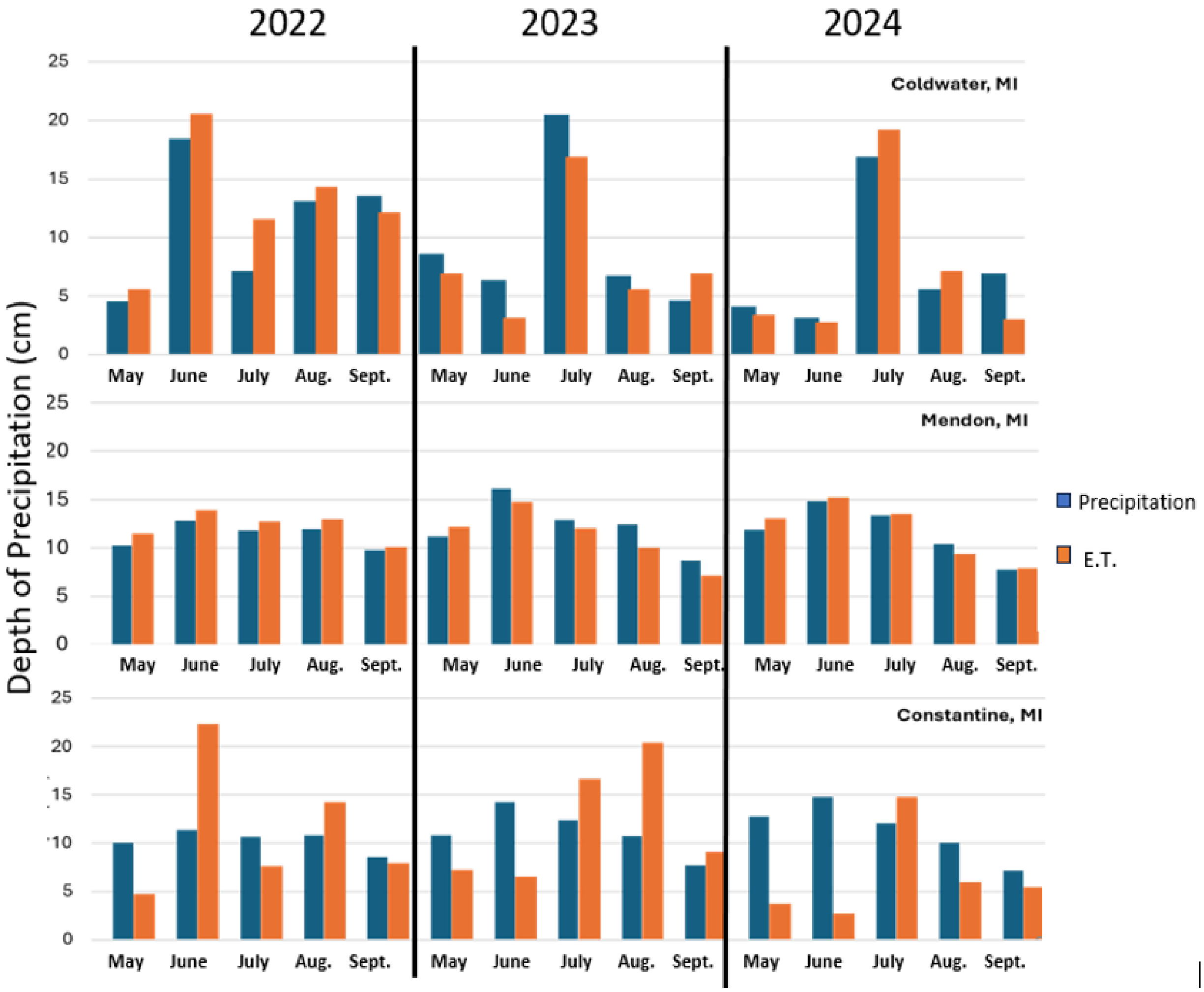

Figure 18. Growing season weather summary for Coldwater (Burlington and Union city sites), Mendon (Parkville site), and Constantine (Sturgis site). Data was collected from National Weather Service (National Weather Service, 2024).

Table 6. Three Rivers Michigan 30-year average rainfall (NOAA, 2024)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1993	2.78	1.21	2.07	3.44	2.97	5.82	2.11	4.97	7.15	4.25	1.76	1.2	39.73
1994	2.61	1.15	1.33	3.14	1.5	5.25	5.12	4.96	2.06	1.92	5.11	1.92	36.07
1995	2.97	0.72	1.64	3.63	3.93	4.06	4.91	5.15	1.88	3.18	4.1	0.85	37.02
1996	2.3	1.57	0.91	3.81	4.09	5.69	2.41	1.89	3.64	3.32	3.15	2.99	35.77
1997	2.38	4.23	3.64		4.49	5.13	2.38	7.5	4.16	2.26	2.24	1.62	
1998	4.3	1.49	3.93	2.82	1.81	2.29	1.62	5.52	1.28	2.55	1.35		
1999	4		1.47	5.34	1.96	3.67	2.43	3.61	1.92	1.13	1.06	2.82	
2000	1.86	1.42	2.04	4.22	6.93	6.07	5.88	1.72	4.15	2.27	4	4.02	44.58
2001	0.77	2.83	0.42	2.76	4.39	3.9	3.96	5.35	4.77	6.81	2.97	2.33	
2002	2.07	1.62	2.08	3.19	5.86	1.93	3.13	4.85	1.28	2.49	2.4	1.23	32.13

Table 6. (cont'd)

2003	1.18	0.7	2.01	4.02	8.55	1.67	3.59	4.42	5.06	2.97	6.89	2.24	43.3
2004		0.65	3.94	0.29	8.59	4.95	4.57	3.94	0.97	2.21	4.21		
2005	5.66	2.38		2.39	2.4	6.27	1.63	4.35	0.65		2.73		
2006		1.52	2.82	1.28	5.92		7.13	5.64					
2007	4.27		1.59	1.16		4.73		2.03					
2008	5.95	3.86	2.03	2.79	2.51	3.46	3.76	0.7	12.99	3.19	1.76	4.28	47.28
2009	1.68	2.91	4.3	4.89	4.02	4.54	1.63	3.28	1.5	6.29	1.32	2.7	39.06
2010	1.02	1.7	1.18	3.22	6.55	8.84	8.05	2.21	2.47	0.9	2.73	0.97	39.84
2011	1.18	3.87	2.15	6.68	5.7		4.61	3.15	5.57	4.42	5.1	2.67	
2012	2.88	2.67	3.4	4.18	1.77	1.5	3.3	4.49	1.86	4.56	0.56	2.86	34.03
2013	4.67	2.24	0.82	6.3	2.57	6.62	1.62	2.3	1.27	3.03	3.4	2.66	37.5
2014	3.23	2.3	1.68	3.29	3.54	8.73	2.78	4.03	2.98	4.94	4.06	1.3	42.86
2015	1.77	1.45	0.47	2.06	6.66	5.82	5.29	3.11	2.29	1.6	2.67	3.82	37.01
2016	1.38	1.45	3.21	3.27	3.33	3.31	3.29	10.63	4.86	3.11	2.89	2.15	42.88
2017	3.3	1.9	5.12	2.78	4.51	1.37	3.32	1.61	1.25	9.56	4.04	1.14	39.9
2018	1.85	6.85	2.21	3.1	9	7.44	2.96	4.7	2.54	4.54	5.1	1.35	51.64
2019	7.59	2.23	2.71	3.8	6.33	4.63	4.09	3.31	6.23	5.92	2.04	2.96	51.84
2020	4.62	2.23	2.93	3.16	4.92	2.59	2.18	2.56	3.11	2.99	1.99	2.3	35.58
2021	1.75	1.08	2.5	1.55	2.09	7.76	4.77	6.73	4.75	7.03	1.1	3.14	44.25
2022	0.73	3.44	2.79	3.35	4.78	3.12	7.98	3.21	1.48	2.99	1.5	1.51	36.88
2023	2.49	3.98	4.24	3.22	1.58	0.8	6.14	3.08	2.09	6.54	1.25	2.53	37.94
Average	2.87	2.26	2.39	3.30	4.44	4.55	3.89	4.03	3.32	3.82	2.88	2.29	40.05

