AMERICAN UNIVERSITY OF BEIRUT

SMART IRRIGATION FOR SWEET CORN: EVAPOTRANSPIRATION-BASED OR SOIL MOISTURE SENSOR-BASED SCHEDULING TECHNIQUE?

by
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AN ABSTRACT OF THE THESIS OF

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Globally, water deficit during the growing season is a major factor limiting sweet corn and overall crop production. Irrigation scheduling is one of the novel methods that can be used to achieve ideal crop yield while saving water. The overall goal of this study was to compare between two smart irrigation scheduling methods, the ET-based and soil moisture sensor-based systems under different treatments and their effects on sweet corn morphometric parameters in improving water productivity while observing sap flow rates in different soil moisture regimes. The two experiments were carried out at the Agricultural Research and Educational Center (AREC) of the American University of Beirut (AUB) in Lebanon's Beqaa Valley. The ET-based experiment had three treatments calculated to be equal to 60%, 90%, and 120% of Penman-Monteith (ET_C), and was automatically set and calculated via an irrigation controller. The soil moisture sensor-based irrigation experiment had SM25%, SM30%, and SM35% which were thresholds recorded from soil moisture sensors whereby an irrigation event was initiated when soil volumetric water content (SVWC) reached the soil water depletion thresholds. All the irrigation treatments had three replicates and had flow meters installed on all six irrigation treatments to measure the applied irrigation water. Results showed a positive linear relationship between fresh ear yield and amount of water applied, regardless of the scheduling method, increasing at the rate of $32kgm^{-3}$. More so, water saving was realized in irrigation treatments ET60%, SM25% and ET90% at 29%, 11%, and 5% respectively. Deficit irrigation in both scheduling methods showed an increase in water productivity except in ET60%, which had a significantly low yield of 11.92 tha^{-1}. High soil moisture conditions proved as detrimental on yield as water stress conditions in the productivity of sweet corn. Sap flow data had a positive relationship with ET and the amount of applied water. Only treatment SM30% had a higher average transpiration rate of 3% higher than ET while treatments SM25% and SM30% had 18% and 9% less than ET respectively. In conclusion, both the ET-based and soil moisture sensor-based irrigation techniques proved efficient in scheduling irrigation to produce high yield and can be used to save irrigation water.

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[1] (d) Solar panel powering the sap flow sensors.

[2] where S is saturation point, FC is field capacity, and PWP is permanent wilting point

[3] The same letter represents an insignificant difference at $P<0.05$

[4] The different letters represent significant difference at $P<0.05$.

[5] The same letter represents an insignificant difference at $P<0.05$

[6] The different letters represent a significant difference at $P<0.05$

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[7] where S is Saturation point at 49.7%, FC is Field capacity at 37.4%, and PWP is the permanent wilting point at 22.2%

[8] The same letter represents an insignificant difference at P<0.05

[9] The same letter represents an insignificant difference at P<0.05

[10] The same letter represents an insignificant difference at P<0.05

[11] A – emergency, B – zero to 8 leaves, C – 8 to 16 leaves, D tasseling and silking, E – maturity

TABLES

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[12] Within the same columns, means with the same letter are insignificantly different at $P<0.05$ (n = 30 from 3 replicates)

[13] Within the same columns, means with the different letter are significantly different at $P<0.05$ from three replicates (n = 120 except for root biomass where n =12)

[14] Within the same columns, means with the same letter are insignificantly different at $P<0.05$ from three replicates (n = 30) based on LSD (Least Significant Difference)

[15] Within the same columns, means with the same letter are insignificantly different at $P<0.05$ from three replicates (n = 60 except for root biomass, n = 12) based on LSD (Least Significant Difference).

[16] Within the same columns, means with the same letter are insignificantly different at $P<0.05$ from three replicates (n = 30) based on LSD (Least Significant Difference)

[17] Within the same columns, means with the same letter are insignificantly different at $P<0.05$

[18] Within the same columns, means with the same letter are insignificantly different at $P<0.05$ from three replicates (n = 30) based on LSD (Least Significant Difference)

[19] Within the same columns, means with the same letter are insignificantly different at $P<0.05$ from three replicates (n = 30) based on LSD (Least Significant Difference).

[20] Within the same columns, the same letter shows an insignificant difference at $P<0.05$

ABBREVIATIONS

%	Percent
^{O}C	Degrees Celsius
AC	Alternating Current
ANOVA	Analysis Of Variance
AREC	Agricultural Research And Education Center
ASW	Available Soil Water
ASWC	Available Soil Water Content
AUB	American University Of Beirut
AVWC	Available Volumetric Water Content
cm^3/hr	Cubic Centimeters Per Hour
C_n	Calibration Coefficient
CS	Campbell Scientific
DAP	Day After Planting
DI	Deficit Irrigation
ET_C	Crop Evapotranspiration
ET_O	Reference Evapotranspiration Rate
F1	Interval Of Days
FAO	Food And Agricultural Organization
FC	Field Capacity
FC	Field Capacity
FDR	Frequency Domain Reflectometry
G	Gram
G	Gross Volume Of Water Per Plant
g/cc	Grams Per Cubic Centimeter
Ha	Hectare
HI	Harvest Index
Hr	Hour

HRM	Heat Ratio Method
K	Potassium
k	Thermal Diffusivity
K_a	Bulk Dielectric Permittivity
Kg	Kilogram
kg/ha	Kilogram Per Hectare
kg/hr	Kilograms Per Hour
kg/m^3	Kilograms Per cubic meter
L/sec	Liters Per Second
LPH	Liters Per Hour
LSD	Least Significant Difference
m^3	Cubic Meters
m^3/ha	Cubic Meters Per Hectare
mA	Mill Ampere
MAD	Management Allowed Depletion
Mm	Millimeter
mm/day	Millimeters Per Day
N	North
NASA	National Aeronautics And Space Administration
Np	Number Of Emitters Per Plant
NPK	Nitrogen, Phosphorous, and Potassium
PAW	Plant Available Water
Pd	Shaded Area
PWP	Wilting Point
Qa	Application Rate
Q_v	Volumetric Water Content
RS	Rain Sensor
S	Saturation
Se	Spacing Between Emitters

SFM	Sap Flow Meter
SH	Shoot Height
SH	Shoot Height
S_L	Spacing Between Driplines
SM	Soil Moisture
SMAP	Soil Moisture Active Passive
Sp	Spacing Along Rows
SPAW	Soil-Plant-Air-Water
Sr	Spacing Between Rows
SV	Solenoid Valve
SVWC	Soil Volumetric Water Content
SWC	Soil Water Content
t	Ton
t ha^{-1}	Tons Per hectare
Ta	Application Time
Td	Daily Water Use
TDR	Time Domain Reflectometry
Ud	Irrigation Requirement
V	Volts
Vh	Heat Pulse Velocity
VWC	Volumetric Water Content
W	Watts
WP	Water Productivity
WU	Water Use
WUE	Water Use Efficiency
x	Distance

CHAPTER 1

INTRODUCTION

Agriculture is by far the biggest consumer of extracted freshwater resources; causing critical water scarcities and shortages in arid and semi-arid areas in the world (Postel, Daily, & Ehrlich, 1996). Agriculture is still being carried out in most regions with no regard for sustainability and water resource conservations. A rapidly increasing population and pressure on limited water resources will only exacerbate the already existing challenges on the availability of water for agriculture, causing food insecurity for future generation (Zwart & Bastiaanssen, 2004). Furthermore, variability in precipitation patterns expected due to climate change, which will ultimately threaten the availability of irrigation water supplies (Padakandla, 2016).

Adapting to these water scarcities will require several techniques and strategies which include improving irrigation management, reducing irrigated land, cultivating crops of lower water requirements, reducing tillage, residue management, growing drought-tolerant varieties, use of advanced irrigation scheduling methods, and others (Elías Fereres & García-Vila, 2019). Irrigation management helps reduce the economic and environmental impacts of over or under irrigation (Datta et al., 2018). For example, over-irrigation not only causes waste of the already limited water resources but also causes economic loss due to higher pumping costs, which also reduces the lifespan of the pump. Moreover, over-irrigation causes heighten loss in fertilizers through leaching and runoffs and hence contaminating downstream and underground water resources. This is not to mention the relationship between yield and applied water, which shows decreased yield with excessive application of irrigation water(Elias Fereres & Soriano, 2006). In contrast, under irrigation negatively impacts crop yield and causing loss of revenue for growers and food insecurity issues in the area (Datta, Taghvaeian, & Stivers, 2017).

Through irrigation management, various irrigation scheduling techniques have been developed such as water balance method, soil water content or soil water potential, plant stress monitoring, computer models and charts to increase irrigation water use efficiency (Jones, 2004; Soulis & Elmaloglou, 2016). Combination of different irrigation scheduling methods has been practiced and endorsed as a means of optimizing irrigation scheduling of crops and preventing water wastage (Deb, Shukla, Sharma, & Mexal, 2013; Navarro-Hellín, Martínez-del-Rincon, Domingo-Miguel, Soto-Valles, & Torres-Sánchez, 2016).

Green and blue water can further be saved through precision irrigation by monitoring of real-time measurements of variables like evapotranspiration (ET), temperature, rainfall and/or soil moisture while investigating crop water use, water use efficiency (WUE), and irrigation efficiency (Evett, Tolk, & Howell, 2005; Rodriguez-Ortega et al., 2017). Green water is the soil moisture from precipitation or irrigation water absorbed by plant roots and lost through the evapotranspiration flux in the hydrologic cycle. Blue water is irrigation/ rainwater that is freely available and can be applied to the soil as irrigation water (Falkenmark & Rockström, 2006). This water can be saved by using smart water technologies like evapotranspiration-based irrigation and soil moisture sensor-based irrigation that can schedule irrigation events based on actual water requirements and crop use considering weather factors (McCready, Dukes, & Miller, 2009; Migliaccio, Schaffer, Crane, & Davies, 2010).

Soil moisture sensor-based irrigation techniques give a measure of available soil water (ASW) which is depleted by plant roots at a rate of evapotranspiration until wilting point. Soil moisture sensors can, therefore, be used in determining when to irrigate and when to stop based on knowledge of existing soil moisture conditions (Cardenas-Lailhacar & Dukes, 2010; Dursun & Ozden, 2011; y Garcia, Guerra, & Hoogenboom, 2009). Quantifying ASW can determine optimum irrigation timing and amount (Lukangu, Savage, & Johnston, 1999). Many studies have been used in scheduling irrigation based on soil moisture status in papaya (Migliaccio et al., 2010), tomatoes (Zotarelli, Scholberg, Dukes, Muñoz-Carpena, & Icerman, 2009), Chile peppers (Sharma, Shukla, Bosland, & Steiner, 2017). Advantages to this method are; ease in practice and automation with some commercially available systems. Major drawbacks to the soil moisture sensor-based scheduling method are the spatial soil moisture heterogeneity, the difficulty in the representation of the entire root-zone and need for calibration of sensors for the different soil types (Jones, 2004).

ET-based irrigation techniques rely on the measurements of crop water use through evapotranspiration which is dependent on the atmospheric conditions like air temperature, humidity, solar radiation, humidity, and wind speed (Kranz, Irmak, Van Donk, Yonts, & Martin, 2008). Field studies demonstrating the use of the ET-based irrigation system include; (H. Jaafar, Khraizat, Bashour, & Haidar, 2017) on biblical hyssop, (Ertek & Kara, 2013; y Garcia et al., 2009) on sweet corn, and (Di Paolo & Rinaldi, 2008; Irmak, Djaman,

& Rudnick, 2016) on maize. Merits to this method are ease in principle on how much water to apply. On the other hand, ET-based irrigation methods rely on the estimation of a local climatic data (ET_O) with lag time and crop coefficients that are often inaccurate leading to cumulative errors (Masmoudi, Masmoudi, Abid-Karray, & Mechlia, 2011; Pauwels & Samson, 2006).

Plant-based irrigation methods can be based on either direct or indirect measurements of plant water status or plant physiological response to drought and include sap flow, stomatal conductance, and many others (Jones, 2004). Sap flow measurements have been used in irrigation management in maize (Jiang et al., 2016), olives and apples (Fernández, Green, Caspari, Diaz-Espejo, & Cuevas, 2008) and soybean (Gerdes, Allison, & Pereira, 1994). The benefits of this method are its sensitivity to moisture deficit, but at the same time needs sophisticated instrumentation and expertise to be used (Jones, 2004).

In this paper, field experiments were conducted on sweet corn under two different irrigation scheduling methods, ET-based, and soil moisture sensor-based, which were at three thresholds for each experiment. The objectives were to (1) determine the effects of ET and soil moisture sensor-based irrigation techniques under different treatments on sweet corn morphometric parameters in improving water productivity; (2) determine the minimum water requirements and maximize sweet corn yield of sweet corn under deficit irrigation (DI) treatments; (3) observe the sap flow rate and its relationship with evapotranspiration under different water regimes and evaluating it as a possible irrigation scheduling method; (4) to measure real-time volumetric water content in the root zone of ET-based irrigation scheduling technology.

CHAPTER 2

LITERATURE REVIEW

In this chapter, botanical classification, economic importance, and recent studies about sweet corn will be discussed. This will be proceeded by an explanation of the smart irrigation scheduling concepts; the soil moisture sensor-based, ET-based, and plant-based (sap flow) in effecting water-saving and improving water use efficiency. Finally, an overview of recent studies on the effect of hydric stress (deficit Irrigation) on sweet corn economic yield will be highlighted.

2.1.Sweet corn classification, cultivation, and recent studies

Sweet corn like other corn varieties is used as food for humans, fodder for livestock and as a raw material for some industries. Sweet corn is one of the most popular vegetables worldwide. It is mostly consumed fresh because of the soft kernels, thin shell, high concentration of sugar, and tastefulness. At the same time though, sweet corn is often canned as often served with other foods as an appetizer or in salads. It can also be preserved by freezing to increase its shelf life and freshness. Alternatively, it is dried, and dough made from the kernels to be used chips, pasta, and other dough products (A. Oktem, M. Simsek, & A. Oktem, 2003). Sweet corn used in this field experiment was of classification Zea mays L. var. merkur belonging to Family Poaceae.

Sweet corn is typically planted in the summer, requiring warm soil temperature (20-30 ^oC) for favorable growth. It is also significantly affected by diurnal changes in temperature (y Garcia et al., 2009). Sweet corn is generally cultivated over an extended period to provide a continuous supply of fresh yield. Varieties of sweet corn take 70 to 100 days to mature from the day after planting (DAP). Studies by (Ertek & Kara, 2013), and (A. Oktem, M. Simsek, & A. G. Oktem, 2003) showed that the average fresh ear yield of sweet corn at full irrigation was 14712.7 kg ha^{-1} and 14350 kg ha^{-1} respectively, but can also go beyond 20000 kg ha-1 (y Garcia et al., 2009).

Sweet corn is a quick-growing crop and high yielding, with one of the highest dry matter per unit quantity of water. Proper irrigation management would achieve maximum yield, quality such as sugar and protein content in addition to enhanced water use efficiencies with minimum water losses conversely, poor irrigation practices with insufficient water provided to sweet corn lead to low yield and hence economic loss. Numerous studies have been conducted to determine the water-yield relationship (Ertek & Kara, 2013; Oktem, 2008; y Garcia et al., 2009).

In this study, a smart irrigation system was assembled based on ET and soil moisture data to schedule irrigation. Sap flow was also measured during the growing season, and its validity determined as an irrigation scheduling technique. The irrigation system was drip since it is potentially much more efficient than any other irrigation method over large fields, which translates into significant water saving (Karlberg, Rockström, Annandale, & Steyn, 2007). Drip irrigation also offers improved yields while using less water and at the same time decreasing the cost of tillage. Through drip irrigation, water is precisely placed where it is needed, and with a high degree of uniformity, which reduces losses due to surface runoff and deep percolation (Elmaloglou & Diamantopoulos, 2010). It is a compound of these features that drip irrigation was preferentially used in this research.

2.2.Smart irrigation scheduling

Irrigation scheduling is principally determining when to start an irrigation cycle and how long to irrigate the zone or set. The time of an irrigation event is symmetrical to the amount of water applied. In essence, irrigation scheduling aims to obtain the optimal level of water supply for crop productivity (Jones, 2004). Worldwide shortages in water are compelling the development of new methods and technologies that would maximize water efficiency through automation in a term called smart irrigation. (Mohamed, Tharakan, & Mini, 2018) proved that smart irrigation systems were 31% more efficient than conventional time-based and manual scheduled sprinklers. More so, the use of smart irrigation minimizes costs and labor requirements (Davis, Dukes, & Miller, 2009). Smart irrigation is a technology of using ET-based and soil moisture sensor-based controllers to automate and minimize excess irrigation by monitoring weather, soil conditions, evaporation, and plant water use to adjust the watering schedule of the site in real-time (McCready et al., 2009).

Weather/ET-based smart irrigation controllers use meteorological data compounding of temperature, wind, solar radiation and humidity to adjust irrigation schedules to supply appropriate irrigation water in accordance to plant needs(Davis &

Dukes, 2010). There are three typical kinds of controllers, and they include; 1) signal-based controllers which use publicly available weather data and grass reference ET is calculated to be finally wirelessly connected to a controller. 2) Historic ET controllers are based on prehistoric water use in different regions and adjusted with temperature and solar radiation to create programmed water use curves. 3) Standalone controllers rely on on-site meteorological data to calculate continuous ET measurements and water requirements consequently (Addink, 2006; Marian, 2008; Riley, 2005). . A standalone controller is what was used in this experimental study.

Overall, there are numerous benefits of using smart irrigation systems which include enhancement and protection of produce quality, improvement in nutrient efficiency and use, maximization of growth for crops under irrigation, reduction in water waste through deep percolation and runoffs, and lastly improvement in efficiency in water conservation and management (Mohamed et al., 2018).

Soil moisture sensor-based smart irrigation controllers rely on continuous monitoring of relative soil moisture content throughout the field to more accurately schedule irrigation events (Mohamed et al., 2018). There are two primary forms of soil moisture sensor-based systems. (1) Suspended cycle irrigation systems have set irrigation scheduling cycles and can use soil moisture data to stop the next schedule when there is still adequate moisture in the soil. (2) Water on demand irrigation system where the user sets lower and upper thresholds based on soil moisture data to initiate and stop irrigation events. In this experimental study, the theory of water on-demand irrigation system was applied.

2.2.1. Evapotranspiration-based irrigation scheduling

ET-based irrigation allows near real-time adjustment of irrigation requirements based on estimated water use by the crop the previous day. In rapidly changing weather, the lag in values may not be relevant to address the irrigation requirements rightfully. To optimally quantify water consumption needs for a plant, the water evaporated from the soil and water consumed by plant roots and lost through transpiration has to be combined to be collectively known as evapotranspiration (ET). Most irrigated water is lost through ET, and by accurately quantifying it, irrigation managers can efficiently determine water use in agricultural fields which in turn supports water conservation, energy savings, mitigation of groundwater depletion, and crop quality optimization (Caya et al., 2018).

ET is defined as a combination of processes where water is lost from the soil surface by evaporation and from the crop by transpiration. ET is mostly influenced by weather parameters like humidity, wind speed, solar radiation, and temperature. In the open fields, evapotranspiration is calculated using a set of equations, Hargreaves-Samani (Hargreaves & Samani, 1985) and Penman-Monteith equations being the most famously used to determine irrigation water needs for a plant (Richard G Allen, Luis S Pereira, Dirk Raes, & Martin Smith, 1998a). In unventilated greenhouses, atmometers can be used to correctly calculate ET based on Penman-Monteith (H. H. Jaafar & Ahmad, 2018).

There is a lot of research that has been conducted on sweet corn and corn water requirement and the effect of water stress in the evaluation of water use efficiency. Different methods have been used in the application of irrigation water; from furrow systems (Pandey, Maranville, & Admou, 2000) to more advanced methods like subsurface drip irrigation (Irmak et al., 2016). Even many more studies have been conducted and present promising results in the implementation of ET-based scheduling methods (Cid, Taghvaeian, & Hansen, 2018; Ertek & Kara, 2013; Irmak et al., 2016; Kiziloglu, Sahin, Kuslu, & Tunc, 2009; y Garcia et al., 2009). While using ET-based scheduling, deficit irrigation (DI) is often used as a farm strategy to provide water savings while maintaining a high yield (Elias Fereres & Soriano, 2006).