4.3.2 On Farm Demonstration: Yield & WUE

Comparisons between irrigated and non-irrigated yields are displayed in figures 19 and 20 for all corn and soybean fields in this study. Figure 19 shows a trend favoring irrigated soybeans that statistically differentiable at an alpha of 0.1, due to a p-value of 0.0589.

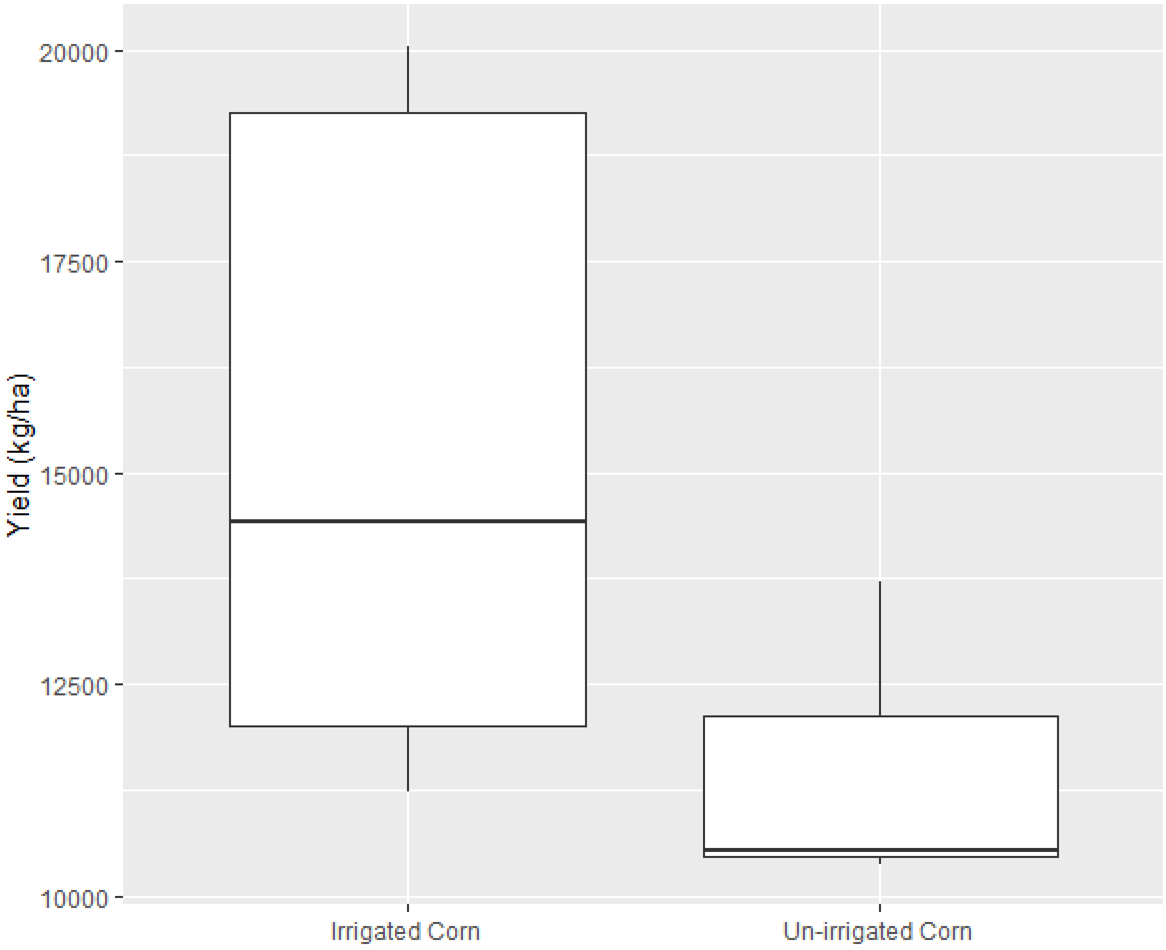

Figure 19. Comparison between irrigated corn and non-irrigated corn treatment areas for the years 2021 to 2023.

Conversely, when comparing the averages of all irrigated corn areas to those of the non-irrigated corn areas, differences are much weaker than in the soybeans. Corn yield data are summarized for all corn plots included in the study in figure 20, with a p-value of 0.115.