Deficit irrigation (DI) is defined as the application of water below the crop ET requirements to improve water use. Deficit irrigation as an optimization strategy can apply irrigation water below the full crop water requirement throughout the growing season or only during the drought-resistant growth stages of a crop cycle without severe yield reduction (Elias Fereres & Soriano, 2006). This technique, however, is limited to recommendations of no less than 60% as water deficit induces crop water stress, ultimately affecting crop growth and development (Greaves & Wang, 2017). Furthermore, studies carried out have shown corn yield is most affected by water scarcity at cob formation (Cakir, 2004). It is therefore imperative that at when carrying out DI, lifesaving irrigation is carried out to replenish the soil water reservoir to minimize the negative effect on yield.

DI emphasizes adjustment in irrigation management and focusing on production (marketable produce) per unit of water consumed (transpiration) rather than production per area and could help cope with water scarcities (Zwart & Bastiaanssen, 2004). Crops often have elaborate mechanisms to deal with water stress depending on their level of drought tolerance, drought resistance, or compensatory growths.

Implementation of DI requires precision in the application of irrigation water and can cause economic loss if miscalculated. Excessive application of irrigation water nullifies the objective of using DI while under-application can cause losses in yield and income (Jones, 2004). Well-designed DI regime, on the other hand, can significantly contribute to the sustainable use of water agriculture by growing more crops with less water leading to growers' profitability(Rodrigues, Paredes, Gonçalves, Alves, & Pereira, 2013).

In this study, Deficit Irrigation (DI) was applied based on ET and was also monitored using soil moisture sensors to improve reliability.

2.2.2. Soil moisture sensor-based irrigation system

Soil moisture is an essential variable in agriculture management. Knowing soil water content (SWC) is imperative to understand the distribution of water within the soil profile and resultant responses on crop performance. Soil-based water measurements are therefore used to adequately strategize water balance estimation and measure water fluxes from crops and on the soil surface. Precise soil water content measurements are also required for investigations of crop water use, water use efficiency, irrigation efficiency, and the hydraulic properties of soils. Hence the use of soil moisture sensors can effectively improve irrigation management (Martin, 2009). Munoz-Carpena, 2008 deduced that automated soil moisture sensor-based irrigation systems were more efficient and had superior substantial water-saving capabilities in comparison to irrigation management based on average prehistoric water conditions (Munoz-Carpena, Bryan, Klassen, & Dukes, 2003).

Soil moisture-based irrigation dates to the origin of irrigated agriculture with various methods used to measure soil volumetric water content. Continuous measurement of soil water moisture in spatial and temporal variability can help in timely predicting when to irrigate (Lukangu et al., 1999). Soil moisture content can be quantitatively measured in many forms as volumetric water content, water potential, gravimetrically, which is a percentage of the total soil volume. Several methods can be used in determining soil moisture content, the first of these included sampling and gravimetric measurement, use of soil moisture sensors and recently also use of remote sensing via satellite.

The ground-based methods of include use of use soil moisture sensors and gravimetric method. The gravimetric method has been credited as the most accurate and involves taking a soil sample from the field to the laboratory for oven drying at 105 ^{o}C for 24-48hr or until the weight of the dry soil sample is stable. Soil moisture weight is deduced as a percentage of soil water on the dry mass basis. By multiplying by the bulk density, the results can be expressed as volumetric water content(Reynolds, 1970). However, it is destructive, time-consuming, and does not give continuous data.

There are numerous non-destructive measurements of soil moisture but mostly use indirect methods to determine soil moisture and include nuclear moderation, electromagnetic sensors tensiometers , gypsum blocks, neutron probes, electromagnetic sensors, electrical resistance sensors, and heat dissipation sensors.

Neutron probe measures soil moisture content on the principle of neutron collision with hydrogen nuclei in water. High energy neutrons from radioactive radium-beryllium or americium-beryllium are emitted into the soil and collide with hydrogen nuclei in water hence slowing down or changing direction in a process called thermalization. The Thermalized neutron density is then measured with a detector, and calibrated against water concentration to give the volumetric water content (Kodikara, Rajeev, Chan, & Gallage, 2013). Neutron probes have an advantage of measuring water content in a bigger sphere than most soil moisture sensors, with a radius of 0.5m around the sensor which in turn reduces errors. The setback to this method is radiation hazards (R. G. Allen, Pereira, Howell, & Jensen, 2011).

Time Domain Reflectometry (TDR) or Frequency Domain Reflectometry (FDR) (capacitance-based) use the change in electrical capacitance of probes inserted into the soil to detect the presence of water. Frequency Domain capacitance probe relies on the fact that the dielectric constant of water is 80 and that of air or soil particles is less than 7. Therefore, the presence of water in the soil between the probe plates produces a highly significant change in its capacitance, which signals the higher the water concentration. The advantage of this method is its quick provision of continuous soil moisture status but hindered by the relatively small volume of soil sampled with a sphere of not more than 1 cm radius around the sensor. This exacerbates with gaps and poor contact between sensors and soil (Oates, Fernández-López, Ferrández-Villena, & Ruiz-Canales, 2017)

The tensiometers work on the principle of soil water potential by indicating the effort required by root systems to extract water from the soil. Tensiometers consist of a porous ceramic tip at the rear end and a vacuum gauge at the top of an airtight, water-filled tube. As the soil dries, water is sucked out through the porous ceramic tip, creating a partial vacuum that is read by the gauge. Tensiometers are advantageous in their ease of use, being cost-friendly, and their suitability in scheduling irrigation cycles. They are on the other hand limited to relatively wet soils as they break suction when operating in dry soil and often overestimate, often overestimating soil matric potential and slow response time (Freire et al., 2018).

Gypsum blocks method of assessing soil moisture works by using two electrodes embedded in blocks of gypsum to measure soil water tension (soil water potential) as a factor of deduced electrical resistance. The resistance between electrodes depends on soil water tension and increases as the soil dries and water gets extracted from the gypsum blocks. Gypsum blocks are credited to being inexpensive but break easily and inconsistently respond to changes in soil moisture (Shock, Barnum, & Seddigh, 1998).

Remote sensing uses active and passive electromagnetic wave and with the use of various models and equations to estimate soil moisture (Njoku & Entekhabi, 1996). Remote sensing offers the possibility to measure the soil moisture content on a low-cost basis for large scale analyses (Wagner, Lemoine, & Rott, 1999). Soil Moisture Active Passive (SMAP) satellite mission was launched on January 31, 2015, by The National Aeronautics and Space Administration (NASA) is one of the recent products developed to directly provide a global mapping of high-resolution soil moisture at a higher resolution. Regardless, this method still has limited accuracy which increases with the presence of significant vegetation cover and limited to recording of less than 10 cm of the soil surface (Peng, Loew, Merlin, & Verhoest, 2017).

Automated soil moisture sensor-based irrigation helps in maintaining a desired soil moisture range in the root zone that is ideal for plant growth (Muñoz-Carpena & Dukes, 2015). In this study, soil moisture was measured using commercially available Campbell scientific moisture sensors CS655. This is a smart sensor that uses innovative techniques to monitor soil volumetric water content (SVWC), based on the soil dielectric concept. The relative permittivity of water is about 80, whereas the other soil constituents like air and soil particles have relative permittivity in the range of 1–7 which makes it an effective method in the measurement of the soil water content (Topp, 2003). The reason for using CS655 soil moisture sensors is their noted accuracy, the high recommendation in irrigation scheduling, and higher precision of results over other sensors (Aguilar, Rogers, & Kisekka, 2015; Chávez & Evett, 2012; J. Singh et al., 2018). This, in addition to the CS655 sensors providing accurate continuous measurement of SWC on the spatial and temporal variability to help predict and schedule an irrigation event (J. Singh et al., 2018).

Soil moisture sensors have some inherent degree of errors and imprecision in measuring soil moisture content. For example, CS655 sensors have been studied and proven to sometimes overestimate soil volumetric water content in clay soil (J. Singh, Lo, Rudnick, Irmak, & Blanco-Canqui, 2019). Notwithstanding, their effectiveness to prevent over-irrigation or crop water stress can be significantly increased by; 1) correct installation in an area representative of the crop being grown. 2) Use in an irrigation shift and system that delivers water evenly. 3) maintaining good contact with soil moisture sensors and soil (Datta et al., 2018).

Previous work done using soil moisture sensor-based irrigation scheduling includes (Irmak et al., 2016) used a PR2/6 Profile Probe which uses TDR technology to schedule irrigation based on the management allowed depletion (MAD). The results showed no water stress at maximum irrigation of sunflower. On the contrary, soil moisture stress has been attributed to leaf drop and overall poor plant growth and production in soybean (Wijewardana et al., 2018). Water use can be reduced up to 70% without negatively impacting crop yield (Muñoz-Carpena & Dukes, 2015). While growing green pepper, there was 505 reduction in water use while using dielectric sensor-based irrigation scheduling without an effect on yield (Munoz-Carpena et al., 2003). More so,

Soil-water retention is unique to a soil type and is a function of pore size distribution. Soil moisture curve is strongly characterized by soil texture, whereby the higher the clay content, the more water retention capacity. A suction force on water is created by evaporation and roots absorption.

Plant Available Water and Management Allowed Depletion

Plant available water (PAW) is the total amount of water held in the plant root zone that can be potentially used by the plant. It is also referred to as water holding capacity, denoting the soil moisture content between field capacity and wilting point (Snyder, 2014). Field capacity is the amount of water that is held between the macropores of soil against gravitational forces after downward gravitational drainage has markedly decreased

It is the management of PAW through irrigation that derives the term Management Allowed Depletion (MAD). This is defined as the maximum amount of Plant Available Water (PAW) allowed to be removed from the soil root zone without stress to the plant before the next irrigation event. The importance of understanding this management strategy is to identify soil moisture depletion thresholds after which marketable yield would be affected. As the soil dries and PAW is continued to be depleted beyond MAD, it reaches the lower limit termed as Permanent wilting point (PWP). Permanent wilting point the lowest boundary of water content in a soil at which indicator plants growing in there, wilt and fail to recover when placed in a humid chamber. PWP like MAD are factors of not only soil characteristics but also vary with different plant types and the climatic environments (Tolk, 2003).

2.2.3. Plant-based irrigation scheduling methods

The plant-based irrigation scheduling methods rely on direct measurements of plant water status or plant physiological processes that respond sensitively to water deficits. When using plant water status, measurements of plant stress are taken directly, but unfortunately, for this method, it is inefficient in telling how much water to apply. Methods used to directly determine plant water status include; visual identification, pressure chamber, psychrometer, tissue water content, pressure probe, and xylem cavitation. Under the indirect measurement through plant physiological processes, the use of sophisticated equipment is required to determine control thresholds when measuring water status. Tools used here are porometer, measurement of stomatal conductance, leaf water potential, thermal sensing, and sap flow sensors (Ihuoma & Madramootoo, 2017; Jones, 2004). Not all of these methods are particularly useful for control and scheduling of highly frequent irrigation, but some have been used in scheduling irrigation. Plant-based irrigation scheduling methods have general drawbacks of not being able to quantify how much water should be applied after threshold values have been identified on when to irrigate. More so, this method requires sophisticated equipment and expertise which may not be available for commercial agriculture (Ihuoma & Madramootoo, 2017; Jones, 2004).

Sap flow

Sap flow technique is one of the plant-based approaches in monitoring water stress. Sap flow technique has explicitly been widely used in irrigation but, in vineyard (Eastham & Gray, 1998), greenhouses (Ehret, Lau, Bittman, Lin, & Shelford, 2001) apples and olives (Giorio & Giorio, 2003; Pereira, Green, & Nova, 2007) and (A. K. Singh, Madramootoo, & Smith, 2010) in corn. Sap flow is a measurement of the flux of water in the xylems of the plant through two main principles, by measuring either the velocity of a heat pulse transmitted from heat source or dissipation of heat energy in the xylem due to convection(R. G. Allen et al., 2011). The measurement of sap flow is particularly crucial in ecological, hydrological, and agronomic studies. Sap flow data has been used to answer the question about plant water use and storage (S. S. Burgess & Dawson, 2008), measurement of transpiration rates (Smith & Allen, 1996), and to evaluate the influence of alternating irrigation on root water uptake and tree water consumption (Fernández et al., 2006). The transpiration data can also be used to evaluate exact amounts of irrigation water applied were used by the plant and what was lost through evaporation on the soil surface.

However, as much as sap flow is mainly due to transpiration when stomata open, an experiment conducted by A. K. Singh (2010) in scheduling irrigation in corn using sap flow noted flaws and lags since sap flow depends on indirect estimates in a change of conductance, which is influenced by weather conditions. Hence changes in stomatal aperture may occur without influencing a change on sap flow (Ihuoma & Madramootoo, 2017; A. K. Singh et al., 2010). More so, (Kumagai, Aoki, Otsuki, & Utsumi, 2009) illustrated a lag in sap flow and transpiration due to sapwood storage.

In this experimental study, sap flow measurements were taken using SFM1 sap flow meters in sweet corn grown under in soil moisture sensor-based irrigation scheduling to draw a relationship between soil water status and sap flow. Besides, sap flow measurements were used to determine water loss from transpiration as subject to total water applied (Granier, 1987). Considering that both evaporation from ground and transpiration from the plant occur together, it is difficult to differentiate between them. Sap flow can be used as a stress estimate measure when the soil moisture is depleted, and also evaluate the influence of alternating irrigation on root water uptake and tree water consumption. Sap is the fluid in the roots, stems, and branches in the tracheary cells of the xylem tissues. Sap is a compound of water, nutrients, and hormones. Sap flow is measured in the sapwood part of the xylem and is synonymous with water movement and can be measured using two different methods that use heat as a tracer. These two methods are; 1) The heat balance method which relies on the mass flow rate of sap as a function of heat dissipation by ascending sap, and 2) the heat pulse method, which uses a heater and temperature sensor probes to calculate sap velocity as a function of time for sap flow to transport heat to a specific point (Gimenez, Gallardo, & Thompson, 2013).

2.3.Crop water productivity

Water productivity (WP) can be defined as the ratio of yield per unit area to irrigation water volumes applied or Evapotranspiration (ET_C) (Elías Fereres & García-Vila, 2019). Evapotranspiration (ET_C) is water loss from the soil by evaporation from the soil surface and transpiration by the plant through the leaf surface to the atmosphere. Approximately 20-30% of growing season ET_C for corn is lost through evaporation. Weather conditions heavily influence daily sweet corn water use with higher ET_C expected with higher air temperature, high wind speed, high solar radiation, low humidity.

Water use efficiency (WUE) on the other hand, particularly considers the water directly used by the plant, excluding other water losses such as evaporation on the surface and deep percolation. WUE is calculated as the ratio of yield produced by a plant to the amount of water lost through transpiration. That is dry matter production (kg/ha) divided by transpiration (mm) and is in units of kg/m^3 (Kirkham, 2005). While, the focus should be put on transpiration and not evaporation, which accounts for water lost on the soil surface rather than contributing directly towards crop yield.

Many studies have been carried out to increase water use efficiency by using soil moisture sensors in scheduling deficit irrigation (Dursun & Ozden, 2011; Thompson, Gallardo, Valdez, & Fernández, 2007). More so about Evapotranspiration-based irrigation methods, various in-depth research has also been carried out (Irmak et al., 2016; H. Jaafar et al., 2017). Water Use Efficiency (WUE) increases have been proven to under deficit irrigation as it eliminates irrigation, although it has a negative impact on yield. (Ertek & Kara, 2013).

In this study, we make a comparison of the two methods of scheduling irrigation (ET-based and soil moisture sensor-based to improve crop water productivity in sweet corn to reduce water use in agriculture.

CHAPTER 3

MATERIAL AND METHODS

The two experiments in this thesis were designed to study the effects of two different irrigation methods, namely; ET-based and soil moisture sensor-based irrigation methods. These methods had different treatments through which irrigation water was prescribed to sweet corn. The field experiment was conducted between June 2018 and September 2018. This chapter will explain the procedures carried out in this study.

3.1.Site description

The study site was located at the American University of Beirut’s Agricultural Research and Education Centre (AREC) in the Beqaa, Lebanon (33^{o}55’83” N, 36^{o}04’18” E; 990 masl). The field plot on which the experiment was carried out was flat and with no clear slope. Figure 1 shows the geographical location of the site.

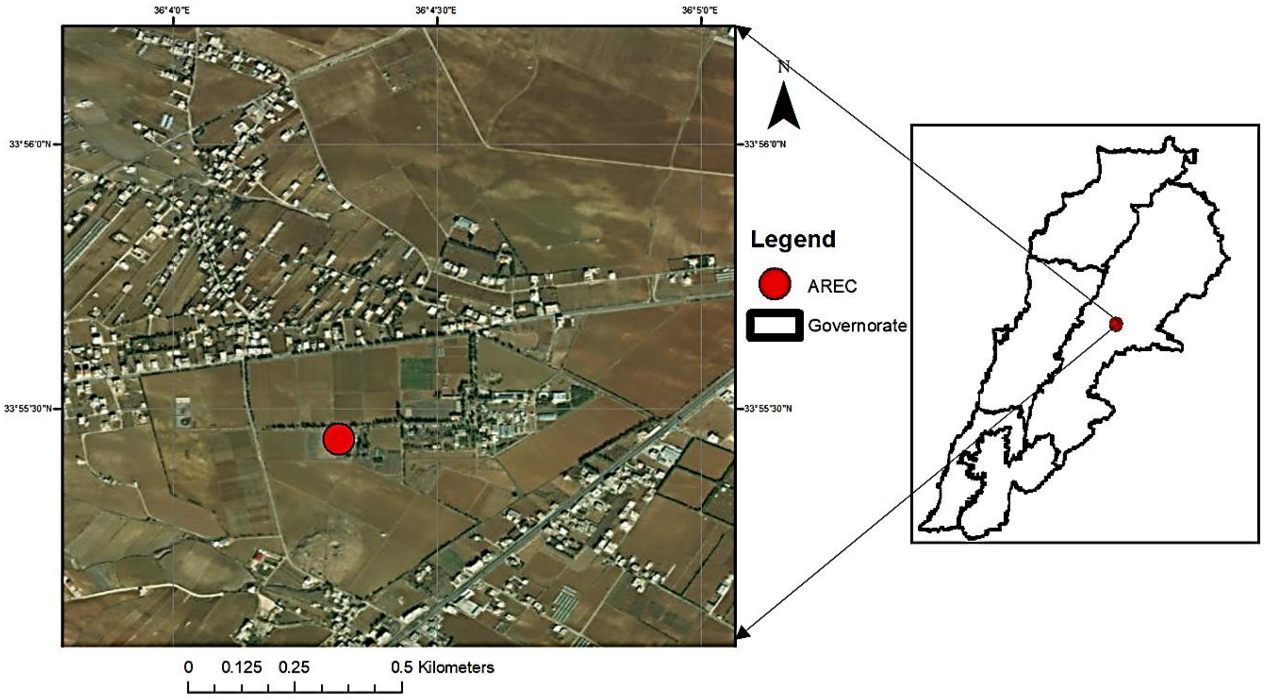


Figure 1. Location of the study area in Beqaa, Lebanon at AREC.

3.2.Climate

The experimental site was characterized by a semiarid climate with dry hot summers from May to September, and very cold winters throughout the rest of the year. The average rainfall is around 500 mm per year; with maximum precipitation of 140mm in January. Long term meteorological data showed no difference from this growing season (H. Jaafar et al., 2017). Daily actual crop evaporation (ET_C) was also calculated as a factor reference crop evaporation (ET_O) and crop coefficient (K_C). ET_O, which is an estimate from comprehensive weather data on-site, was calculated using the ref-ET software (R. Allen, 2009; Annandale, Jovanovic, Benade, & Allen, 2002). Below is a graph showing climate data and (ET_C) from the regional meteorological station at AREC

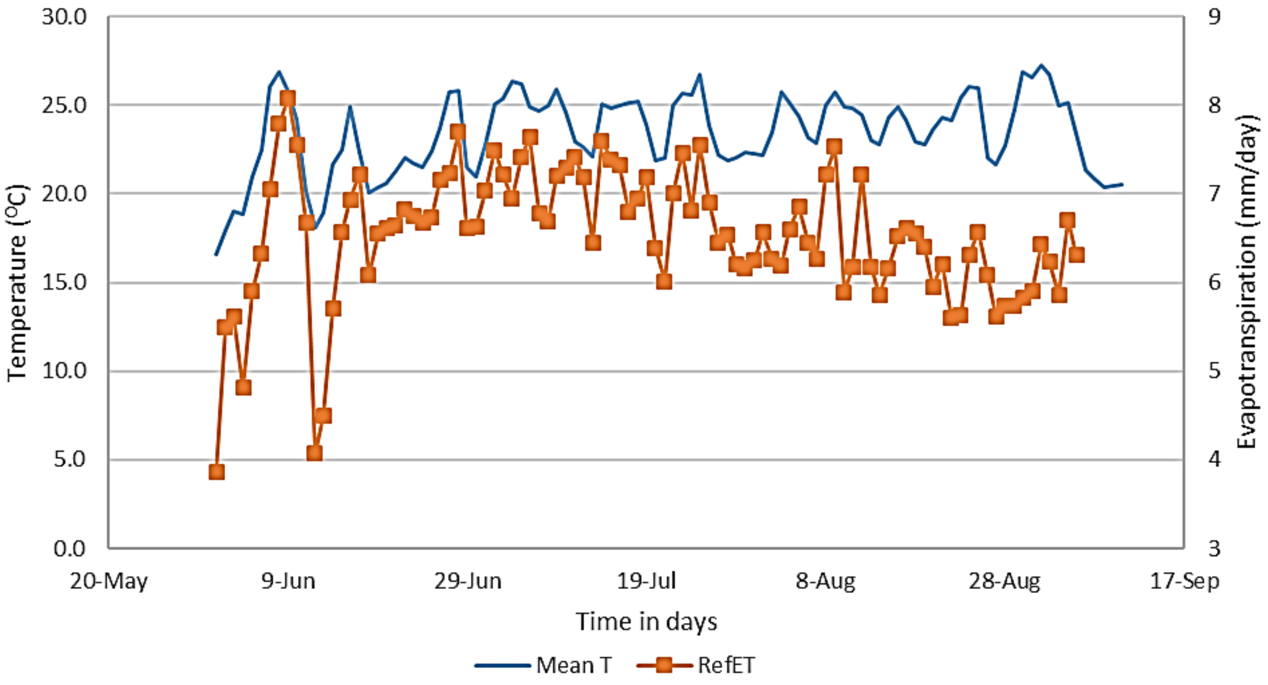


Figure 2. Temperatures, and ET_O during the crop growing period at the local meteorological station, AREC from June to September 2019.

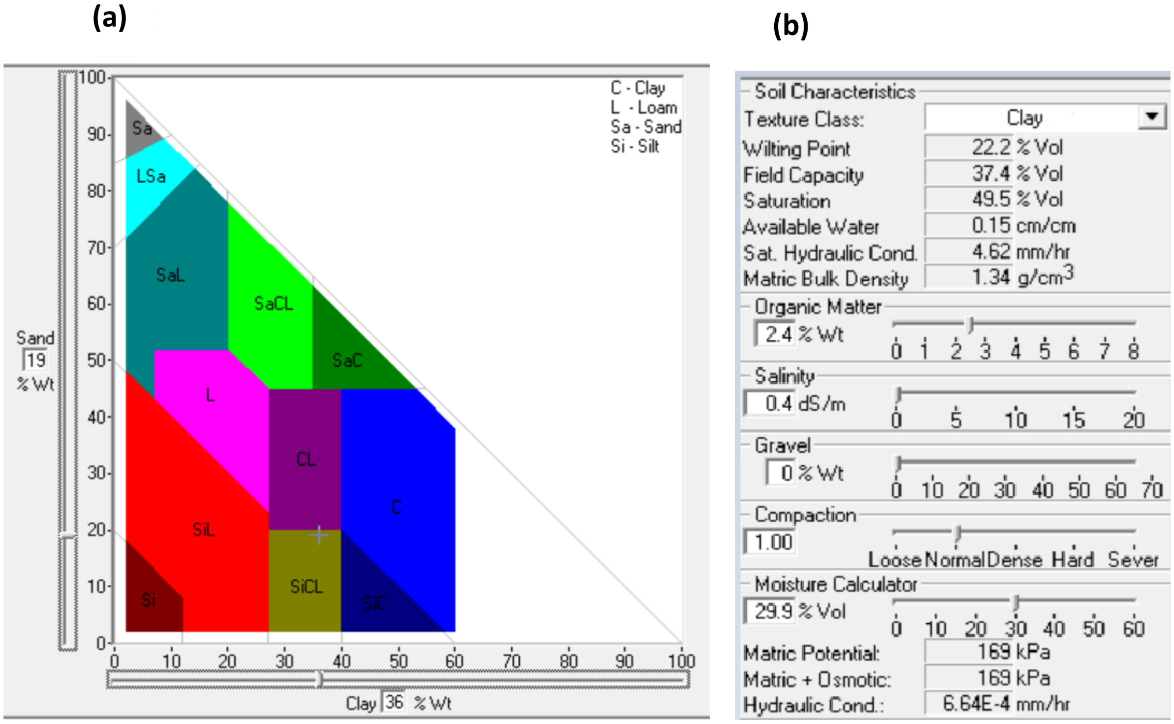
3.3.Soil analysis

A detailed soil analysis of physicochemical properties was carried out by (H. Jaafar et al., 2017) at AREC from the same plot where this research experiment was conducted.

3.3.1. Physical analysis

The soil type was shallow gravelly clay, with a percentage of sand at 19%, silt at 36% and clay at 45%. Estimated soil moisture properties were from the Soil-Plant-Air-Water (SPAW) model described by (Saxton & Rawls, 2006); wilting point was at 27.0%, field capacity at 40.4% and saturation at 49.7%. Figure 3 shows the processing of some of the soil physical characteristics to get hydrological values via SPAW hydrology software. The SPAW hydrology is a computer model that simulates hydrological properties in a one-dimensional water budget depth such as runoff, infiltration, evapotranspiration, soil water profiles, and percolation (Saxton & Willey, 2005). This model has been successfully used to estimate soil moisture properties (Shrestha & Shrestha, 2016), (Saxton & Rawls, 2006; Zwart & Bastiaanssen, 2004), (Ouyang, Feng, Read, Leininger, & Jenkins, 2016)

A bulk density test was determined in this experiment by using a cylinder method. In this method, the weight of the dry soil was divided by the total volume of soil and was established as 1.33g/cc which consistent with the SPAW model output of 1.31g/cc



Soil Characteristics
Texture Class: Clay
Wilting Point 22.2 % Vol
Field Capacity 37.4 % Vol
Saturation 49.5 % Vol
Available Water 0.15 cm/cm
Sat. Hydraulic Cond. 4.62 mm/hr
Matric Bulk Density 1.34 g/cm3

Organic Matter
2.4 % Wt

Salinity
0.4 dS/m

Gravel
0 % Wt

Compaction
1.00

Moisture Calculator
29.9 % Vol
Matric Potential: 169 kPa
Matric + Osmotic: 169 kPa
Hydraulic Cond.: 6.64E-4 mm/hr

Figure 3. SPAW hydrology inputs and output showing the Wilting point, field capacity, and levels in the sampled soil

3.3.2. Chemical analysis

According to (H. Jaafar et al., 2017), the soil samples had a pH of 7.89, electrical conductivity of 0.4 dS/m, $CaCO_3$ of 32.5% and an organic matter content of 2.48%. The available nutrient supply of phosphorus, Potassium, and Nitrogen were 19.9, 530, and 30 respectively in ppm.

3.4.Cultural practices

Sowing was carried out on June 6, 2018, with sweet corn seeds (Zea mays L. var. merkur) which were of a hybrid variety having a germination ratio of 90%. Row spacing was 75 cm and on-row spacing of 20.4 cm. Each plot had a size of 13.5 m^2 with four rows. Seeds were sown at a depth of 5-6 cm depth using a planter.

Nitrogen, Phosphorous, and Potassium (NPK) fertilizer of ration 15:15:15 was also consequently added to the rows at a rate of 250kg/ha. Nitrogen Phosphorus and potassium are primary fertilizers of paramount importance to sweet corn growth and productivity. Nitrogen was added to prevent deficiency which would cause stunted vegetative growth, pale lower leaves and adversely affecting the cob and grain sizes (Almodares, Jafarinia, & Hadi, 2009; Zhao, Reddy, Kakani, & Reddy, 2005). Phosphorus deficiency, on the other hand, causes stunted growth due to poor root development (De Grazia, Tittonell, Germinara, & Chiesa, 2003). And lastly, potassium deficiency whose symptoms are brown scorching and curling of leaf tips as well as chlorosis between leaf veins which would affect photosynthesis and hence poor yield.

To control weeds, periodic hand weeding, and 2,4-D herbicide was applied 40 days after planting (DAP) at concertation of 50 cm^3 in 12 liters of water (4.58 cc/liter of water) for the whole field.

All experimental plots were irrigated the same amount of water at the beginning for uniform plant establishment. After the emergence of the sweet corn seedlings, irrigation was performed according to the prescribed irrigation treatments.

Harvesting was carried out on September 4, 2018, 90 DAP. Aboveground biomass and root biomass were all evaluated. The dry weight of the aboveground biomass was calculated by drying the sweet corn in the oven at 75^0C until a constant weight was reached (conventionally after 48 hours). The moisture percentage in the different irrigation treatments was determined as a ratio of the difference between the fresh and dry aboveground biomasses to fresh aboveground biomass.

3.5.Irrigation system, treatments, and experimental design

Two experiments were carried out with two different methods of irrigation scheduling to the various subplots. These were the soil moisture sensor-based and evapotranspiration-based methods. Each of these two methods had three treatments, three replicates, making a total of 18 experimental plots of 6m by 2.25m dimensions and 1.5m apart to avoid interference. Figure 4 shows the layout and distribution of the experimental plots.

Water was sourced from a well, underlying marl limestone aquifer with total dissolved solids of 320 mg/l (H. Jaafar et al., 2017). Water was pumped into the irrigation pond from where it was further pumped into the irrigation reservoir located at the experimental site. Two pumps were used with the first one installed at the irrigation pond and controlled by an automatic floating valve installed inside the irrigation reservoir which always kept the reservoir full. Water from the irrigation reservoir was pumped to the experimental field by the second pump. This second pump was directly controlled by the irrigation controller and automatically operated upon each irrigation interval.

A drip irrigation system was installed on the experimental field. The main irrigation line was a 63 mm polyethylene pipe buried under-ground with irrigation laterals distributed throughout the system. A tapping was taken from one of the risers to feed the secondary network through a 32 mm pipe connecting to the six solenoid valves each corresponding to a different irrigation treatment (ET60%, ET90%, ET120%, SM 25%, SM 30%, and SM 35%).

Downstream the solenoid valves, each sub-main line of 32 mm diameter was connected to 3 manifolds leading to 3 replicate plots of that irrigation treatment. The manifolds were connected to 4 driplines of 16 mm diameter, which were distributed in the experimental plot. The drip lines were placed at a 0.75 m distance (SL), and inline emitters were spaced at a 0.4m distance (Se). Drip emitters had an average discharge rate of 3.7 lhr^{-1} at a pressure of 1 bar from the 20 sampled. Inter- emitter spacing was dependent on several factors such as discharge rate, crop cultivated, and soil hydraulic properties to enable an overlap of wetted fonts at the end of the irrigation time. Details about the irrigation network and layout of the experimental plots are presented in Figure 4

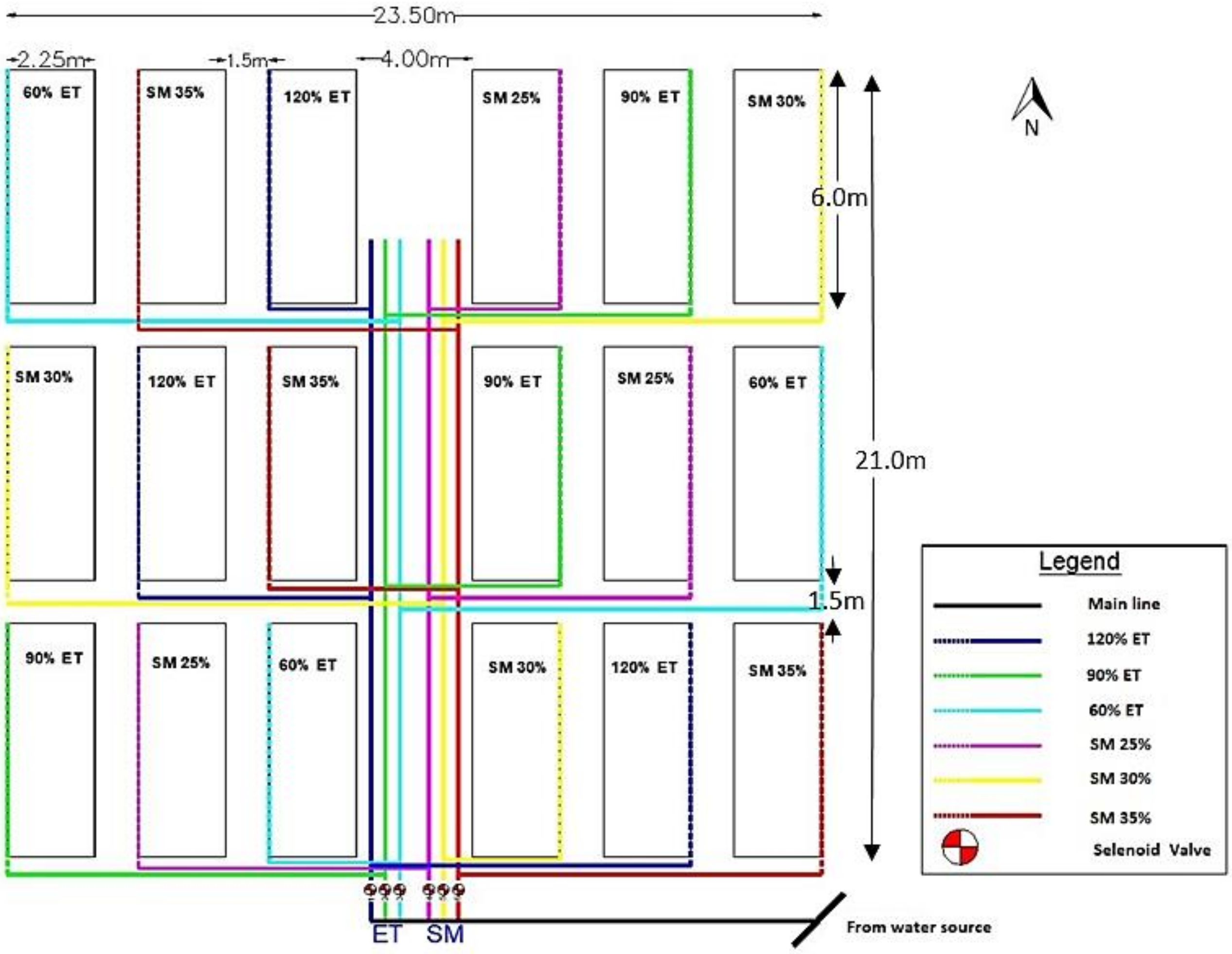


Figure 4. Irrigation system layout and experimental design.

3.5.1. The Evapotranspiration (ET)-based irrigation system

The irrigation system in this experiment was an ET-based irrigation water management system. This system consisted of three equal interval irrigation treatments (60%ET$_C$, 90%ET$_C$, and 120% ET$_C$) based on percentages of Grass-reference FAO Penman-Monteith (ET$_O$) that was calculated using the REF-ET software (R. Allen, 2009) using daily meteorological data from AREC weather station. ET_O is multiplied by the crop coefficients (KC) of sweet corn to get crop evapotranspiration (ET_C). In the Mediterranean region, KC is 0.3, 1.15 and 1.05 for Kc initial, Kc mid and Kc end respectively with initial taking 20 days and mid taking 50 days and end taking 20 days (Richard G Allen, Luis S Pereira, D Raes, & Martin Smith, 1998b)

The evapotranspiration-based irrigation system fully automated from the reservoir, with two pumps, the main network, weather station, one controller, weather station, flow sensor, three 32-mm solenoid valves (each corresponding to a different irrigation treatment) and flow meters.

3.5.1.1. Automated Irrigation Control System Components

The automated control system consisted of Weathermatic SL1600 controller, 3G card, SLW5 wireless weather station, and a flow sensor, as illustrated in Figure 5.

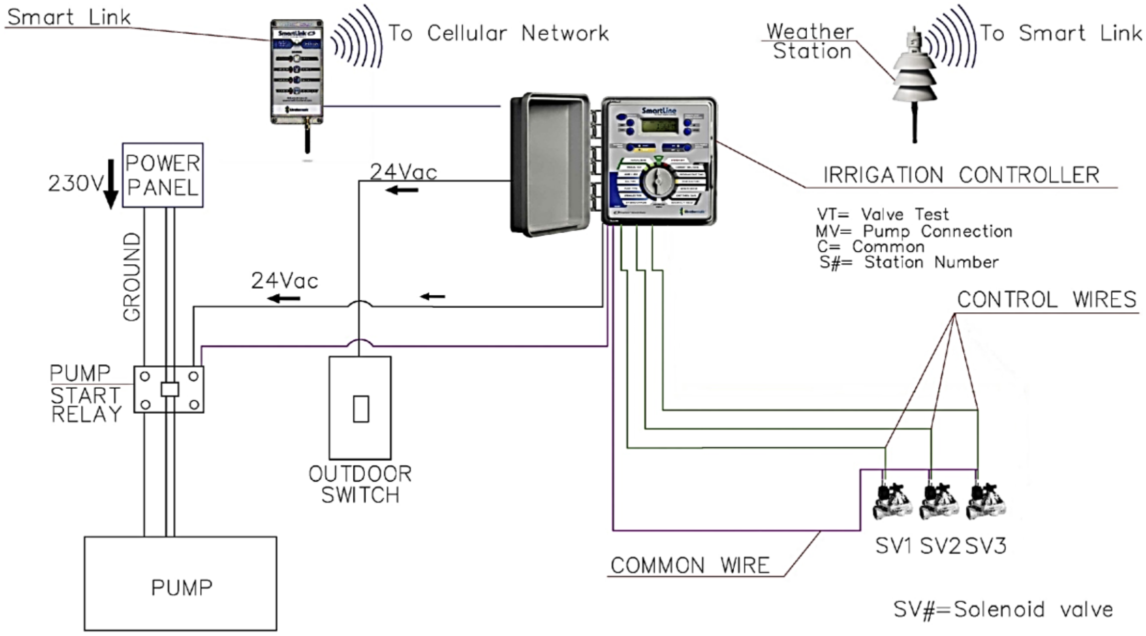


Figure 5. The wiring of the solenoid valves pump and relay connections to the irrigation controller (Jaafar et al., 2017)

3.5.1.2. Control system

The control of the ET irrigation system was facilitated by a Weathermatic SL1600 controller located at the irrigation head house near the experimental site. The controller was a 3-station base model and was commanding, using low-voltage wiring, to open and close the 24V AC solenoid valves.

Given the inputs in the controller, water was automatically pumped from the reservoir through the command of the three stations in the irrigation controller. Each irrigation treatment was controlled using a 32-mm diameter solenoid valve wired to the controller, with the controller automatically determining the run time. Total water flow for each treatment was measured with a flowmeter installed downstream of each solenoid valve. Irrigation was scheduled at an interval of two days. The weather station (Model SLW5, WeathermaticTM, Garland, Texas, USA) installed in the experimental field monitored daily high and low temperatures. With the controller, the user inputs latitudes to determine extraterrestrial solar radiation. It also had a rain sensor designed to interrupt scheduled irrigation events after a certain depth of rainfall. It was installed close to the experimental field and wireless connection to the controller (SL1600) to run as an ET-based irrigation system. Downstream, the controller was connected to three solenoid valves on the main line and was labeled as SV1, SV2, and SV3 corresponding to 3 irrigation treatments ET60%, ET90% and ET120% respectively

3.5.1.3. Irrigation treatments and scheduling

These treatments were 60%ET, 90%ET, and 120% ET as earlier stated and represented a percentage of ET_O . Irrigation was automatically scheduled every two days throughout the growing season.