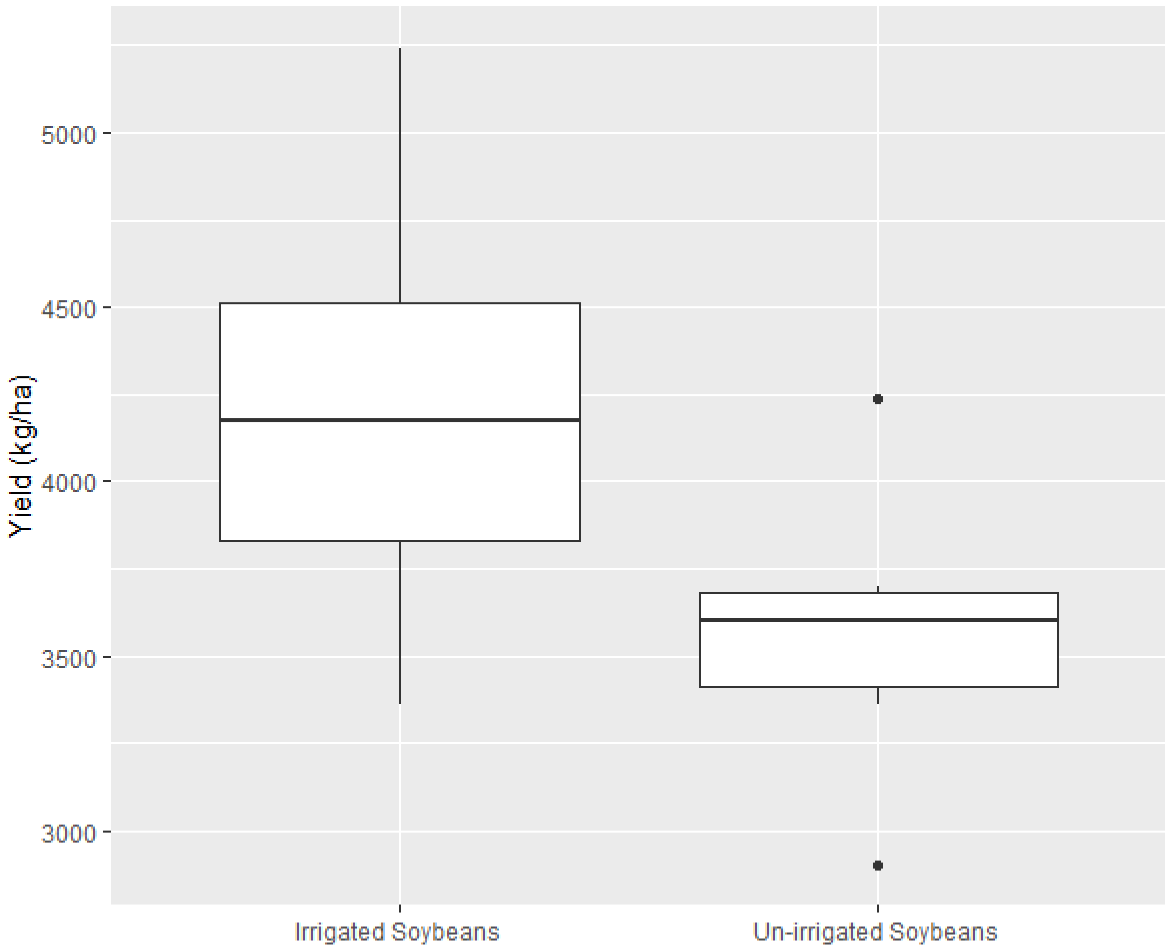

Figure 20. Comparison between irrigated soybean and non-irrigated soybean treatment areas for the years 2021 to 2023.

Figures 21 and 22 show the average corn yield and average WUE from all sites, over the duration of the study. Average corn yield was nearly identical for the under-, recommended, and over-irrigated treatment areas while the growers and unirrigated areas display visibly lower yields. Figure 22 shows that WUE decreased as irrigation volume and frequency were increased in corn.

Figure 21. Summarized corn yield from all four demonstration sites over the three-year duration of the study. Crops were planted in rotation resulting in a total of five successful replications of the study.

Figure 22. Summarized corn WUE from all four demonstration sites over the three-year duration of the study. Crops were planted in rotation resulting in a total of five successful replications of the study.

Soybean yield and WUE are summarized for all soybean plots included in the study. Figures 21 and 22 show an average soybean yield and average WUE for 2021 to 2023. Yields were generally similar with the exception of the under-irrigated and non-irrigated experimental treatment. WUE results follow a similar trend but include an increase in the upper range for the under-irrigated area and a decrease in the upper range of the over-irrigated treatment.

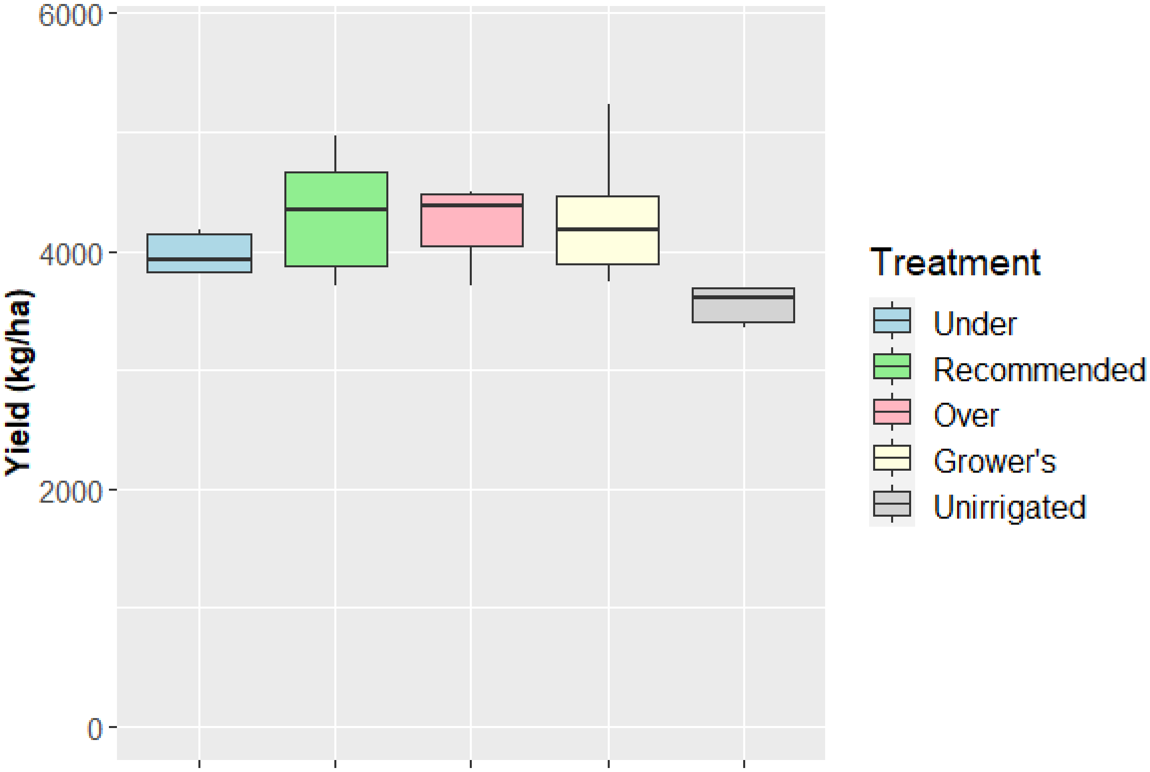

Figure 21. Summarized Soybean yield from all four demonstration sites over the three-year duration of the study. Crops were planted in rotation resulting in a total of six successful replications of the study.

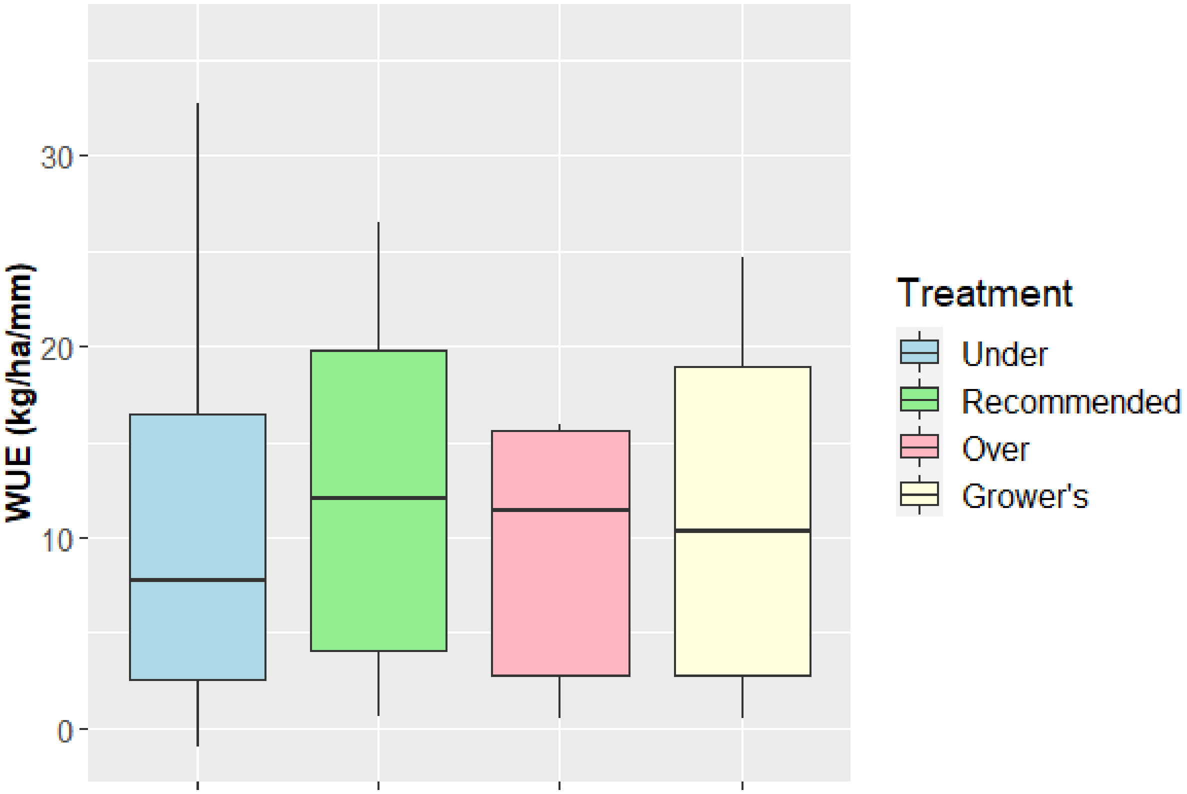

Figure 22. Summarized soybean WUE from all four demonstration sites over the three-year duration of the study. Crops were planted in rotation resulting in a total of six successful replications of the study.

4.3.3 Impact of Irrigation and Precipitation on Yields

The relationship between water applications (irrigation and precipitation) on corn and soybean yields was observed. Figure 25 shows a slight upward trend in yield when irrigation and precipitation increase. Conversely, increased irrigation and rainfall in soybean production resulted in decreased soybean yields.

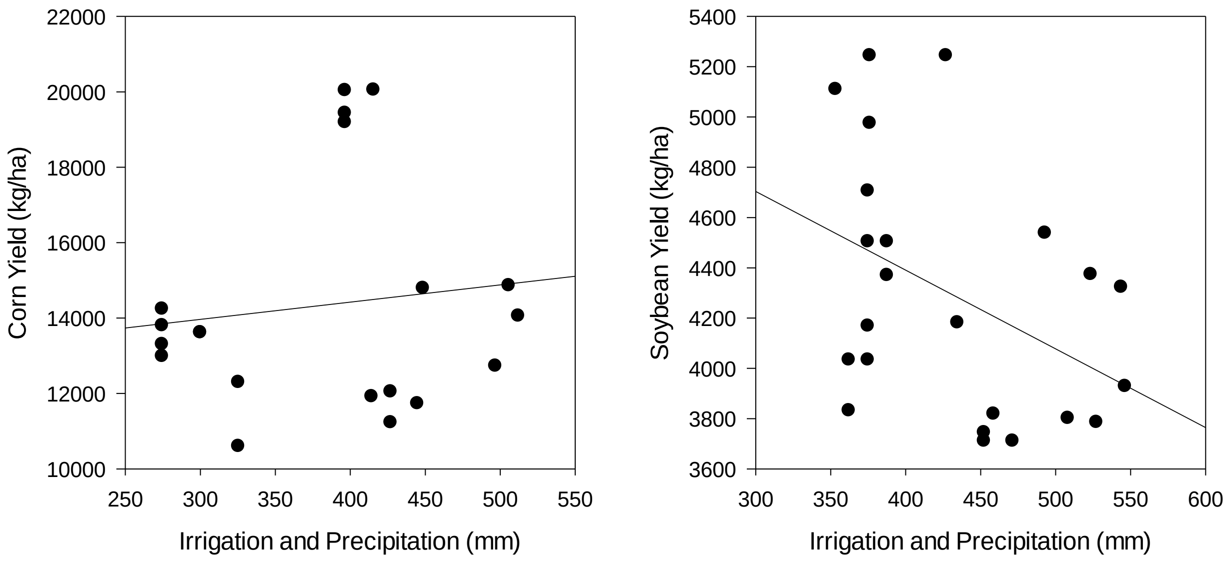

Figure 25. Relationship between water (irrigation and precipitation) and corn and soybean yields.

4.3.4 Statistics

Average yield and WUE values for all treatments in this study are analyzed in Table four, using Tukey's pairwise comparison methods, listing P-values as a matric for establishing a statistical difference. Comparisons between the scheduling-based methods and the unirrigated areas show the lowest values. All of the compared treatment statistics resulted in P-values above the selected value of alpha (0.05). Comparisons to unirrigated areas cannot be made with WUE due to introducing a value of zero into the devisor of the irrigation WUE equation (equation #1). Many comparisons have extremely high comparative P-values and elevated number of samples required for statistical power due to the number of replicates, frequent rainfall and similar resulting yields and WUEs.

Table 7. Results for Tukey's pairwise comparison for all treatments in study

Treatments Compared		P-value			
		Corn Yield	Soybean Yield	Corn WUE	Soybean WUE
Grower's	Under	0.9972	0.9843	0.785	0.9997
Grower's	Recommended	0.993	0.9999	0.9495	0.9997
Grower's	Over	0.9981	0.9991	0.997	0.9075
Grower's	Unirrigated	0.8805	0.138	NA	NA
Under	Recommended	0.9999	0.9688	0.975	0.9976
Under	Over	0.9999	0.9368	0.8708	0.9374
Under	Unirrigated	0.7243	0.3349	NA	NA
Recommended	Over	0.9999	0.9999	0.9846	0.8716
Recommended	Unirrigated	0.6759	0.112	NA	NA
Over	Unirrigated	0.742	0.0847	NA	NA

Average yield and WUE values for all treatments in this study are analyzed in Table five, using Tukey's pairwise comparison methods, listing number of samples required to create a statistical power of 0.80 as a measure of potential for future studies. Comparisons between the scheduling-based methods and the unirrigated areas show the highest values. Comparisons to unirrigated areas cannot be made with WUE due to introducing a value of zero into the devisor of the irrigation WUE equation (equation #1).