3.5.1.4. Sample calculation for controller input

Emitter discharges – 3.7 Lph at a pressure of 1 bar

Spacing of dripper = 0.2 and 0.75m

Daily water use Td

$\mathrm{Td} = 0.1\ \mathrm{Ud}\sqrt{\mathrm{Pd}}$; (Keller & Bliesner, 1990)

Where Ud is irrigation requirement and Pd is the shaded area (80%)

$\mathrm{Ud} = \frac{\mathrm{ETc}}{\mathrm{efficiency}} = \frac{8.84}{0.8}$ = 10.425mm

The efficiency of the irrigation system was estimated at 80%,

Maximum $\mathrm{ET_C}$ during the growing season was for irrigation treatment ET 120% = 8.34 mm/day

And therefore, $\mathrm{Td} = 0.1 \times 10.425\sqrt{80} = 9.32$ mm

Depth $\mathrm{d} = \mathrm{Td} \times \mathrm{f1}$; where f1 is the interval of days between irrigation = 2 days

$\mathrm{d} = 9.23 \times 2 = 18.46$ mm

Gross volume of water per plant $\mathrm{G} = \mathrm{K}\frac{\mathrm{d}}{\mathrm{f}}$ SpSr (Keller & Bliesner, 1990)

Where Sp is spacing along rows = 0.2m, and Sr is spacing between rows = 0.75m

$\mathrm{G} = 1 \times \frac{18.46}{2}\ 0.75 \times 0.2 = 1.398$ Liters/plant/day

Application time during peak hours $\mathrm{Ta} = {}^{\mathrm{G}}/_{(\mathrm{NpQa})}$ (Keller & Bliesner, 1990)

where Np is the number of emitters per plant and Qa is the application rate

$\mathrm{Ta} = {}^{1.398}/_{(0.5 \times 3.75\,)}$ = 0.7456 hours/day = 45 minutes per day

At an irrigation interval of 2 days, the peak irrigation time was 1 hour and 30 minutes for irrigation treatment ET120%. Corresponding calculations were carried out for other irrigation treatments, ET90% and ET60%.

3.5.2. Soil moisture sensor-based irrigation treatment

The soil moisture sensor-based irrigation had three irrigation treatment; SM25%, SM30%, and SM35% which were thresholds of soil volumetric water content at which irrigation was scheduled. Campbell scientific moisture sensors CS655 were used in this experiment. The soil moisture sensors were installed after sweet corn emergence, initially in a vertical position on the soil surface until July 28, 2018, when they were reinstalled in a horizontal position at a depth of 25cm.

3.5.2.1.CS655 soil moisture sensor

CS655 are typical volumetric sensors and are designed to estimate soil volumetric water content (VWC) based on the dielectric constant of the soil (Munoz-Carpena, Ritter, & Bosch, 2004). The dielectric constant of water is higher than other soil constituents, such as air hence able to accurately determine soil water content.

CS655 soil moisture sensor is a smart sensor that uses innovative technology to monitor soil volumetric-water content, bulk electrical conductivity, and temperature. It measures soil electrical conductivity (EC), relative dielectric permittivity, volumetric water content, soil temperature (Halley, 2016). The CS655 has 12 cm length of stainless-steel rods which makes it easy to install in hard soil. CS655 soil moisture sensor outputs an SDI-12 signal that is measured by a data logger (CR850 datalogger, Campbell Scientific, Logan, UT) which is read through specific programs (Loggernet was used in this research experiment) installed on the computer. The CR850 datalogger uses an external power supply, and with low power consumption, it can operate for extended periods on a 12 V battery recharged with a solar panel.

CS655 soil moisture sensors are noted to be accurate and highly recommended in irrigation scheduling and have been used to give precise results (Chávez & Evett, 2012; Datta et al., 2018). CS655 soil moisture measurements are based on the calculation of dielectric permittivity of the media and finally applying the Topp equation (Topp et al. 1980) to estimate volumetric water content. Despite working well in a wide range of mineral soils as tested in a controlled environment by a manufacturer, the Topp equation underestimates water content of some organic, volcanic and fine-textured soil hence requiring field (Hignett & Evett, 2008)

Topp equation for calculating soil volumetric water content

$$\mathrm{Q_v}(\mathrm{K_a}) = \mathrm{C_0} + \mathrm{C_1}\mathrm{K_a} \times C_2\mathrm{K_a}^2 + \ldots + C_n\mathrm{K_a}^n \quad \text{(Campbell Scientific, 2017)}$$

Where: Q_v is the volumetric water content (% or m^3/m^3),

K_a is the bulk dielectric permittivity (unitless)of the soil and

C_n is the calibration coefficients; Linear equation was used in this experiment, representing only C_0 and C_1.

3.5.2.2.Calibration of the soil moisture sensors

To calibrate the soil moisture sensors, a series of procedures were carried out. This was to get the volumetric water content that aligned with a more accurately measured dielectric permittivity.

Foremost, the CS650 were inserted into the soil surface, and permittivity output was observed until it was constant before taking the recording. Soil core samples were then taken of that point. This process is repeated for other nine samples of varying soil moisture. Subsequently, the gravimetric water content of the soil sample was calculated, which is a ratio of soil moisture to the mass of dry soil. To determine soil moisture, oven drying of the soil was carried out for 24hrs at 105 ^{O}C. Bulk density was calculated, which is the mass of dry soil divided by its volume. And lastly, the volumetric water content was derived by getting the product of gravimetric water content and soil bulk density. Table 1 shows a summary of measured parameters which include the weight of the wet soil sample and dry weight sample, gravimetric water content, calculated gravimetric water content, and soil volumetric water content (SVWC) and recordings from the CS655 which were permittivity, and VWC. A graph in Figure 6 shows the equation that was derived from calibration.

Table 1. Values of the collected soil samples in the calibration of CS650 soil moisture sensors

Soil sample	Initial weight (g)	Permittivity (Unitless)	Sensor-VWC (%)	Oven dry weight (g)	Gravimetric water content (g/g)	Bulk density(g/cc)	Determined VWC (%)
1	396.0	23.33	0.38	302.1	0.31	1.19	0.37
2	362.2	19.7	0.34	289.3	0.25	1.14	0.29
3	366.4	13.06	0.27	306.8	0.19	1.21	0.24
4	364.0	4.93	0.08	330.0	0.10	1.30	0.13
5	392.0	20.79	0.41	298.0	0.32	1.18	0.37
6	384.0	4.71	0.07	352.0	0.09	1.39	0.13
7	440.6	25.56	0.49	318.9	0.38	1.26	0.48

Volume of can = 253.49 cc, average bulk density = 1.24g/cc

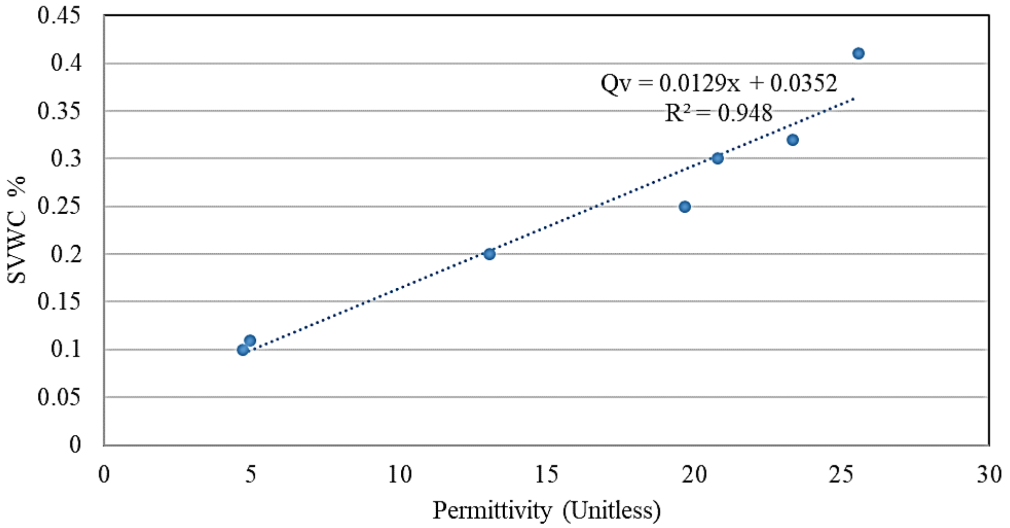


Figure 6. Calibration graph of calculated volumetric water content against permittivity.

3.5.2.3. Irrigation treatments and scheduling.

Irrigation scheduling in this experiment was carried out in 3 different soil moisture sensor-based irrigation treatments to evaluate the sweet corn morphometric responses. The three-soil moisture sensor-based irrigation treatments were SM25%, SM30%, and SM35% and represented thresholds of soil volumetric water content at which irrigation was carried out. Irrigation being carried out at these thresholds SM25%, SM30% and SM35% meant that 0. 3cm/cm, 0.8cm/cm, and 0.13cm/cm available water respectively out of the full potential available water of 0.15cm/cm was maintained in each of those treatments.

These treatments were replicated three times to make a total of 9 randomized subplots. In each subplot, a soil moisture sensor (CS655) was installed in the center. Soil moisture readings from the three replicates were averaged to schedule an irrigation event for a given treatment as recommended by (Jones, 2004) as soil moisture was variable in the different plots of the same treatment (Dabach, Shani, & Lazarovitch, 2015)

In the initial stages of the field experiment, after sweet corn emergence until 50 DAP, soil moisture sensors were placed vertically on the soil surface. Since the soil moisture sensor rods were 12cm, it was only soil moisture data from the top 12cm from the soil surface that was being recorded. The justification for this was because sweet corn roots at this primary stage did not go beyond that depth. Irrigation scheduling at this stage and soil depth was conducted when VWC reached thresholds of 15%, 20% and 25%. The soil moisture sensors were later horizontally installed at a depth of 25cm to be more representative and cover most of the sweet roots which are in the top 30cm from the soil surface (Wiesler & Horst, 1994). Irrigation treatments at this stage were SM25%, SM30%, and SM35% until the end of the experiment. Since soil moisture generally increases down the soil profile (Lal, 1974), it was assumed that sweet roots below 25cm depth still has access to irrigation water.

Accuracy of the soil moisture sensors to provide more soil moisture measurement is enhanced through horizontal installation in the soil profile to detect wetting fronts (Campbell Scientific, 2017). A CS655 soil moisture sensors were carefully installed in each of the experimental plots ensuring good sensor-soil contact and minimized air voids that would lower the accuracy in data recorded. Soil moisture data were collected continuously in 1-minute increments to a data logger. The valves were manually opened to start an irrigation event based on the thresholds in each treatment and closed when SVWC reached saturation.

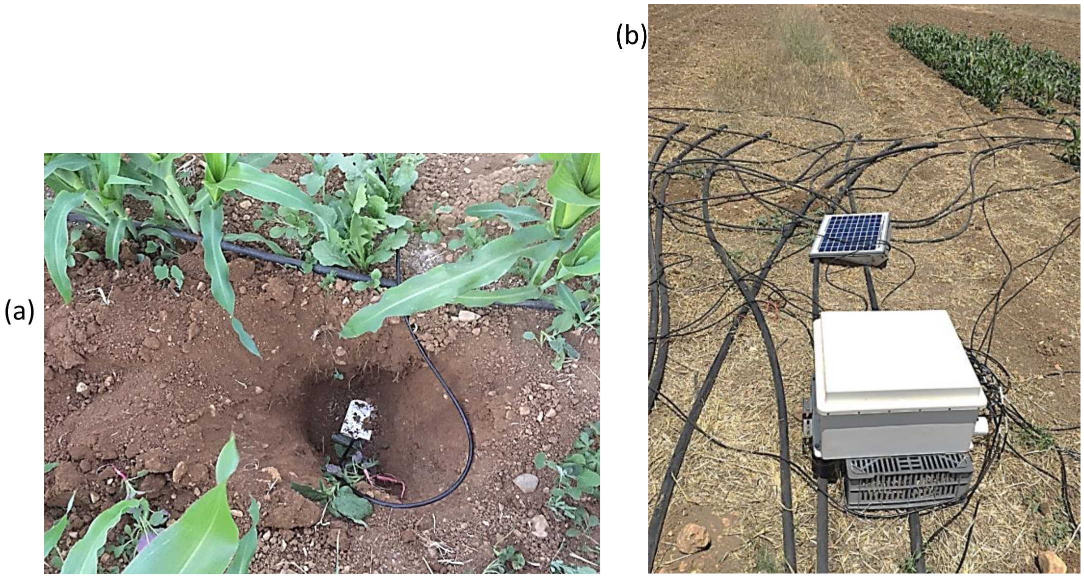


Figure 7. (a) Horizontal installation of CS655 in the soil and (b) box containing the data logger connected to a solar panel.

3.6.Sap flow

In this research, sap flow was measured in selected sweet corn to observe the sap flow rate and its relationship with evapotranspiration under different water regimes and evaluating it as a possible irrigation scheduling method.

In this study, we used Sap Flow Meter (SFM1) supplied by ICT international (S. Burgess & Downey, 2014). The SFM1 Sap Flow Meter is a standalone instrument, custom-designed to precisely measure Sap Velocity and Sap Flow of plants using the Heat-Ratio Method (HRM). SFM1 Sap Flow Meters were installed on stems of random sweet corn in soil moisture-based irrigation treatments; that is SM25% SM30% SM35%. Sap flow readings were taken every 10 minutes from August 28 to September 4 of 2018.

3.6.1. Sap flow design

The sap flow meter (SFM1) consists of a set of three measurement probes and an integrated, standalone data logger with software for instrument configuration and data downloading. The three surgical grade stainless steel probes that are corrosion-resistant, with high-strength. The probes are 35mm of lengths. Two of the three probes are colored blue for measurement and the other one red for heating. Of the two blue probes, one is labeled downstream for top and the other upstream for bottom during installation. They are designed with two thermistors located 7.5 mm and 22.5 mm from the tip. The heater probe (red) has high resistance filament that produced a high and efficient amount of heat. Heaters are designed to be powered by 12 Volts for a period of ~2-8 seconds.

3.6.2. Heat Ratio Method (HRM)

Heat Ratio Method uses a short pulse of heat as a tracer to measure sap velocity and volumetric water flow in xylem tissues of the plant. Using the two temperature sensor probes and the heat probe, this method calculates the magnitude and direction of water flux by measuring the ratio of heat transported between two symmetrically spaced temperature sensors. The heat pulse velocity was calculated by Marshall 1958

$$\mathrm{Vh} = \frac{\mathrm{k}}{\mathrm{x}} \; \mathrm{In} \; \left(\frac{\mathrm{v1}}{\mathrm{v2}}\right) 3600$$

Whereby:

Vh is heat pulse velocity (cm/hr),

k is thermal diffusivity of fresh plant tissue = 2.5 x10^{-3}cm^{2} S^{-1}, x is distance (cm) between the heater and either temperature probe = 0.6cm, and

v1 and v2 are the increase in temperature (from initial temperatures) at equidistant points downstream and upstream, respectively, x cm from the heater.

3.6.3. ***Power source***

Though the SFM1 sap flow has an internal battery to ensure continuous supply, it requires an external power option when being operated in the field. The internal battery is a 4.2 V lithium battery and needs to be trickle charged by the external power supply to maintain its full charge. In this experiment, a 20W solar panel was directly connected via the non-polarized two-wire power-bus, using the unique power bus-plugs on either side of the instrument. It has a current consumption of 25mA but can rise to 670mA during a measurement cycle.

3.6.4. ***Measurement cycle and processing of sap flow***.

Measurement cycle input was set at a 10 minutes time interval. Each thermistor took an 80 second average of the initial sapwood temperatures by firing a heat pulse through the heat probe. The thermistors then measured the increases in sapwood temperature. These temperatures were compared and then averaged between the two measurement probes. The difference in temperature for thermistors down and upstream from the heater were summed to obtain an average ratio of downstream temperature increase to upstream temperature increase. This was done between 60 and 100 seconds. Mathematical calculations were then internally processed and performed on the upstream and downstream ratios according to the Marshal equation to derive the heat pulse velocity.

Measurements were then recorded on the Micro SD inside the sap flow meter as needle temperatures (^oC), raw heat pulse velocity (cm/hr), corrected sap velocity cm/hr or sap flow (cm^3/hr or kg/hr).

In the measurements control, either probe temperature mode or sap flow mode can be selected. Whereas the former is highly recommended for detailed scientific research, the later which uses the default value of thermal diffusivity to calculate heat pulse velocity is more commonly used. Therefore, sap flow mode was used in this experiment.

3.6.5. Installation, data collection and uninstallation procedure in the field

The circumference of the sweet corn stem was measured and was in a range of 6cm to 6.5cm and with a stem diameter of 2cm for the three sweet corn plants that were selected. Three parallel holes were drilled through the clear part of the stem on the third internode between the second and third nodes from the ground. This was made by carefully pushing a needle by hand through the stem as it was not very hard to require a drilling machine. The three holes were equally spaced at 0.5 cm apart. The SFMI was well positioned near the measurement needles to avoid strain on cables. The needles were then inserted in the drill holes on the stem. This was done starting with the upstream (bottom) needle, then heater and finally the downstream (top) needle. Since the needles were extending beyond the stem, they were insulated with foam to avoid direct sunlight which may conduct heat back along the stainless-steel needles, creating an error in temperature and measurement of heat pulse. Data were collected from August 28, 2018, until September 4, 2018, and stored on a micro SD card inside the SFM1. Data which was later downloaded through a USB cable connected between a computer equipped with ICT software and the SFM1. Data downloaded was in Comma Separated Values (*.CSV) file format. To uninstall that SFM1, the needles were carefully pulled out of the stem. In Figure 8, an illustration of how sap flow is measured based on the Heat Ratio equation and the SFM1 installation on a sweet corn plant.

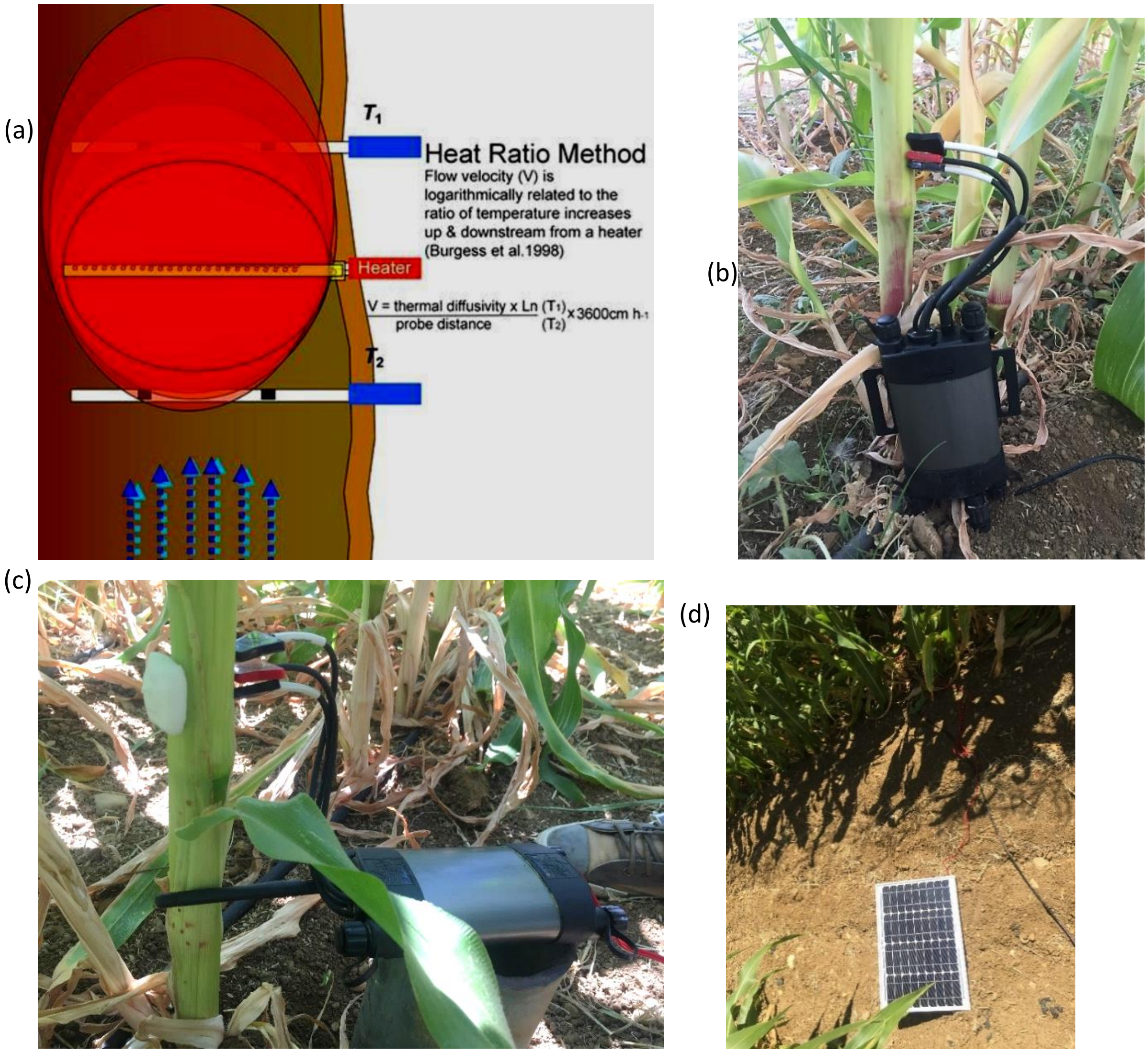


Figure 8. (a) The heat ratio method (S. Burgess & Downey, 2014). (b) and (c) The field installation set up of the sap flow meter on a sweet corn stem (d) Solar panel powering the sap flow sensors.