Table 8. Pairwise test of statistical power for all treatments in study

Treatments Compared		Power Test (samples required to achieve a power of 0.80)			
		Corn Yield	Soybean Yield	Corn WUE	Soybean WUE
Grower's	Under	257	188	32	218
Grower's	Recommended	170	4,469	79	217
Grower's	Over	356	870	598	719

Table 8. (cont'd)

Grower's	Unirrigated	22	9	NA	NA
Under	Recommended	3,357	120	163	4,091,485
Under	Over	25,741	84	45	924
Under	Unirrigated	11	13	NA	NA
Recommended	Over	2,013	2,507	167	924
Recommended	Unirrigated	11	8	NA	NA
Over	Unirrigated	14	8	NA	NA

4.3.5 Economics

The economics of the applied irrigation treatments are calculated on each treatment's three-year average for all corn and soybean fields in the study. Calculations account for the average corn value in 2023 which was 0.0349 United States Dollars (USD) per kilogram, the average soybean value in 2023 of 0.0985 USD per kg, average yield of each treatment, and either diesel or electric pumping costs (United States Department of Agriculture, National Agricultural Statistics Service, 2024). These calculations assume two different rates for operating wells and center-pivot irrigation systems: an electric rate of 0.36 USD per hectare millimeter and a diesel rate of 1.029 USD per hectare millimeter (United States Department of Agriculture, National Agricultural Statistics Service, 2024). The columns labeled cost (diesel and electric) reflect the expense of pumping and powering the irrigation system per millimeter of irrigation applied to each hectare. Whereas the columns labeled profit (diesel and electric) display the value of the crop produced per millimeter of irrigation applied to each hectare.

Table 9. Economics of irrigating corn by treatment

Corn	Avg. Yield	Avg. Irrigation	Electric Expense	Net Profit	Diesel Expense	Diesel Profit
	(kg/ha)	(mm)	(USD / ha mm)	(USD / ha mm)	(USD / ha mm)	(USD / ha mm)
Under Irrigated	14,681	99	-1.33	96.42	-3.81	93.95
Recommended Irrigation	15,183	123	-1.64	99.45	-4.70	96.40
Over Irrigated	13,740	137	-1.84	89.65	-5.25	86.24
Grower's	14,053	120	-1.60	91.97	-4.58	89.00
Unirrigated	12,108	0	0.00	80.63	0.00	80.63

Table 10. Economics of irrigating soybeans by treatment

Soybeans	Avg Yield	Avg. Irrigation	Electric Expense	Electric Profit	Diesel Expense	Diesel Profit
	(kg/ha)	(mm)	(USD / ha mm)	(USD / ha mm)	(USD / ha mm)	(USD / ha mm)
Under Irrigated	4,127	59	-0.80	76.75	-2.28	75.27
Recommended Irrigation	4,315	79	-1.06	80.02	-3.04	78.05
Over Irrigated	4,356	104	-1.39	80.46	-3.96	77.88
Grower's	4,282	89	-1.19	79.26	-3.40	77.05
Unirrigated	3,569	0	0.00	67.06	0.00	67.06

4.3.6 Irrigation Management Survey

To understand the producer's existing irrigation methods and the potential to improve their practices, 69 producers, from southern Michigan and northern Indian, who primarily grow corn and soybeans, were asked four questions in a survey. In survey question one participants were asked; "What are your current irrigation management techniques?" Most respondents reported crop monitoring (48 responses) and weather-based scheduling (34 responses) as their current irrigation management techniques. A considerable number of respondents also indicated utilizing soil condition evaluation (27 responses). A smaller proportion of farmers reported irrigating when neighbors do (5 responses), or other methods (13 responses).

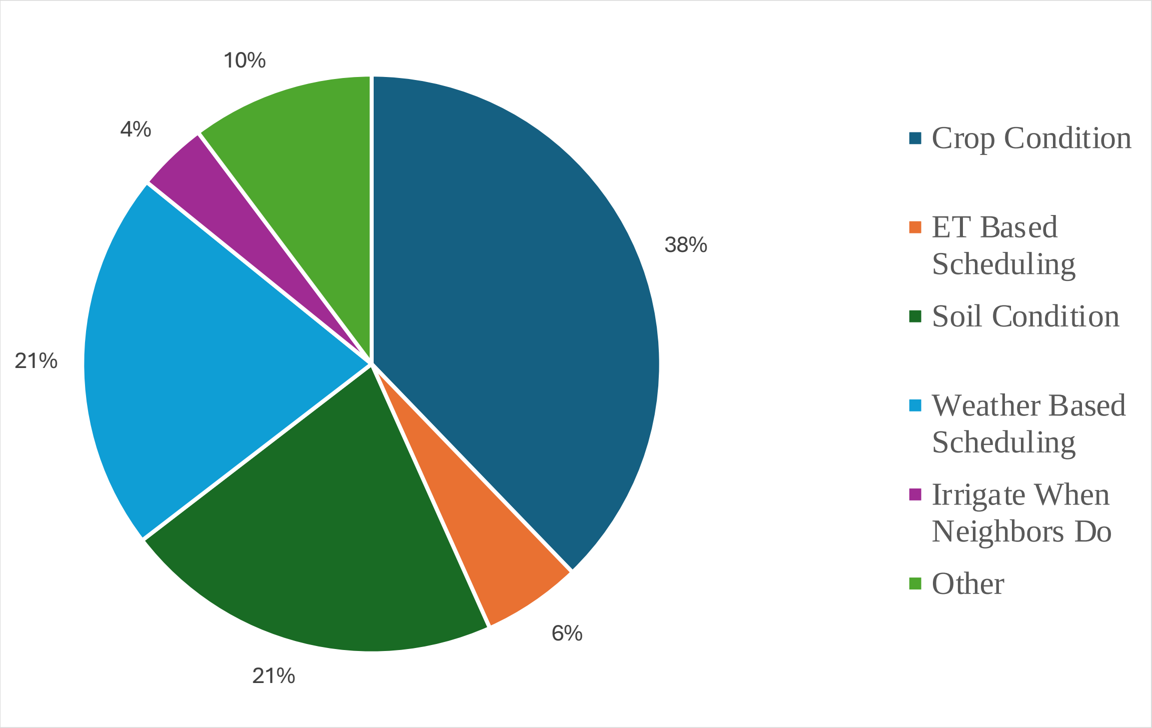

Figure 26. Survey results for question #1: “What are your current irrigation management techniques?”.

The survey also asked; “If you were to change your current methods of irrigation management, what methods would you use?” in question two. When asked about potential changes to their current irrigation management methods, respondents expressed interest in adopting new technologies and strategies. The most commonly selected method was IoT-based sensor monitoring (24 responses), followed by crop condition monitoring (14 responses) and ET-based scheduling (10 responses). Those who responded “other” justified their response as “not interested in changing” or “not applicable.”

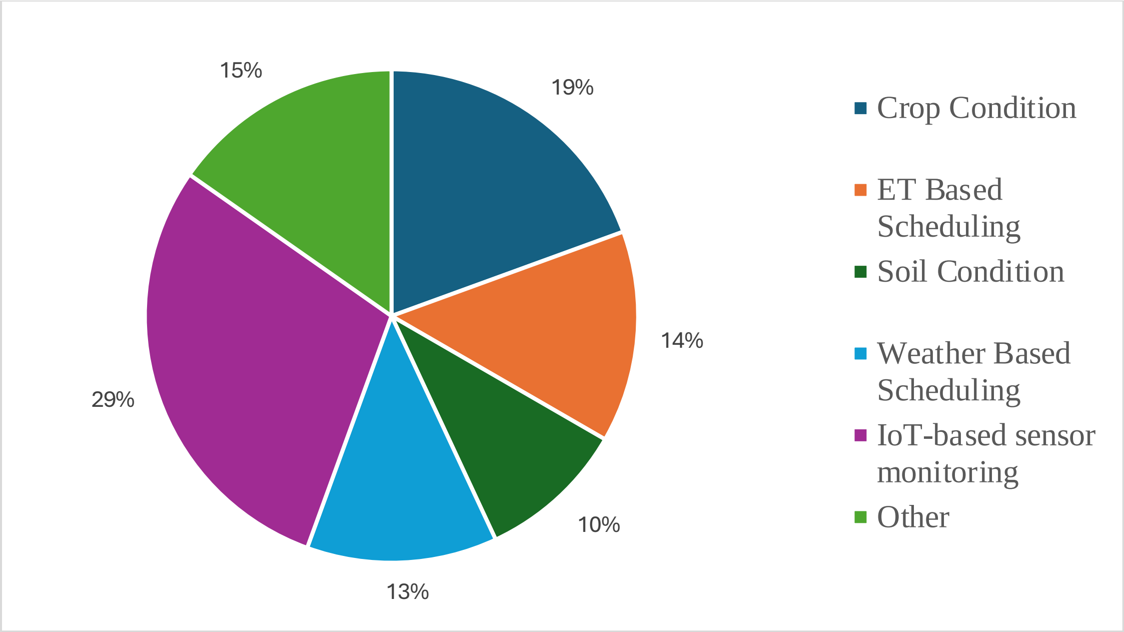

Figure 27. Survey results for question #2: “If you were to change your current methods of irrigation management, what methods would you use?”.

For survey question three, participants were asked; “What incentives or improvements would increase your interest in improving your irrigation management methods?” Regarding incentives for improving irrigation management methods, the majority of respondents identified improved yield (61 responses) as the primary motivator. This was followed by energy savings (36 responses) and improved economics (34 responses). Reduced water use (28 responses) and complying with policy (5 responses) were also mentioned, albeit to a lesser extent.

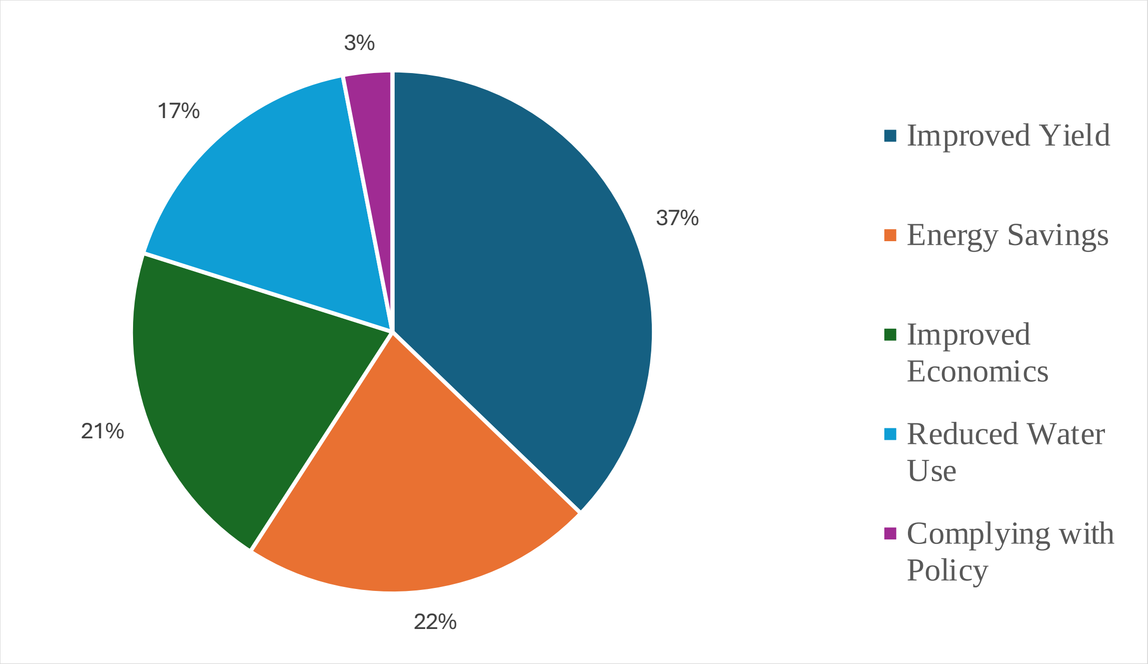

Figure 28. Survey results for question #3: “What incentives or improvements would increase your interest in improving your irrigation management methods?”.

4.4 Discussion

4.4.1 Effect of Irrigation Scheduling on WUE and Yields

The efficient management of water resources in agriculture is paramount for sustainable crop production and environmental stewardship. The impact of irrigation scheduling on water use efficiency (WUE), defined as the improvement in yield divided by the amount of irrigation applied, was investigated in this study. WUE between the treatments from corn (P-value = 0.607) and soybean (P-value = 0.962) fields were not statistically significant different. In theory optimized irrigation scheduling practices, including the timing and amount of water application, have the potential to influence crop water use and performance. By aligning irrigation practices with crop water requirements throughout the growing season, growers should be able to enhance soil moisture availability, promote optimal plant growth, and mitigate the risk of water stress-induced yield losses. The results in the boxplots of Figures 23 and 24 do not display a statistically significant difference between the irrigation application treatments. The low number of samples and relatively high variability of field conditions are suspected to be the causes of insignificance. Therefore, the P-values are not low enough to prove a statistical difference at an alpha value of 0.05 as seen in Table 4.

Although the volume of precipitation Michigan receives is occasionally sufficient in terms of maximizing crop yield, it is rare that the timing of precipitation events aligns with the crop's demands. Hence the need for irrigation to meet the needs of the crop between precipitation events. However, over the course of this three-year study precipitation supplied enough water to limit the number of irrigation applications that could be made under the experimental design described in Table 3. The relatively small volume applied to the recommended irrigation treatment areas can be compared to the sum of each month's precipitation in Figure 18. In years where more applications are required, it is reasonable to assume that results may differ from the trends observed in this study. In the case of the under-irrigated experimental treatment, crop stress and evaporative losses incurred during the application of irrigation theoretically drive differences in yield and WUE. On the other hand, the over-irrigated experimental treatment should theoretically suffer in terms of water use efficiency due to the treatment's increased total application volume and number of applications made. In both of these treatments, the critical factor driving a difference in water use efficiency is time under which precipitation is not sufficient and irrigation may need to be applied. Every time a precipitation event fills the soil profile, there is a period in which all treatments are subject to the same conditions, reducing the opportunity for WUE to be impacted under this study's experimental design. Additionally, the unusually high non-irrigated treatment area yields are also supportive of the idea that the impacts of the treatments were likely masked by frequent precipitation in the years of study. As seen in Figures 19, and 20, the un-irrigated areas were unusually similar to the irrigated areas, with the corn fields not displaying a strong statistical difference. In Table 6, it can be seen that although total precipitation may have been similar to the thirty-year average precipitation for this area, it can also be seen that this volume comes in consistent intervals during some seasons and sporadically in others. In this study, fields included in the data set had between one and eight irrigation applications as permitted by the methods, creating a large difference in potential for effect to take place.