CHAPTER 4

RESULTS AND DISCUSSION

This research focuses on the effect of the different irrigation treatments based on ET and soil moisture sensor-based scheduling techniques. The effects of these on sweet corn growth, yield, water productivity, and sap flows were investigated. All data were analyzed using analysis of variance (ANOVA) using SPSS statistical package. According to the method by (Steel & Torrie, 1980), the significant difference between group means was calculated using Least Significant Difference (LSD) at $P < 0.05$. The response of the sweet corn to the applied water in each irrigation treatments was investigated by measurement of morphometric parameters which included; shoot height, aboveground biomass, and grain yield in addition to sap flow in conductive organs (xylem). Calculated parameters of harvest index, water productivity, sap flow, and water productivity were also analyzed. The growing period that started on June 6, 2018, through the different growth stages, as shown in Figure 9, was concluded with harvesting on September 4, 2018, and results were as follows.

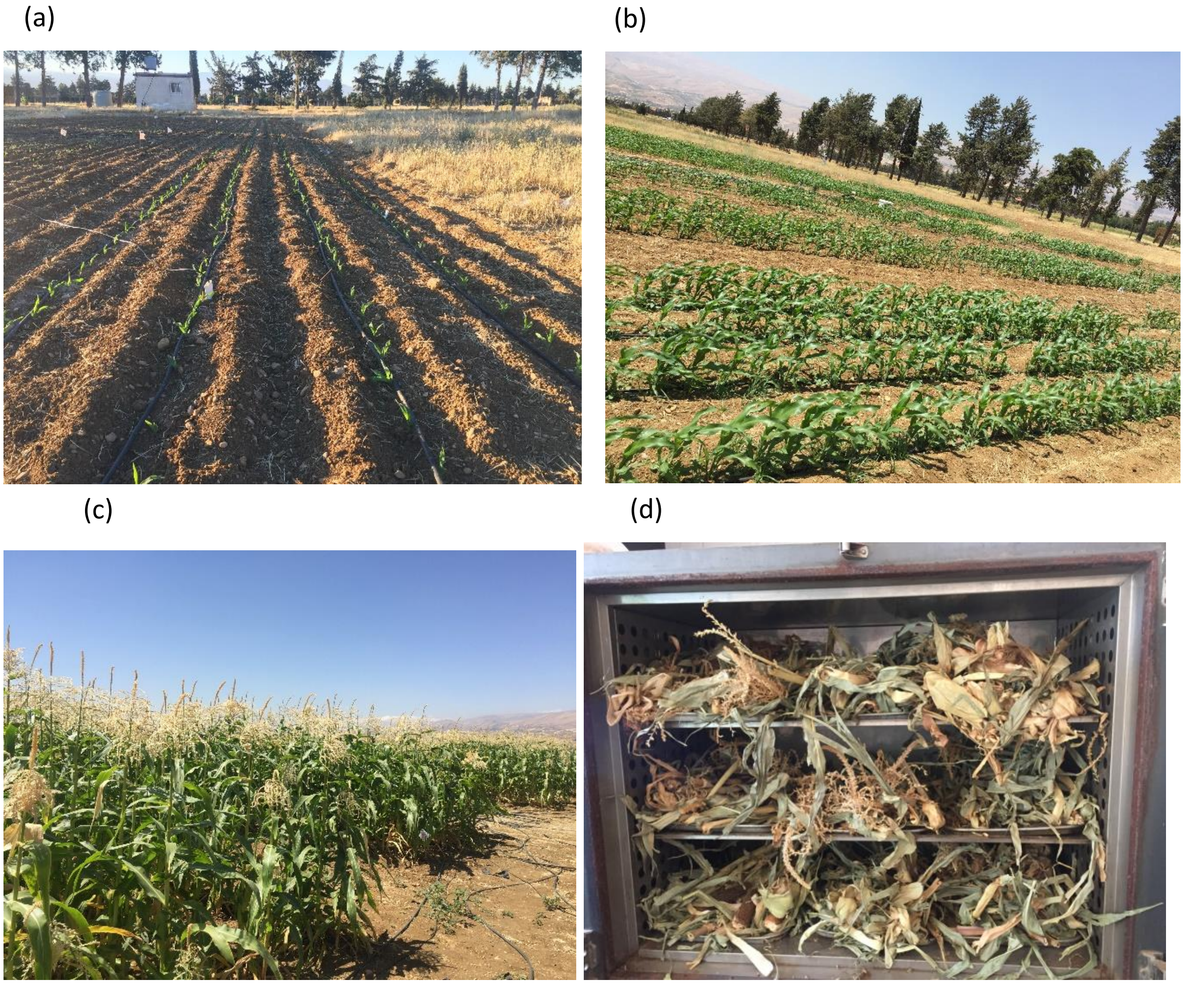
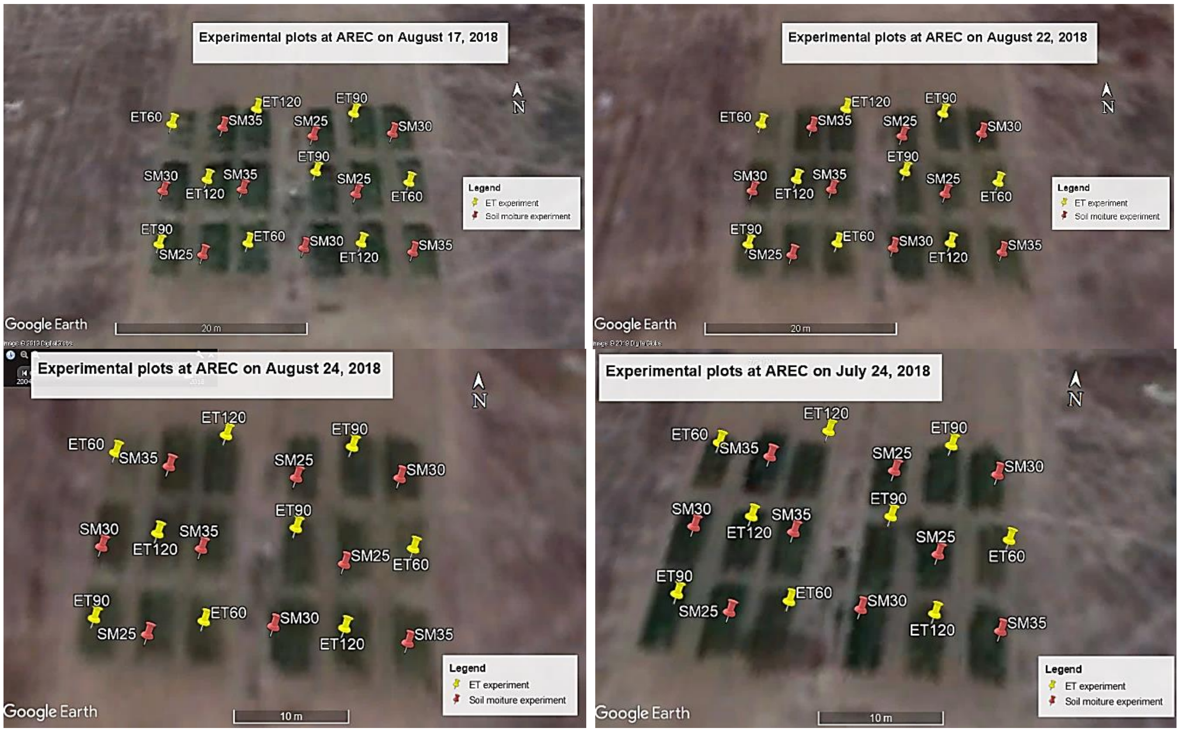


Figure 9. (a) Sweet corn 11 DAP (b) sweet corn 30 DAP (c) sweet corn 80 DAP (d) aboveground biomass of sweet corn being oven dried.

4.1.Visual analysis of satellite imagery

From Figure 10, the effect of the different irrigation treatments can be visualized from the satellite image obtained from google earth during the growing season, showing the field experiment layout and visual analysis of the different irrigation treatments on sweet corn in the experimental plots. The plots with the highest water deficit were the most severely affected with wilting and exhibit a lighter tone of green. This is more elaborate in the ET60%. Conversely, the plots that show a deeper green color are least affected by the irrigation treatments applied to them. This is illustrated more clearly in irrigation treatment ET120%, and SM30%.


Experimental plots at AREC on August 17, 2018

Experimental plots at AREC on August 22, 2018

Experimental plots at AREC on August 24, 2018

Experimental plots at AREC on July 24, 2018

Figure 10. Satellite imagery of the treatments taken on different dates during the growing season.

4.2.ET-based irrigation experiment results

4.2.1. Irrigation treatments and soil moisture analysis

The first irrigation was carried out on June 6, 2018, and the last on September 4, 2018. Irrigation intervals on all treatments were 2 days except on day 81 DAP where it was 3 days. Irrigation time varied according to ET_O which is a factor of crop growth stage, and prevailing meteorological phenomena. The cumulative irrigation water applied in the three

ET treatments was as follows: 566 mm, 770 mm and 971mm for ET60%, ET90%, and ET120% respectively.

Soil water in the 0-25 cm depth was continuously measured throughout the crop growing season in almost every plot using soil moisture sensors (CS655). Of the 3 replicates in each treatment, a soil moisture sensor was installed in 2 except in irrigation treatment ET60% where 3 probes were installed. Soil moisture data were collected continuously in 1-minute increments to a data logger. Average sensor data from the subplots representing the same treatment were considered as the soil moisture content in the entire treatment and is shown in Figure 11**.**

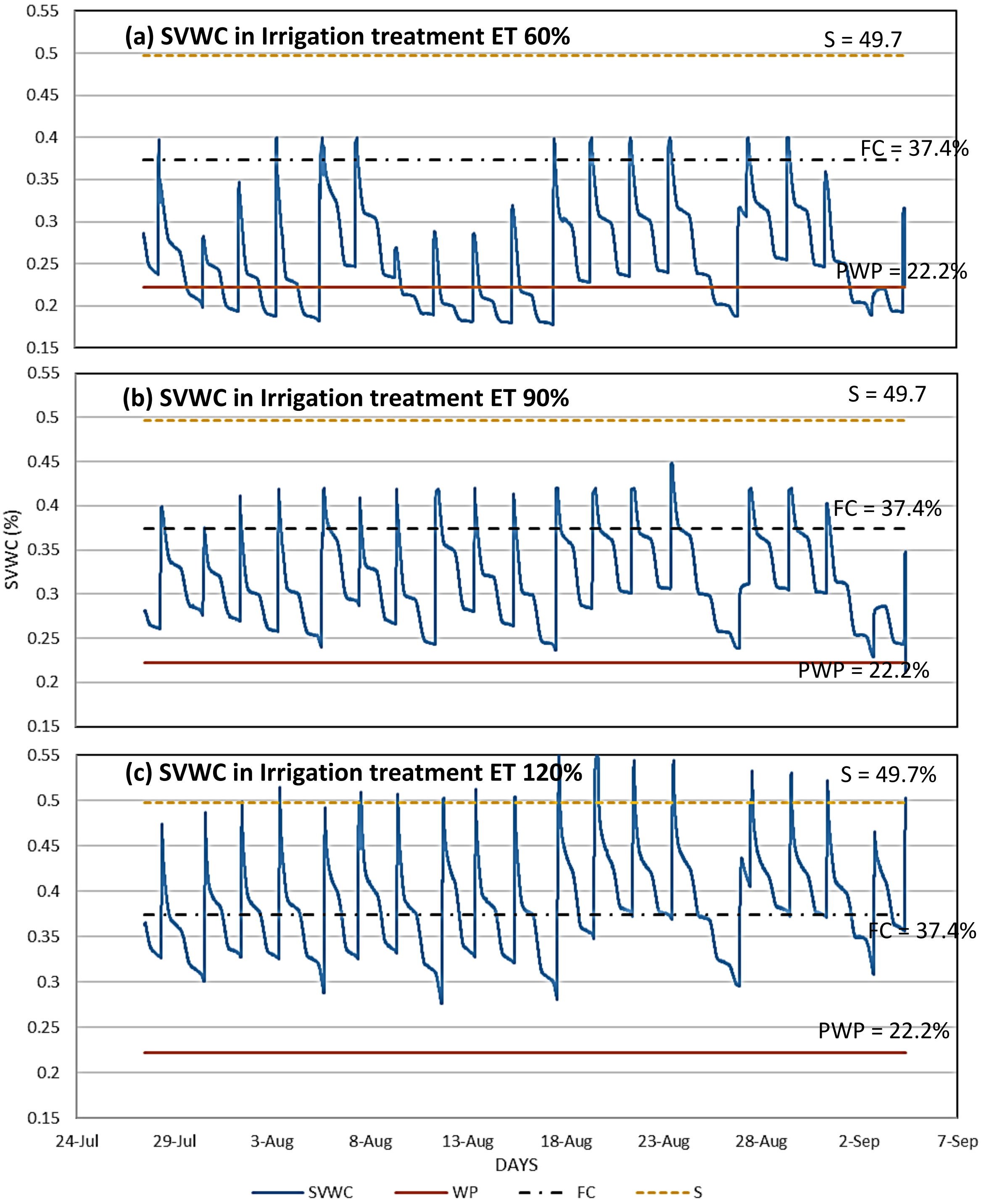


Figure 11. Soil Volumetric Water Content in Evapotranspiration-based irrigation treatments where S is saturation point, FC is field capacity, and PWP is permanent wilting point.

In irrigation treatment ET60%, applied irrigation water did not recurrently reach field capacity (FC) and was depleted to levels close to permanent wilting point (PWP) before the next irrigation event. Ultimately, this induced wilting and severe water deficits for the sweet corn in this irrigation treatment which would surely translate in negative effects on maize yield (Patel, Patel, & Patel, 2006) and other qualitative parameters (A. Singh, Roy, & Kaur, 2007). Lifesaving irrigation was carried at different times to rejuvenate the corn under these deficit conditions which is the reason for the inconsistency in the pattern of Soil Volumetric Water Content (SVWC). Average soil moisture percent in irrigation treatment ET 60% was 25% which is close to below PWP. Whereas in this experiment, wilting point was reached at based on soil readings during the growth period, the plant was able to recover. This is because permanent wilting point is not only soil specific but also influenced by the climate and the crop type (Tolk, 2003) and also the fact that soil moisture that drains after an irrigation event is not completely lost and can be accessed by the sweet corn roots.

In irrigation treatment ET90%, irrigation was carried out at slightly above wilting point at averagely 25% SVWC. This is because this irrigation treatment providing 10% less than the plant water needs as verified by soil moisture reading. Average Soil Volumetric Water Content (SVWC) in irrigation treatment ET 90% was at approximately 32%. Additionally, considering that most of the irrigation took place at around 27% to 30% VWC, it represents a MAD of 70%. Applied irrigation water was approaching slightly above field capacity (FC) at approximately 42% of the SVWC, which is way below saturation; hence no water losses through runoff or deep percolation below the root zone.

Soil moisture analysis in irrigation treatment ET120% indicated that upon an irrigation event, the SVWC often went above saturation point, certain to lead to irrigation water loss through deep drainage. Irrigation was mostly carried out at averagely 32% until on 18 August 2018 where it was 35% of SVWC. This represents approximately 23% MAD which may potentially create a poor balance of air and water in the soil, hence limiting yield.

4.2.2. Effect of treatments on crop growth.

This analysis focuses on a comparison of three treatments based on soil moisture sensor-based irrigation scheduling on sweet corn shoot height and cob length as shown in Table 2.

Table 2. Effects of irrigation on the morphometric characteristics (shoot height and ear length) of field-grown sweet corn at harvest. Within the same columns, means with the same letter are insignificantly different at $P<0.05$ ($n = 30$ from 3 replicates)

Irrigation treatment	Shoot height (cm)	Ear length (cm)
ET60%	151.67a	17.20a
ET90%	195.20b	20.97b
ET120%	203.17c	21.37b

4.2.2.1. Shoot height

The shoot height (SH) response towards irrigation treatment was measured on the day of harvest, 90 days after planting (DAP). Treatment ET60% had the lowest mean shoot height of 151.67cm and standard deviation 12.02. ET90% had mean SH of 195cm and with the lowest standard deviation of 7.388. Treatment ET120% had the highest mean height of 203.17 cm and a standard deviation of 12.78.

A comparison of these means values of SH using the student pair-wise LSD showed that there was a significant difference among all treatments towards irrigation. ($F= 52.36$, $P= 0.05$, $n = 30$). Only irrigation treatment ET60% was significantly different ($p < 0.001$) from the two other treatments, ET90%, and ET120%. The mean shoot height in ET120% was 43.5 cm or 21% higher than that in irrigation treatment ET60% and 3% higher than treatment ET90%. Figure 12 the collected shoot height data in the form of range and median values of sweet corn in the three irrigation treatments. The figure further details the levels of significant difference in shoot height whereby different letters, (a, b, c) in irrigation treatment SM25% and SM30% and SM35% represents a significant difference at $P<0.05$.

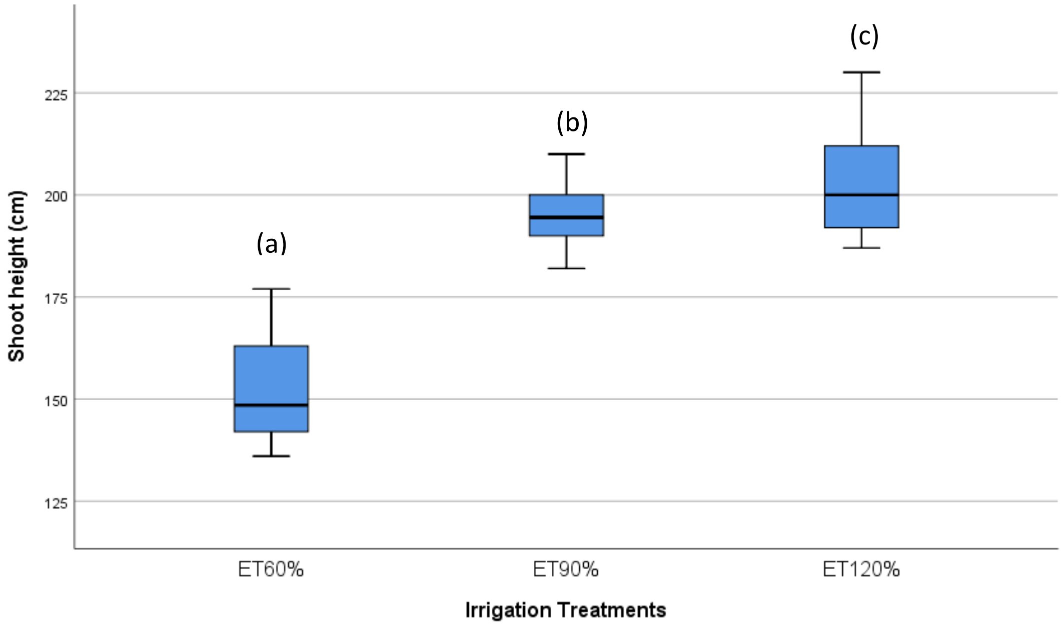


Figure 12 The range and median of collected data on Shoot Height (SH) of sweet corn in the ET-based irrigation treatments. The same letter represents an insignificant difference at P<0.05

4.2.2.2.Ear length

Irrigation treatment ET120% recorded the highest mean for ear length of 21.3 cm and was insignificantly different from the sweet corn ear length in irrigation treatments ET90% with a mere 2% difference. Sweet corn in treatment ET60% had the least mean ear length of 17.2cm and significant different from that in other treatments. (F= 15.57, P < 0.05)

4.2.3. Biomass response to irrigation treatments.

Morphometric characteristics in terms of aboveground fresh (FY) and dry weight (DY), roots biomass, ear yield, and grain yield were evaluated after harvest, as shown in the summary Table 3.

Table 3. Effects of irrigation in the morphometric characteristics of field-grown sweet corn at harvest. Within the same columns, means with the different letter are significantly different at P<0.05 from three replicates (n = 120 except for root biomass where n =12)

Irrigation treatment	Above ground (t/ha)		Root biomass (t/ha)	Ear yield (t/ha)		Grain Yield (t/ha)
	Fresh weight	Dry weight		Fresh weight	Dry weight	
ET60%	26.54a	8.66a	7.17a	11.92a	5.53a	2.54a
ET90%	39.87b	12.03b	13.00b	21.81b	6.53b	4.95b
ET120%	48.75c	14.17c	15.39b	26.42c	7.41c	6.41c

4.2.3.1. Aboveground fresh and dry biomass response to irrigation treatment

The highest aboveground fresh weight was recorded in irrigation treatment ET120% at 48.75 t/ha and then in ET90% and the least was in ET60% which was almost half of that in ET120% at 26.54 t/ha. Previous studies have found similar effects of deficit irrigation on aboveground biomass (Ertek & Kara, 2013; Kresović et al., 2016). The mean aboveground fresh biomass was significantly different in all the irrigation treatments (F= 1.769, P<0.001). However, at P<0.0001 fresh aboveground biomass in treatments ET120% and ET90% showed no significant difference in their mean aboveground, although there is an

18% difference. An almost linear response to irrigation was noted in aboveground fresh and dry biomasses as shown in Figure 13. It further shows a graphical analysis, giving the range and median values of the collected data on fresh weight of ears of sweet corn in the three irrigation treatments.

After oven drying, the means of aboveground dry biomass followed similar trends as their fresh weight in with significant differences among in all irrigation treatments. The highest mean dry weight aboveground biomass was in treatment ET120% and was 39.3% and 24.1% higher than in treatment ET60% and ET90% respectively.

The highest mean moisture percentage was in irrigation treatment ET120% at of 70.9% although it was not significantly different from other treatments (F= 1.714, P< 0.001), ET90% at 69.8% and ET60% at 69.8%. This shows a predictable linear relationship between moisture percentage and irrigation water applied.

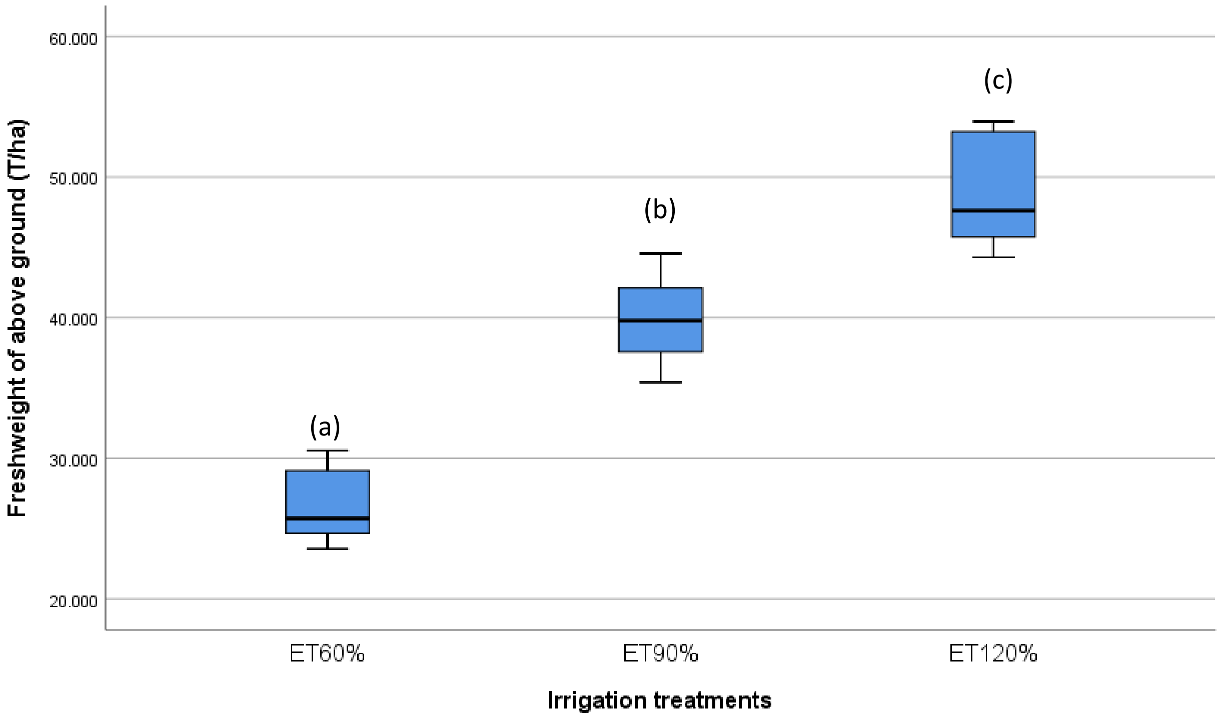


Figure 13. The range and median of collected data on fresh weight aboveground of sweet corn in the ET-based irrigation treatments. The different letters represent significant difference at $P<0.05$.

4.2.3.2.Root biomass

Root biomass was measured by uprooting the sweet corn using a shovel, and the roots were washed of soil under running water before taking their weights. Albeit the mean root biomass in treatment ET120 was highest, it was not significantly different from that in ET90%, that is 13 t/ha vs 15.39 t/ha. Root biomass in irrigation treatment ET60% recorded the least value at 7.17 t/ha and significantly different from the other treatments ($F = 1.714$, $P<0.001$).

4.2.3.3. The fresh and dry weight of ears/cobs.

Fresh weight of ears was measured right after harvesting the sweet corn from the irrigation plots. The fresh weight of ears in ET60% was the least at 11.92 t/ha with only 66% marketable. This fresh ear yield in ET60% is less than half the weight of what was harvested in ET120% that recorded the highest, representing 26.42 t/ha. There was a significant difference in the mean weights of the fresh weight of ears in all the irrigation treatments ($P<0.001$). Previous studies have produced the same results showing a negative effect on yield with increased water stress/ deficit irrigation (Ertek & Kara, 2013; Kresović, Gajić, Tapanarova, & Dugalić, 2018; Vial, Lefroy, & Fukai, 2015). Figure 14 shows the range and median values of the collected data on fresh weight of ears of sweet corn in the three ET-based irrigation treatments. A linear relationship can be observed between fresh weight of ears and ET, gradually decreasing between treatment ET90% and ET120%.

Measurements of the dry weight of ears were taken after drying the fresh ears in the oven for 2 days at 75^{O}C. The recorded dry weight of ears had a similar trend as that of its fresh weight. Sweet corn in irrigation treatment ET120% had the highest mean dry weight of ears at 7.14 t/ha, and then ET90% with 6.53 t/ha and the least in treatment ET60% with 5.53 t/ha. All irrigation treatments showed a significant difference in mean dry weight of ears at ($P<0.05$, F= 13.68).

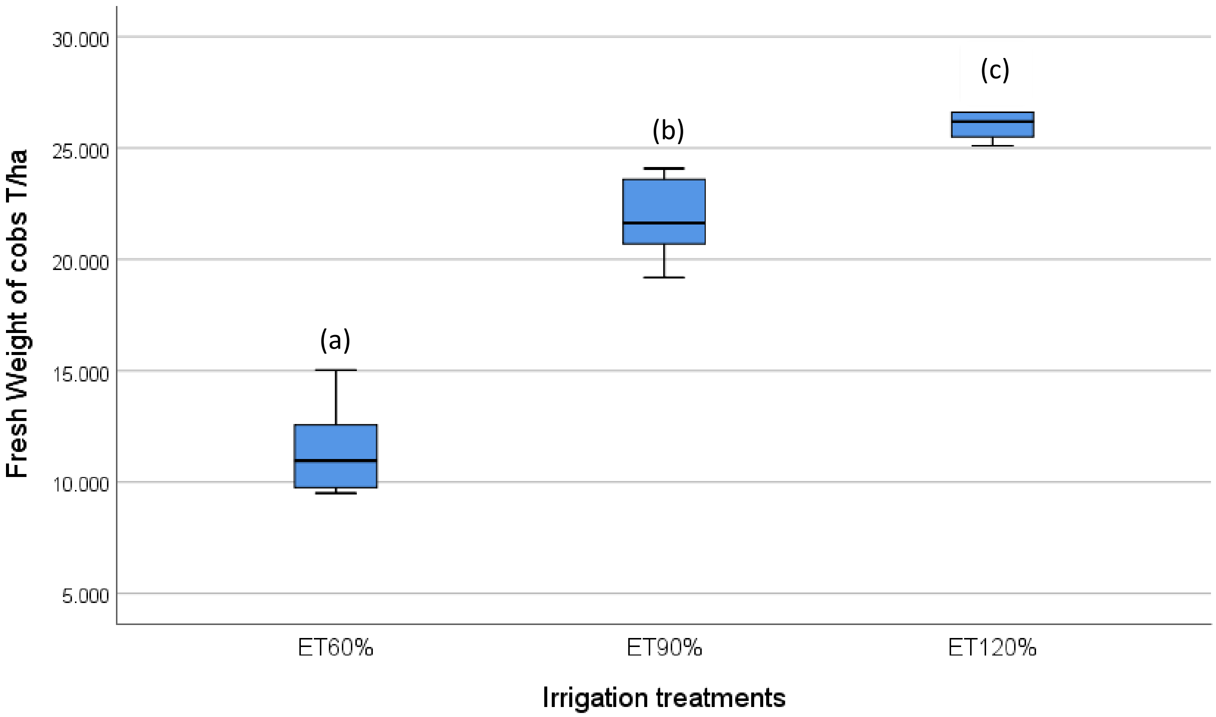


Figure 14. The range and median of collected data on ears fresh weight of sweet corn against treatments ET60%, ET90%, and ET120%. The same letter represents an insignificant difference at $P<0.05$.

4.2.3.4. Grain yield and grains to ear ratio

Kernels/grain yield of the sweet corn was measured after drying the ears in the oven. Subsequently, the grains were removed from the cob and weighed. The highest grain yield was realized in irrigation treatment ET120% and was more than twice that in ET60%, as shown in table 7. Grain yield increased linearly with seasonal crop evapotranspiration and irrigation amount, as shown in Figure 15. The mean grain yield from the different irrigation treatments was significantly different. ($P<0.001$, $F= 82.04$).

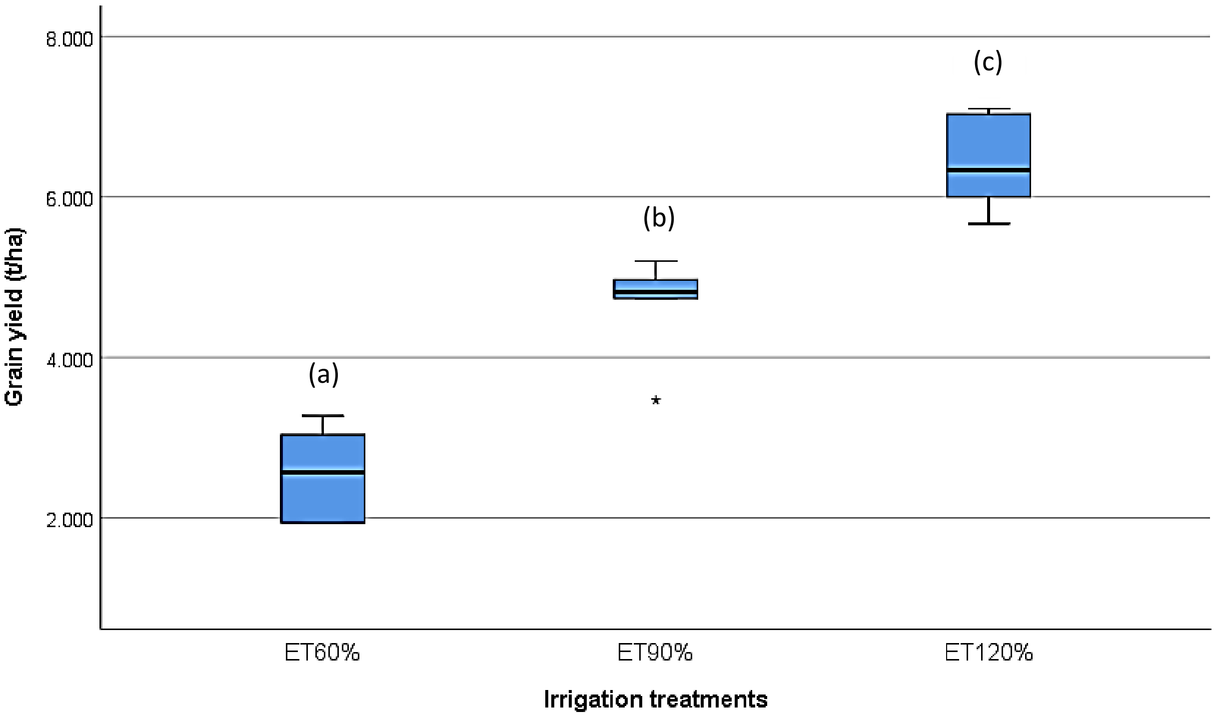


Figure 15. The range and median of collected data on grain yield of sweet corn against treatments ET60%, ET90%, and ET120%. The different letters represent a significant difference at P<0.05.

Grains to ear ratio represented the weight of grains divided by the total weight of the ear. This was important to note which irrigation treatment would produce the most grain/kernels per ear. The mean ratios were 0.72, 0.76 and 0.87 representing irrigation treatment ET60%, ET90% and ET120%.

4.2.3.5. Harvest index.

The harvest index takes into consideration the economic component of the marketable yield as a ratio to the total shoot matter. Since the major marketable yield of sweet corn is fresh ears, the harvest index was calculated as a ratio of fresh weight of ears to fresh aboveground biomass.

The least mean HI in the three irrigation treatments in ET60% at 0.449 and was significantly different from the others. Although HI was highest in irrigation treatment ET90%, it was not significantly different to that ET120% at 0.551 and 0.545 respectively and was ($P<0.05$, $F = 2.26$).

4.2.4. Water Productivity

Water productivity (WP) was calculated as the ratio of the fresh weight of ears to the seasonal water applied. Water applied and yield were noticeably related with a higher application of irrigation water projecting a higher fresh weight of ear yield. Figure 16 shows the recorded water productivity in different ET-based irrigation treatments. The different letters show the difference in significance at $P<0.05$.

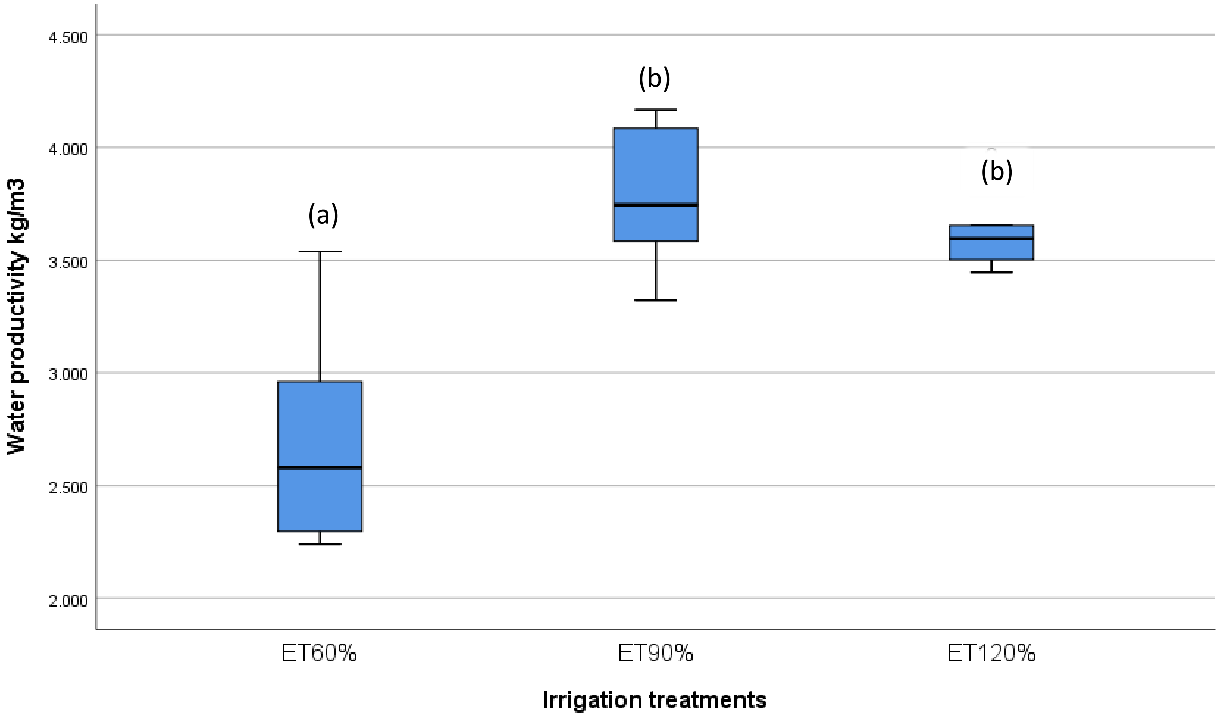


Figure 16. Water productivity of fresh weight of ears (kg m^{-3}) of sweet corn in the irrigation treatments ET60%, ET90%, and ET120%.

Water productivity is observed to increase with increased water stress from ET90% at 3.8 kgm^{-3} to ET120% at 3.6 km^{-3} as similarly observed with other studies (Cid et al., 2018; Viswanatha, Ramachandrappa, & Nanjappa, 2002). Water productivity increases with deficit irrigation (Kresović et al., 2016). The low water productivity in irrigation treatment ET60% was because of the significantly low yield realized.

4.3.Soil moisture sensor-based irrigation experiment results

The analysis focuses on a comparison of three treatments based on soil moisture sensor-based irrigation scheduling on sweet corn.

4.3.1. Irrigation treatments and soil moisture analysis.

The first irrigation was performed on June 6, 2018, and the last on September 4, 2018. The cumulated irrigation water applied in the three SM treatments was as follows, 717mm, 1050mm, and 969mm for irrigation treatments SM25%, SM30%, and SM35% respectively.

Soil temperature data collected varied depending on the depth recorded. There were significant variations at the top 12cm, with soil temperature readings almost matching the diurnal change of air temperature, ranging between 15 ^{O}C and 38 ^{O}C between June 22, 2018, and July 8, 2018. This was measured with the soil moisture sensors installed vertically at the soil surface. At average root zone depth of 25cm, the soil temperature was more stable between 23 ^{O}C and 26 ^{O}C. Figure 17 shows the soil temperatures recorded in at different depths during the growing season.

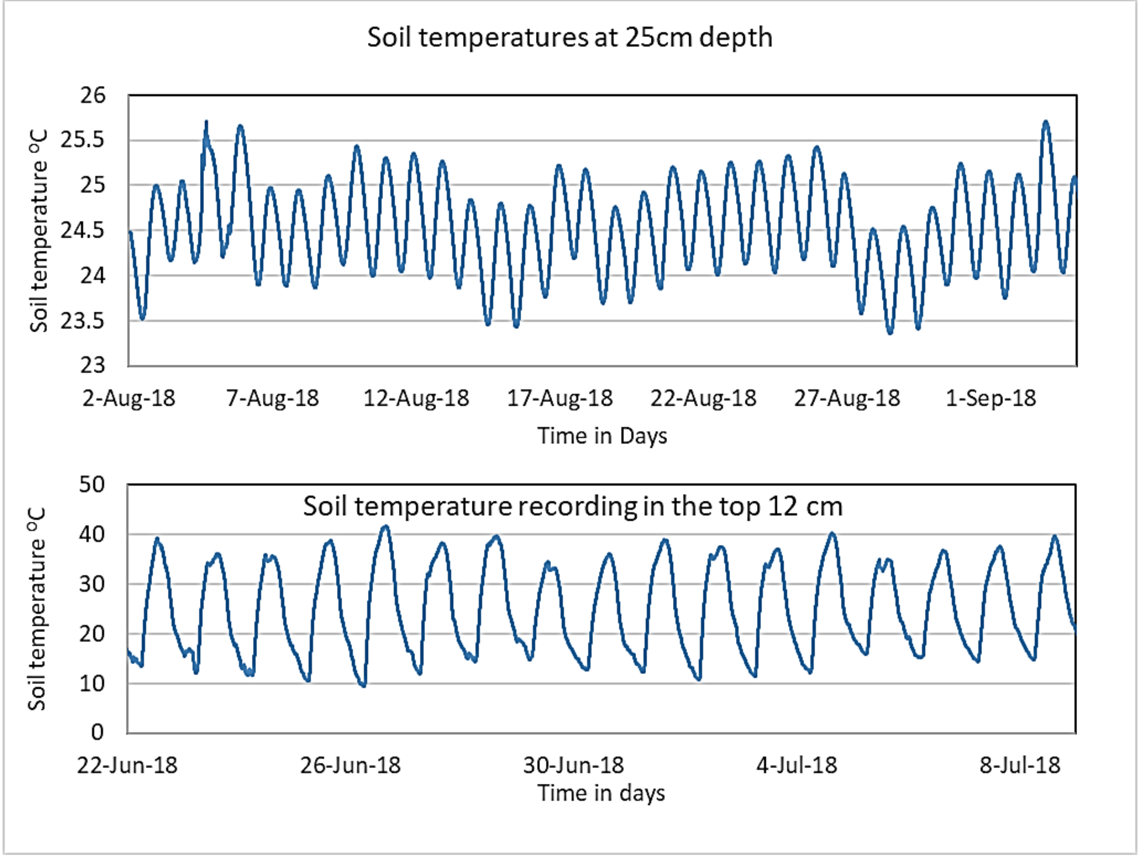


Figure 17. Soil temperatures at different soil depths taken by the soil moisture sensors during the growing season.