A more noticeable difference is displayed when the volume of water applied is accounted for in the WUE equation as compared to this study's yields. While none of the treatments indicate a statistically significant difference in terms of WUE at an alpha of 0.05, it is noticeable that the averages for the different experimental treatments are not as similar as the averages for yield. It may be apparent that the total irrigation volumes applied per treatment have more impact on the resulting WUE than the yields do since yields were quite similar. However, the response observed is not a linear trend, even at reasonable irrigation volumes and thresholds. While frequent and heavy rainfall might be the cause of similar results for the over-irrigated and recommended irrigation treatment areas, the under-irrigated treatments should have been favored by the experimental design. While it's possible that there was little opportunity for the impact of the treatments to take effect, it is also possible that different treatments may have been more appropriate at different times throughout the growing season. While application volumes were adjusted in the early stages of crop development to better suit the crops needs and rooting depth, it is likely that different experimental treatments may have aligned with certain precipitation events at specific times throughout the growing season. In the ideal scenario, the soil moisture would drop to the irrigation threshold value, then triggering irrigation, and then irrigation would be applied filling the soil profile to field capacity. After irrigation, the soil profile would dry back down to the irrigation threshold at the time of precipitation, completing a full cycle of the process. Conversely other experimental treatments which did not align with precipitation events would likely require an additional irrigation application or loose the impact of remaining soil moisture provided by the initial application that was pushed below the root zone by rainfall. This lends to the concept that a more flexible approach to irrigation scheduling may be required to observe its full potential.

4.4.2 Challenges of Weather on Irrigation Management in Sandy Soils

The challenges posed by weather on irrigation management in sandy soils are significant and multifaceted, particularly in the case of more intense and irregular rainfall events. Sandy soils have unique characteristics that influence water retention and drainage, making them especially vulnerable to the impacts of changing weather patterns. One of the key issues with sandy soils is their low water-holding capacity. Unlike clay or loam soils, which can retain moisture for longer periods, sandy soils drain quickly, which can lead to water stress for crops, especially during dry spells. However, when faced with intense or irregular rainfall events, sandy soils can become saturated rapidly, leading to increased runoff and leaching. This creates a challenge for irrigation management, as there is limited capacity to store rainfall. Sandy soil's relatively low water holding capacity is also a benefit as it increases drainage, reducing the risk of flooding which affords producers more control over their field's soil moisture than a heavier soil. Maintaining soil moisture at unnecessarily high levels is inefficient due to the soil's low soil water storage capacity for potential precipitation, which could lead to an increased risk of runoff if storage is rapidly exceeded. Managing this excess water effectively without stressing the crop, wasting resources, and leaching valuable nutrients is a challenge, especially in humid climate regions. In regions experiencing more intense and irregular precipitation events, irrigation strategies must adapt to accommodate fluctuations while maintaining efficiency and practicality. This highlights the importance of selecting an irrigation volume and threshold that accounts for the soil characteristics, crop, and weather conditions. Additionally, these results lead to the implication that a more pliable irrigation scheduling method would be ideal.

Efficient irrigation management requires striking a delicate balance between utilizing precipitation and supplementing it with irrigation when necessary. This balance becomes increasingly difficult to achieve with erratic weather patterns. As seen in Figure 14, the area of this study has received an increasingly inconsistent amount of precipitation in recent years. The irrigation needed to improve yields and water use efficiency is typically infrequent and relatively small in volume as compared to the total demand for corn and soybeans grown in Michigan. This underscores the need for precise timing of each irrigation application and calculation of irrigation volume based on soil, crop, rooting depth, and forecasted precipitation.

Weather forecasting, especially the prediction of precipitation timing and volume, has been a historical challenge. It has been found that the reproductive stages of corn and soybeans are more sensitive to fluctuations in soil moisture (Payero, 2009). Thus, this period contains the highest potential for irrigation to impact yield (Payero, 2009). While this study focused on adhering to the experimental design during the same critical stages, significant differences in WUE were not observed. This is likely due to the availability of soil moisture due to precipitation during critical stages and the smaller differences between experimental treatments utilized in this study. In Figure 25 it can be seen that corn and soybeans reacted differently to increasing combined volumes of irrigation and precipitation. While corn has a positive trendline indicating that increased irrigation and precipitation can increase yield under the right conditions in this area, Soybean data from Figure 25 has a negative trendline suggesting that a more minimalistic approach to irrigation should yield better on average in this area. This is not to say that soybean fields should exhibit signs of wilt before irrigating, but rather that a focus on maintaining soil moisture above the selected irrigation threshold is likely to be a better strategy than filling the soil profile to field capacity when considering yields. Although disease presence was minimal or consistent between treatments in this study, it is possible that disease played a role that was not observed. For instance, a study on white mold suggests that the soybeans have a disease severity index that increases with increasing total precipitation, when total precipitation in the month of July is between 20 mm and 108mm (Fall et al., 2017).

In another study where frequent and substantial precipitation took place during the growing season, statistically significant differences were observed between experimental treatments, allegedly due to a more pliable scheduling technique with more sophisticated weather forecasting (Mahdavi & Fujimaki, 2024). As described by methods of supplemental irrigation, efficient irrigation methods in the particular location of this study apply a volume just large enough to maintain soil moisture above the irrigation threshold until the next precipitation event. This may indicate that directly observing available water through the use of in situ soil moisture monitoring could be more advantageous than calculating the current available water as done in ET-based scheduling methods. Utilizing irrigation scheduling with the aid of soil moisture monitoring reduces potential errors in estimating current conditions while maintaining the best approach to forecasting the future conditions of the soil profile and crop’s needs. In a study with more strenuous water constraints, it was found that irrigation scheduling methods that combined multiple techniques were over 50% more effective than fixed interval and frequency applications (De Pascale et al., 2011). This study’s results, although not statistically differentiated, suggest the ideal volume is somewhere between applying just enough to maintain the soil moisture above the irrigation threshold until the time of the next precipitation event and applying a volume that does not exceed the water holding capacity of the profile at the time of the next precipitation event.

Similar approaches to improving irrigation application timing and volume have been attempted using mathematical and observational methods for several decades with success (Stegman, 1983). How close one allows the soil moisture to get to the irrigation threshold and field capacity depends on one's perceived values of water and crops as resources. It is likely that implementing irrigation scheduling methods and utilizing advanced monitoring technologies in conjunction has the potential to mitigate the impacts of weather variability on crop production and improve water use efficiency in sandy soil environments. Comparing the WUE of the grower's methods in corn (figure 22) to any of the other experimental treatments shows the potential of irrigation scheduling methods.

4.4.3 Impact of WUE on Economics

As with any practice, the costs of irrigation must be outweighed by the benefits in order to justify making the investment in an irrigation application. One of the biggest obstacles to the adoption of irrigation management practices is a lack of cost effectiveness, even when water use efficiency is high (Koech & Langat, 2018). Tables 6 and 7 show that although the yields favor higher irrigation volume treatments, the average profits for both corn and soybeans support the recommended irrigation treatment and under-irrigated treatment. In Michigan, 2,306 irrigation systems and wells are still powered by diesel (USDA, 2024). The price of operating diesel powered pumps and irrigation systems has increased dramatically in the last decade, for the calculations in this study diesel pumping cost is assumed at about 10 USD per hectare cm. Considering the recent increase in diesel prices, this is a conservative estimate that drives the economic choice to favor applications similar to the recommended irrigation treatment or under irrigated treatment, even more so than the economics of electric power. Labor costs were not included in this calculation as all center pivots in this study were operated remotely. Additionally, the labor costs of center pivot irrigation per acre are generally low in comparison to improvements in profit. Likewise, the fixed costs of the center pivot, pump, and accompanying hardware were not included as they are assumed to be constant values across the different treatments. Even while only assessing the impact of pumping the water for irrigation and powering the center pivot itself, a quick calculation of the profit values from Tables 6 and 7, applied to a sizable field reveals the potential for thousands of dollars of impact between many of the treatments. Although economics are essential to making cost effective irrigation applications, they are far from the only value one should consider. In this study, significant differences in yield and WUE were not observed, thus there is little justification to apply more than what the recommended irrigation treatment's scheduling suggests. However, there is reasoning to apply more than the under-irrigated treatment scheduling suggests, based on the economics and mitigation of risk to plant health. It is logical to buffer the system by applying a slightly larger volume of irrigation and maintain the soil moisture above the crops wilting point due to the unpredictability of climatic conditions, so long as the selected volume does not exceed the soil's water holding capacity. There were multiple instances in this study where the peak demand of the crop landed on a dry spell, this caused the available water in the under irrigated area to quickly diminish due to the application volume not filling the profile. This led to far more frequent applications, which in a dry growing season could become costly and induce unnecessary stress on the crop.

4.4.4 Irrigation Management Survey

A survey was conducted in the winter of 2024, in southwest Michigan to assess producer's perceptions of irrigation and motivation to improve their irrigation management practices. This survey inquired about the participants driving factor for irrigation scheduling adoption with the hope of better tailoring our efforts to the area's needs. The results of the survey conducted for the purposes of this study provide valuable insights into the current practices and preferences of Michigan and Indiana farmers regarding irrigation management. The predominance of crop monitoring and ET-based scheduling among current techniques, as seen in Figure 25, suggests a reliance on observational and environmental data for decision-making. A similar survey conducted upon Michigan producers who operated irrigation indicated 90% of respondents were observing the condition of the crop to decide when to irrigate (United States Department of Agriculture, National Agricultural Statistics Service, 2019). The same survey reported only 7% of Michigan irrigators reported utilizing a soil moisture sensing device to help them decide when to irrigate (United States Department of Agriculture, National Agricultural Statistics Service, 2019). However, the interest in adopting IoT-based soil moisture monitoring methods (figure 26) indicates a growing recognition of the potential benefits of technology driven approaches to irrigation scheduling.

The preference for remote soil moisture sensing reflects a desire for real-time, site-specific information to guide irrigation decisions. This aligns with the increasing availability and affordability of sensor technologies, which offer producers the ability to monitor soil moisture levels with greater precision and efficiency. Similarly, the interest in ET-based irrigation management indicates a recognition of the importance of accounting for ET rates in irrigation scheduling to optimize water use efficiency. It is arguable that these methods are each other's counterparts, both capable of providing similar quantitative data for producers to base their irrigation management decisions on.

The identified incentives for improving irrigation management, particularly the emphasis on improved yield and energy savings, highlight the key motivations driving farmers' decisions. By focusing on strategies that offer tangible benefits such as increased productivity and reduced resource consumption, stakeholders can better promote the adoption of sustainable irrigation practices. The reasoning behind not selecting improved economics or water savings more often is unclear. While it is logical that producers are interested in achieving high yields, expend the least amount of energy, and use the lowest amount of water to do so, all of these components are interlinked by economics. Under certain circumstances, as is the case with many seed contracts in Michigan, producers are not directly paid by yield but rather by relative performance to other fields planted to the same variety. For the sites examined in other parts of this study, all corn and soybeans were planted for grain production in which revenue would, in theory, be based directly on yield and grain quality. However, many of the producers who participated in the survey may have had a more competitive perspective as they may have been farming under seed contracts where yield is comparatively analyzed. Unlike the four fields that were analyzed in this study, which were used for grain production, respondents were likely to have some fields intended for seed production. Since seed production contracts are based on performance and often have increased profits, there is less tolerance for the risk of wilt which might explain some respondent's preferences for yield above other options. This, along with the areas abundant water supplies, likely causes producers to favor improving yield and energy savings over a more cumulative metric, like improved economics. Since water is paid for in the cost of pumping, be it electric or diesel powered, it makes sense that utilities are more prevalently analyzed by producers than water use as it is a more direct value they pay. Overall, the survey results (figure 27) suggest a willingness among Michigan farmers to explore innovative approaches to irrigation management that prioritize efficiency, productivity, and sustainability. As technology continues to advance and awareness of water scarcity and environmental concerns grows, the adoption of precision irrigation techniques and data-driven decision-making are likely to become increasingly prevalent in agricultural settings.

4.5 Conclusion

The efficient management of water resources in agriculture is crucial for ensuring sustainable crop production and environmental stewardship. In this study, the impact of irrigation scheduling on WUE was explored, with a focus on improving crop yields while minimizing water consumption. Although there were no statistically significant differences between treatments, several key insights emerged, emphasizing the complex relationship between irrigation practices, soil moisture, and crop performance. Optimized irrigation scheduling practices, including timing and volume adjustments, hold potential to enhance soil moisture availability, promote optimal plant growth, and mitigate the risk of water stress-induced yield losses. While statistically significant differences in yield were not observed among irrigation treatments, the results underscored the importance of aligning irrigation practices with crop water requirements throughout the growing season. The differences in averages between WUEs indicate that there is a nonlinear response with a point of diminishing return. Factors such as the volume and frequency of precipitation events, as well as soil characteristics, played significant roles in influencing the effectiveness of irrigation strategies.

Challenges posed by weather variability, particularly in sandy soil environments, highlighted the need for adaptive irrigation management approaches. The potential for irrigation scheduling and soil moisture monitoring is likely underestimated in this study as the number of irrigation applications was relatively low compared to an average year. The potential response in a drought year would be much more revealing as the effective treatment periods would be longer. The economic implications of irrigation management were also examined, with a focus on balancing the costs of irrigation against the benefits of improved yields and water use efficiency. While higher irrigation volumes favored increased yields, the recommended irrigation treatment, as well as under-irrigated approaches, demonstrated favorable economic outcomes. Once again, this effect may be underestimated as the total irrigation required for the duration of this study was relatively low. This study emphasized the importance of selecting irrigation volumes and thresholds that account for soil characteristics, crop needs, and weather fluctuations, underscoring the necessity of a flexible and data-driven approach to irrigation management. Using a more flexible scheduling approach than the strict volumes and thresholds in this study is likely to further optimize irrigation water use efficiency, creating more observable responses to the irrigation treatments.

Overall, the study demonstrates the potential of integrating advanced monitoring technologies and data-driven decision-making into irrigation management practices. As water scarcity and environmental challenges become increasingly threatening, the adoption of precision irrigation techniques is poised to play a critical role in ensuring the viability and resilience of crop production systems. By prioritizing efficiency, productivity, and sustainability, producers can work towards a more resilient and environmentally responsible agricultural sector.

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