Figure 18 and 19 shows the 3 soil moisture sensor-based irrigation treatments, initially irrigated at SM15%, SM20% and SM25% in top 12 cm when the soil moisture sensors were vertically installed at the surface later as SM25%, SM30%, and SM35% respectively when they were repositioned horizontally in the soil profile at 25cm depth. The rapid decrease in recorded soil volumetric water content right after an irrigation event is due to loss of gravitational water, which afterward takes gradual decline due to suction by plant roots and evaporation on the soil surface.

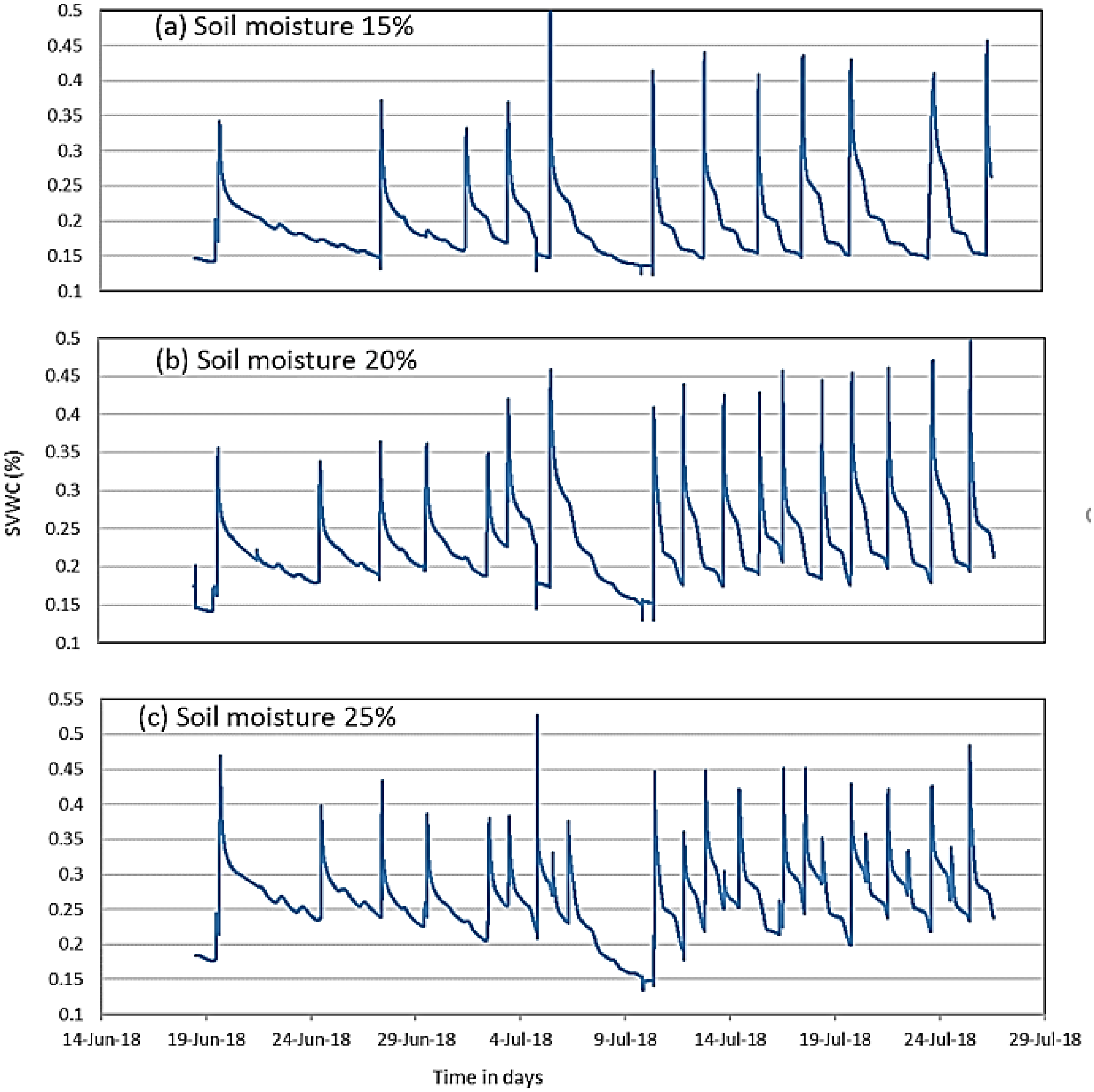


Figure 18. Soil Volumetric Water Content (SVWC) in soil moisture sensor-based irrigation treatments (a) SM15 %, (b) SM20% and (c) SM25%) at 12 cm depth

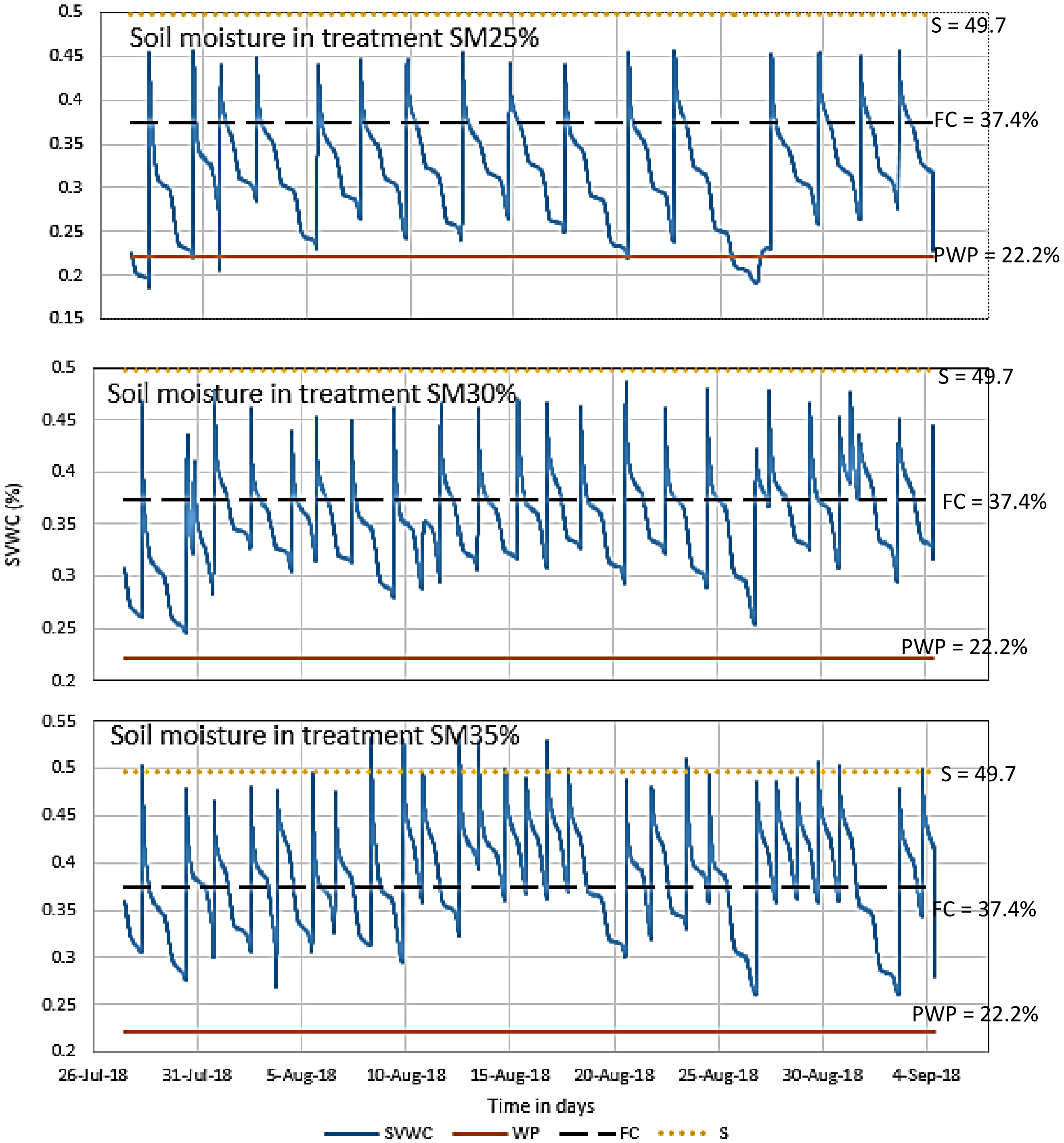


Figure 19. Soil Volumetric Water Content (SVWC) in soil moisture sensor-based irrigation treatments at 25cm depth where S is Saturation point at 49.7%, FC is Field capacity at 37.4%, and PWP is the permanent wilting point at 22.2%.

The irrigation intervals in irrigation treatment SM25% were the longest in comparison with the others at an average of 3 days. Further analysis of Soil Volumetric Water Content (SVWC) in irrigation treatment SM25%, shows that although irrigation was meant to be carried out when the moisture content was 25%, there were intervals it went slightly lower. Irrigation at 25% soil moisture is significantly very close to wilting threshold point of 22.2%, equivalent to 18.4% of depleted plant-available water or 81.6% MAD. Although the average SVWC is 31%, there was induced water stress on sweet corn in this treatment as it was below the recommended 50% of the manageable allowed depletion (R. G. Allen et al., 1998a). For periods when VWC went below wilting point and the plant did not permanently wilt is because drained water may have been available to the crop roots which extend beyond the 25cm depth at which sensors were installed (Datta et al., 2017).

In irrigation treatment SM30%, soil moisture was kept well between wilting point and field saturation. There is no water stress occurring in this treatment. The average soil moisture in this treatment was at 34%, which allowed the right balance in air and moisture in the pores. The irrigation interval in this treatment was moderate, averaging at two days before the next irrigation event. Irrigation at 30% VWC represented 50% MAD before the next irrigation event was scheduled.

Soil moisture in Irrigation treatment SM35% had the shortest irrigation interval of averagely one day. This treatment also recorded the highest in terms of average moisture percentage at 38%, which is slightly above field capacity of 38%. Irrigating at 35% SVWC meant that only 23% of available soil moisture had been depleted (MAD) which is considerably higher than the recommended 50% MAD. Although there is no water stress, the high SVWC may have hindered aeration in this specific treatment and would cause a negative effect on yield (De Bruyn, 1982).

4.3.2. Results on vegetative growth parameters.

This analysis focuses on a comparison of three treatments based on soil moisture sensor-based irrigation scheduling on sweet corn. Table 4 shows data collected on shoot height and cob length.

Table 4. Mean comparisons for shoot height and ear length of field-grown sweet corn at harvest in soil moisture sensor-based irrigation treatments. Within the same columns, means with the same letter are insignificantly different at $P<0.05$ from three replicates ($n = 30$) based on LSD (Least Significant Difference)

Irrigation treatment	Shoot height (cm)	Cob length (cm)
SM25%	185.83a	19.867a
SM30%	213.00b	21.417b
SM35%	208.60b	21.783b

4.3.2.1. Shoot height.

Shoot height (SH) was measured at harvest, 90 days after planting (DAP). There was a significant difference in SH among the irrigation treatments, with sweet corn in SM25% significantly shorter ($P<0.05$) than the others (SM30% and SM35%) at an average of 185cm. The mean shoot height in these subsequent treatments, SM30%, and SM35%

showed no significant difference. This was despite sweet corn in SM30 having the highest mean SH at 213cm and SM35% at 208 cm, as shown in Table 4.

4.3.2.2.Ear length

Ear length in the irrigation treatments varied, following an almost similar trend with shoot height. From Table 2, the shortest in relations to mean ear length was in treatment SM25% and highest in SM30% by a difference of 9%. There was no significant difference in mean ear length for irrigation treatments SM30% and SM35%, contrary to that in SM25%.

4.3.3. Yield responses towards irrigation treatments.

The response of parametric measurements corresponding to aboveground biomass (fresh and dry), fresh and dry weight of ears and grain yield relative to the amount of water applied in each irrigation treatment. A summary of these results is shown in Table 5.

Table 5. Mean comparisons for aboveground biomass, root biomass, ear yield, and grain yield of field-grown sweet corn at harvest. Within the same columns, means with the same

letter are insignificantly different at P<0.05 from three replicates (n = 60 except for root biomass, n = 12) based on LSD (Least Significant Difference).

Irrigation treatment	Aboveground biomass (t/ha)			Root biomass (t/ha)	Ear yield (t/ha)		Grain Yield (t/ha)
	Fresh weight	Dry weight	Moisture %		Fresh weight	Dry weight	
SM25%	44.33a	13.75a	68.95a	10.50a	25.43a	7.58a	6.08a
SM30%	56.29b	16.14b	71.34b	13.89a	33.70b	9.12b	6.47a
SM35%	50.41a	13.44a	73.09b	11.27a	23.42a	7.62a	6.20a

4.3.3.1.Aboveground biomass response to irrigation treatment

The aboveground biomass of sweet corn represented the shoot compounding of stem, leaves, ears and everything else except the roots. The fresh weight of aboveground biomass was measured right after harvest on September 4, 2018. The measurements of the data collected are summarized in Table 3.

Fresh weight of aboveground biomass was highest in irrigation treatment SM30% and least in SM25% albeit insignificantly different from that in SM35%. This represented a reduction in fresh weight of 22%. There was no significant difference in fresh weight of aboveground biomass for sweet corn in irrigation treatments SM35% and SM30% ($P < 0.05$, F= 4.28). Figure 20 illustrates the fresh aboveground biomass in the form of range and median values of the collected data of sweet corn in the form of box plots for the three irrigation treatments. The figure further details the levels of significance in the difference in fresh aboveground biomass whereby letters, (b) represents a significant difference in aboveground biomass in irrigation treatment SM30% from treatments SM25% and SM30% represented by (a) at P<0.05.

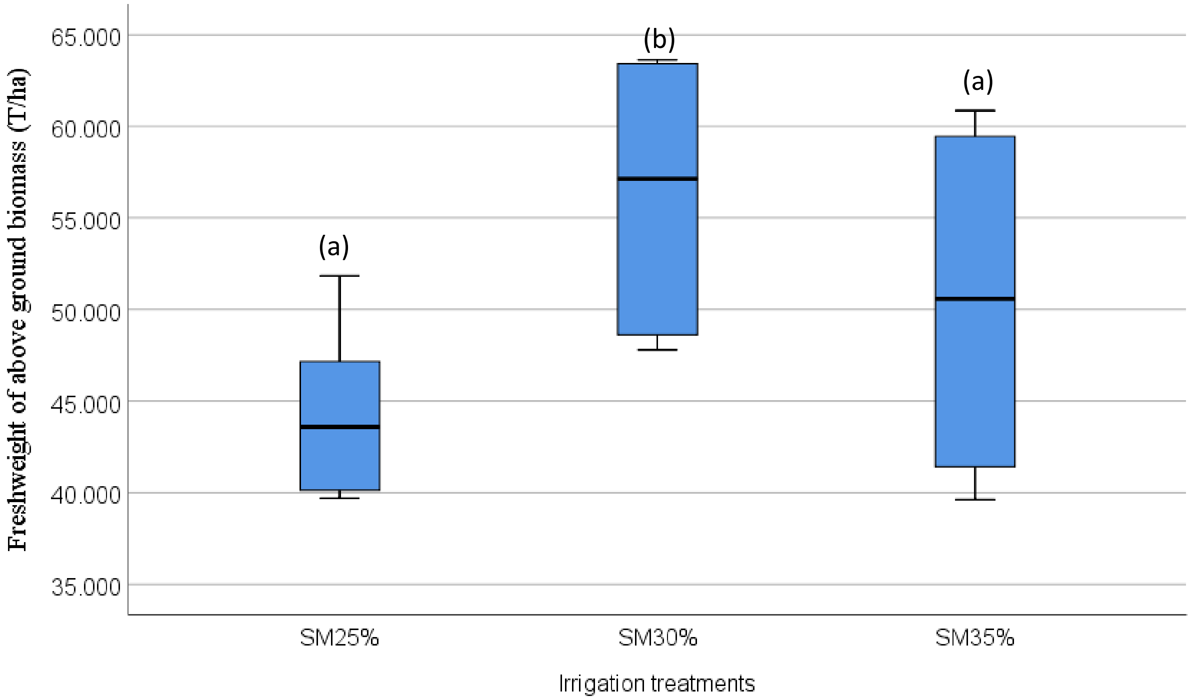


Figure 20. The range and median of collected data on fresh weight aboveground of sweet corn in treatments SM25%, SM30%, and SM35%. The same letter represents an insignificant difference at P<0.05

Irrigation treatment SM30% recorded the highest mean dry weight of aboveground biomass and was significantly different from that in other treatments (P < 0.05, F = 13.04). Sweet corn in irrigation treatment SM35% had the highest moisture percentage of aboveground biomass at 73% which after oven drying resulted in its low dry weight.

4.3.3.2. Root biomass

Root biomass (underground biomass) was measured after uprooting the sweet corn using a shovel, and the roots washed of soil under running water before being cut off the stem and their weights taken. Root biomass of the sweet corn showed no significant difference among all irrigation treatments ($P < 0.05$, $F = 1.173$). This was despite a difference of 13% between the highest and lowest root biomass in irrigation treatment SM30% and SM25% respectively. The average root biomass was of 11.27 t/ha for all treatments.

4.3.3.3. Fresh weight and dry weight of ears.

The mean fresh and dry weight of the sweet corn ears from the three irrigation treatments was highest in SM30% at 33.7 t/ha and 9.12 t/ha respectively. Conversely, mean fresh and dry weights of ears in irrigation treatments SM25% and SM35% revealed no significant difference as shown in Table 3. The low yield in treatments SM25% is due to the deficit form of irrigation being carried out above the recommended 50% MAD hence water stress on that sweet corn resulting in a negative effect on yield. In irrigation treatment SM30%, MAD was at 50% which meant ample soil moisture and air balance and hence high yield in terms of dry and fresh weight of ears. On the other hand, the 23% MAD in irrigation treatment SM35% may have caused poor aeration and hence lower yield. Figure 21 shows the range and median values of the collected data on fresh weight of ears of sweet corn in the three irrigation treatments. The figure further details the levels of significance in the difference in fresh weight of ears whereby same letter (a) in treatment SM25% and

SM35% represents an insignificant difference and (b) with treatment SM30% showing a significant difference from other treatments at P<0.05.

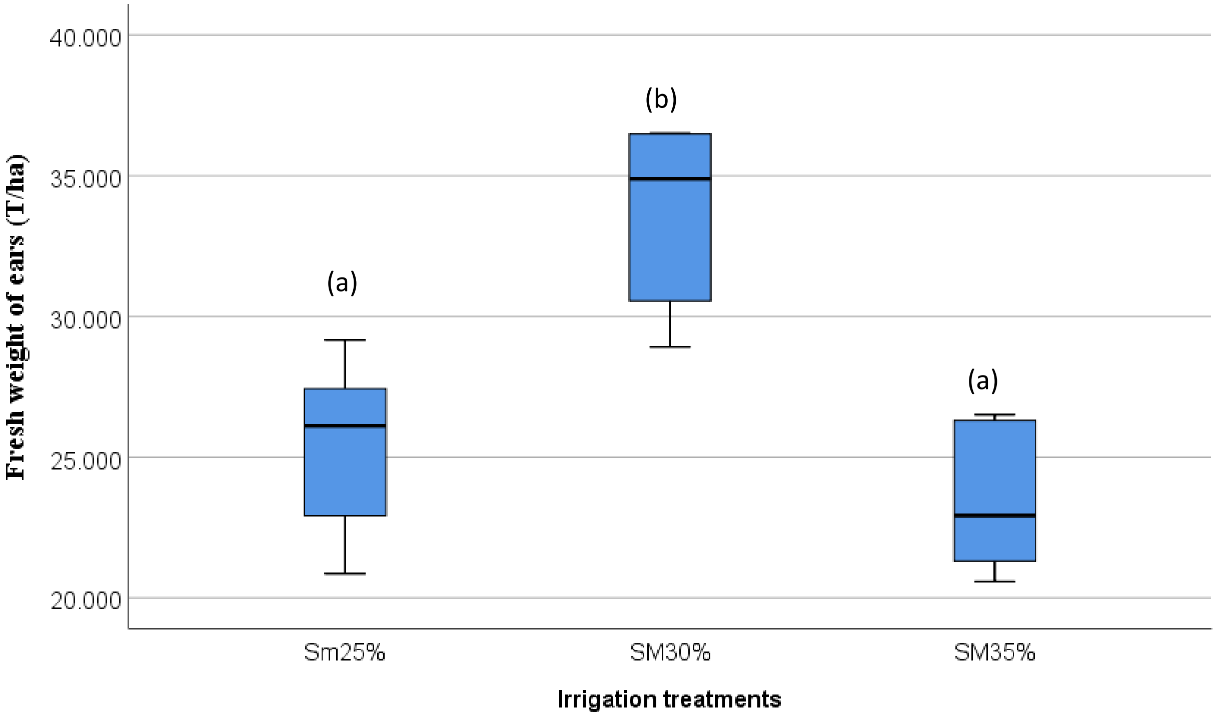


Figure 21. The range and median of collected data on fresh weight of ears of sweet corn against treatments SM25%, SM30%, and SM35%. The same letter represents an insignificant difference at P<0.05.

4.3.3.4.<u>Kernels/grain yield.</u>

Kernels/grain yield of the sweet corn was measured after drying the ears in the oven. Subsequently, the grains were removed from the cob and weighed.

Grain/ kernels yield from the three irrigation treatments unlike other measured parameter showed insignificant difference among all treatments (P < 0.05, F =.294). The highest mean of grain yield was realized in irrigation treatment SM30% at 6.47 t/ha and was not more than 6% in comparison to that in treatments SM25% and SM35%. A study by

(Yildirim, Kodal, Selanay, Yildirim, & Ozturk, 1996) shows that increases in irrigation water do not necessarily result in a significant increase in grain yield.

4.3.3.5. Harvest index.

The harvest index takes into consideration the economic component of the marketable yield as a ratio to the total shoot matter. HI, therefore, forms a useful measure of yield efficiency (Huetsch & Schubert, 2017). Since the key marketable yield of sweet corn is fresh ears, the harvest index was calculated as a ratio of fresh weight of ears to fresh aboveground biomass. There was a significant difference in mean HI between sweet corn in irrigation treatment SM30% and SM25%, which represented the highest and least at 0.6 and 0.47 respectively. HI was the same in treatments SM35% and SM30%. This is illustrated in Figure 22 shows the range, median values of the collected data on HI of sweet corn in the three irrigation treatments. The levels of significant differences in grain yield are clarified by letters, same letter (a) in irrigation treatment SM30% and SM35% represents an insignificant difference in HI and (b) in SM25% shows a difference with the other treatments at $P<0.05$.

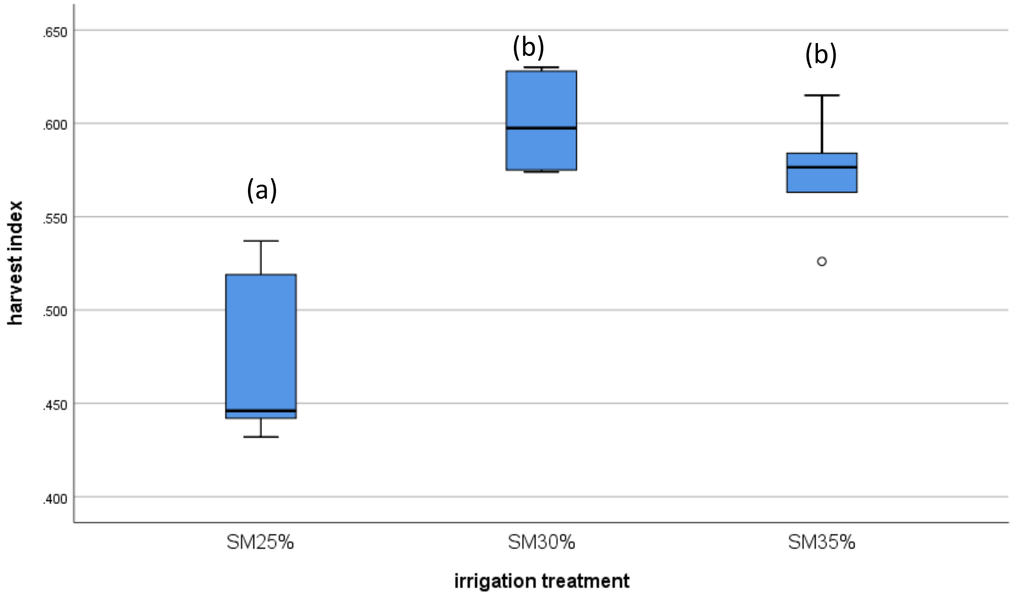


Figure 22. Harvest Index of sweet corn in the different irrigation treatments SM25%, SM30%, and SM35%. The same letter represents an insignificant difference at $P<0.05$

4.3.4. Water use and water productivity

Water productivity was calculated as a ratio of fresh and dry biomass of ear yield to cumulative ET_C or total water use (WU) (Elias Fereres & Soriano, 2006).

$Water\ productivity = \frac{yield}{WU}$, where yield represents fresh or dry ear yield.

Table 6 shows the mean values of water productivity of fresh weight and dry weight of sweet corn ears in the three-soil moisture sensor-based irrigation treatments.

Table 6. Mean comparisons for water use and water productivity of field-grown sweet corn at harvest. Within the same columns, means with the same letter are insignificantly

different at $P<0.05$ from three replicates (n = 30) based on LSD (Least Significant Difference)

Irrigation treatment	Water applied (mm)	Water productivity of ears (T m^{-3})	
		Fresh weight	Dry weight
SM25%	717	4.73a	2.56a
SM30%	1050	4.28a	2.05b
SM35%	969	3.22b	1.85b

Water productivity decreased with an increase in soil moisture content, with the highest WP in irrigation treatment SM25% and lowest in SM35% for both fresh weight and dry weight of sweet corn. Although previous studies water productivity is reported to decrease with increase in applied irrigation water (Di Paolo & Rinaldi, 2008), this was only not the case in irrigation treatments SM30%. Nevertheless, less applied water in treatment SM25% and SM35% showed a 32% increase in water productivity for the fresh weight of ears with a significant difference.

4.3.5. Sap flow

Measurements from the sap flow meter were corrected sap velocity (cm/hr), corrected sap flow (kg/hr) and needle temperature (^{O}C). Corrected sap flow which is calculated from sap velocity is defined as an absolute measure of the volumetric mass flow of water or sap within the xylem vessels in sweet corn (S. Burgess & Downey, 2014).

Using the Sap Flow Tool software, this corrected sap flow was converted to daily cumulated sap volume (cm^3) and sap flow rates (cm^3/hr) by inputting the correction factors (Steppe et al., 2008). Data corrections done in the Sap Flow Tool Software on the wood properties included stem circumference, stem diameter in the range 1.9-2.3 cm (Bethenod, Katerji, Goujet, Bertolini, & Rana, 2000), bark thickness estimated at 0.004cm (Chen, 2015), sapwood dry weight of 60.61 ±3.64% (Igathinathane, Womac, Sokhansanj, & Pordesimo, 2006), xylem radius, and sapwood depth. Other corrections on sensor properties were also made with probe spacing, thermistor distance, first thermistor depth, and wound diameter are shown in Table 7. Data generated from the sap flow too software was in the form of hourly flow rates and is shown in Figure 23. Out of the hourly flow rates, estimates of water transmitted per day were generated and compared to ET, as shown in Table 8.

Table 7. The correction factors and the values made in the sap flow tool settings

Stem and sensor properties	Corrections
Stem circumference	6.9 cm
Stem diameter	2 cm
Bark thickness	0.004 cm
Xylem radius	1 cm
Sapwood depth	0.45 cm
Thermal diffusivity	0.0025 cm^2/s
Sapwood fresh weight	1 g
Sapwood dry weight	0.63 g
Probe spacing	0.5 cm
First thermistor depth	1.5 cm
Wound diameter	0.17 cm

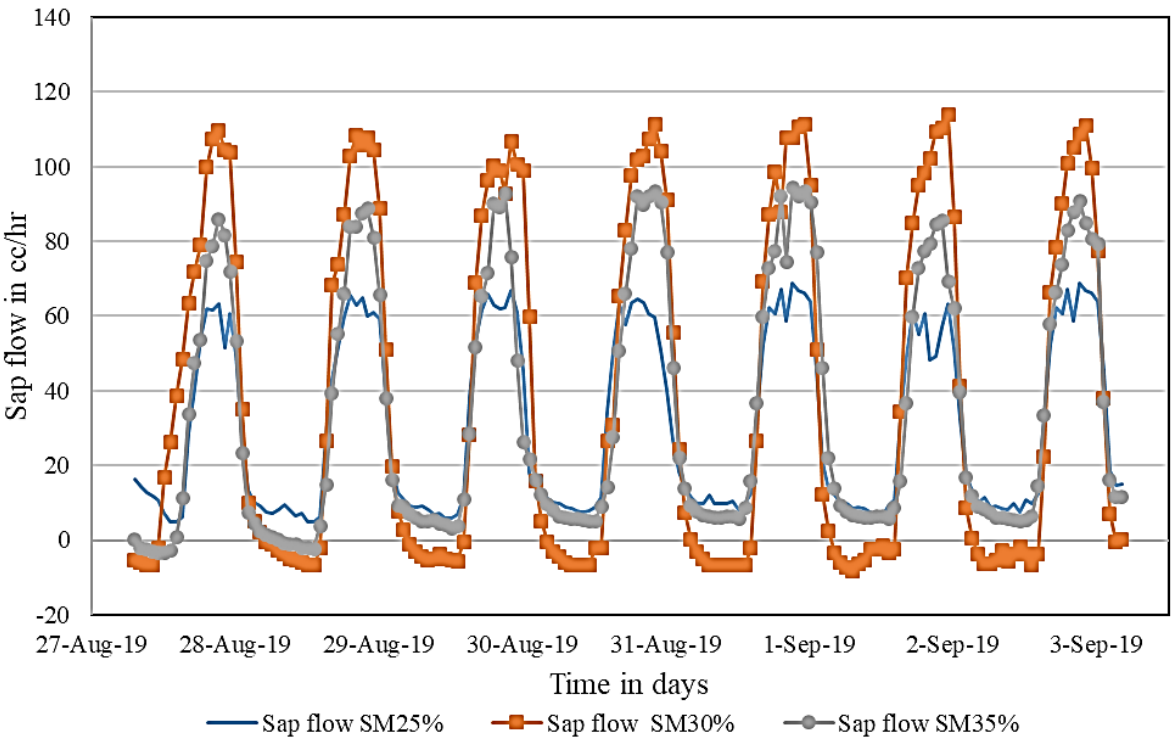


Figure 23. Graphical representation of sap flow (cm3/hr) against time in irrigation treatments SM25%, SM30%, and SM35%.

The crests and trough of the graph represent diurnal changes given all other parameters like water availability are constant and can be used to understand changes in access to water. There is a high velocity of sap through the sweet corn stem during the daytime when there is light radiation. As light decreases so does sap flow showing a direct relationship between solar radiation and xylem sap flow (Gerdes et al., 1994; Jiang et al., 2016; Uddin, Smith, Hancock, & Foley, 2014). High sap flow during the day represents an increase in demand for the exchange of water for carbon dioxide (CO_2) to carry out photosynthesis while the near-zero sap flow at night correlates to no photosynthesis. The highest peaks are observed in irrigation treatment SM30% at averagely 110 cm^3hr^{-1}, followed by SM35% at 85 cm^3hr^{-1} and the lowest were in SM25% at 65 cm^3hr^{-1}. This can explain the high yield in irrigation treatment SM35% and the lower yields in other treatments.

On comparison of sap flow rates to applied irrigation water during the period measurement were taken, there was a positive relationship. Applied irrigation water while collecting sap flow data in treatments SM25%, SM30%, and SM35% was 7.18mm, 10.90mm, and 8.78mm in that order. Deficit irrigation has been previously proven to restrict transpiration in olive trees and correlating sap flow to water use. (Fernández et al., 2006). This can, therefore, be related to results in this study, showing a direct positive correlation with the amount of water applied, sap flow rates.

The generated hourly sap flow was summed up to create daily rates (cm^3/day) that were then converted to sap flow transpiration (mm/day) which was then compared to ET per day (mm/day). Sap flow does not always reflect transpiration through the leaves due to factors like capacitance effects from the storage of water in stems, hydraulic redistribution; a process plants tend to adapt with water stress (Gimenez et al., 2013). However, in other studies, sap flow has been estimated to be proportional to transpiration to as much as 90% of the total water (Fernández et al., 2006). High accuracy can therefore be reached in determining transpiration since almost 99% of daily water uptake (sap flow) is lost through transpiration (Bethenod et al., 2000). The other 1% of the water withdrawn by the plant is assimilated into the plant through photosynthesis as the rest is mostly transpired (Scherer, Seelig, & Franzen, 1996). Therefore, transpiration flow can be measured as the ascent of sap within xylem tissue (Gimenez et al., 2013).

Daily sap flow rates were computed to sap flow transpiration/day, by dividing the daily flow rates by the crop spacing of 0.75m by 0.2m assuming 100% canopy coverage. The computed results are displayed in Table 8.

$$Daily \text{ flow rates or water used by the plant (transpiration)}$$

$$= \frac{(Daily\ flow\ rate\ cc/day\ ) * 10mm/cm}{(0.75m\ \times 0.20m\ \times 10000cc/m}$$

Table 8. The calculated daily flow rates or water used by the plant (transpiration), ET_O, and soil moisture in the three irrigation treatments across the days when sap flow was measured.

Date	Transpiration in SM25% (mm/day)	Transpiration in SM30% (mm/day)	Transpiration in SM35 % (mm/day)	ET_O (mm/day)
28-Aug-18	4.24	6.45	4.11	5.74
29-Aug-18	4.75	6.09	4.97	5.73
30-Aug-18	4.79	6.11	5.03	5.82
31-Aug-18	5.07	6.43	6.13	5.9
1-Sep-18	5.29	6.02	6.81	6.43
2-Sep-18	4.58	6.04	5.26	6.23
3-Sep-18	5.13	5.80	5.80	5.86
Average	4.84	6.14	5.44	5.96

Analysis of transpiration rates show the highest being recorded in irrigation treatment SM30% and was 21% higher than in the lowest recording in irrigation treatment SM35% as shown in Table 8. In general, transpiration rates derived from sap flow rates were closely related to daily ET. Only treatment SM30% had a higher transpiration rate of 3% more, with others 18% and 9% less than ET for treatments SM25% and SM30% respectively. Sap flow transpiration previously investigated was 88±95% of actual evapotranspiration (Bethenod et al., 2000; Miner, Ham, & Kluitenberg, 2017; Uddin et al., 2014).

4.4. Comparison of ET and soil moisture sensor-based irrigation systems.

In this part, results from two irrigation methods (ET-based, and soil moisture sensor-based) will be compared and thoroughly discussed to indicated the effect of various irrigation methods and treatments on crop growth, aboveground fresh and dry weight, yield and the interaction of crop water productivity and water use efficiency. Table 9 shows the amount of applied water (mm) in the different treatments with an additional hypothetical treatment of ET100% across the growing season at an interval of 10 days. 30mm of irrigation water was added, right after planting to flood the experimental plots. Lifesaving irrigation was also applied in irrigation treatment ET60%.

Table 9. Irrigation water applied (mm) in the different treatments across the growing season (days).

Days after planting (DAP)	ET-based				Soil moisture sensor-based		
	ET60%	ET90%	ET120%	ET100%	SM25%	SM30%	SM35%
0	30	30	30	30	30	30	30
10	52.2	44.2	41.5	8.71	12.7	114.1	111.2
20	41.1	37.1	35.8	40.92	21.4	72.1	70.6
30	10.6	31.4	61.1	55.36	96.8	102.9	76
40	43.8	49	46.1	83.82	38.1	53	56.1
50	66.7	118.1	142.8	112.16	57	110.9	103.7
60	63	108.3	126.4	117.17	127.7	133.7	83.1
70	70	97.7	133.4	117.99	131.6	141.1	178.4
80	97.7	136.8	185.8	109.91	87	116.2	92.2
91	91.1	117.5	168.3	101.56	115.1	176.9	168.2
Total	566.4	770.2	971.1	807.60	717.5	1051	969.5

A comparison of the ET-based irrigation system and the ET100% show a close relationship. The total amount of water applied at the end of the growing season for irrigation treatments ET60%, ET90%, and ET120% would be -29%, -5% and +20% when compared to the ET100% treatment. The highest amount of irrigation water was in SM30% and the least in ET60%. On the other hand, in the soil moisture sensor-based experiment, only irrigation treatment SM25% would be water-saving at 11%.

Figure 24 shows the cumulative readings from the flow meters on the different irrigation treatments throughout the growing season.

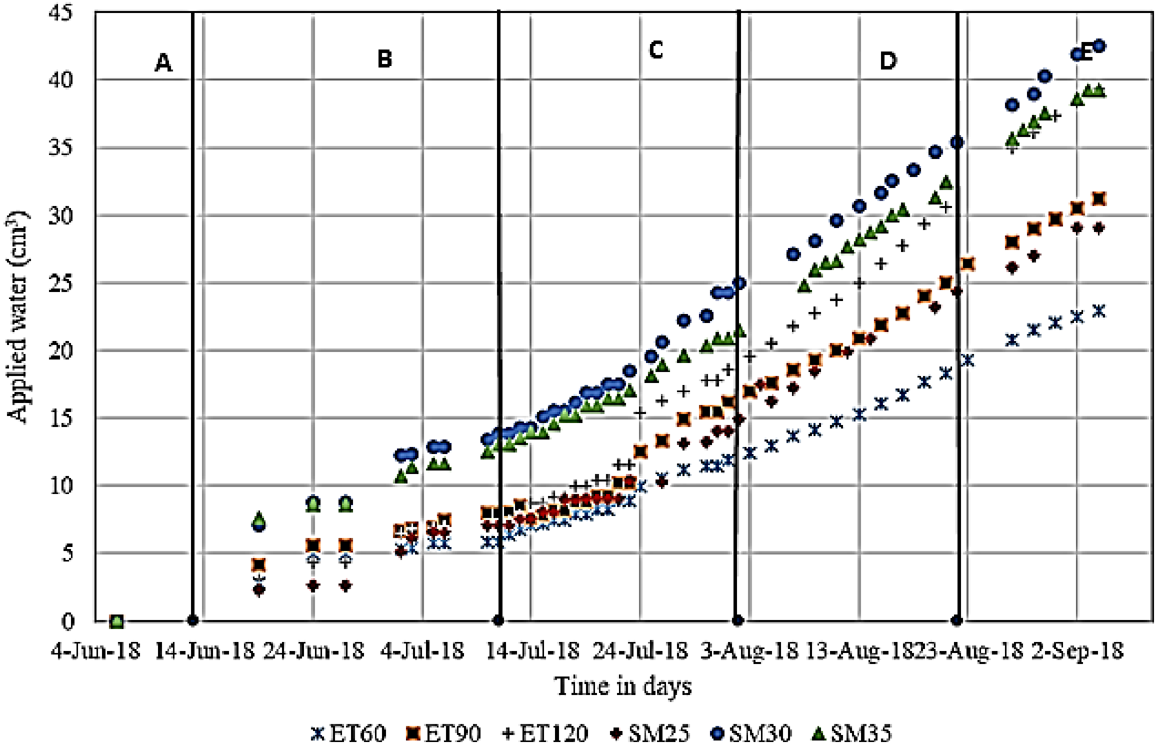


Figure 24. Flow meter readings from SM sensor-based irrigation experiment and ET-based irrigation experiment during the various growth stages A – emergency, B – zero to 8 leaves, C – 8 to 16 leaves, D tasseling and silking, E – maturity.

In the ET-based treatments, the amount of irrigation water applied at the start of the growing season exponentially increases with time at 16 leaves as ET_O also proliferates in accordance with the growth stages; initial, development, mid and late-stage (R. Allen, L. Pereira, D. Raes, & M. Smith, 1998). Whereas in soil moisture sensor-based irrigation treatments, there is a general gradual increase across the growing season, as shown in Figure 24.

Table 10. Average soil moisture taken every 10 days in each of the irrigation treatments. Within the same columns, means with the same letter are insignificantly different at $P<0.05$

Treatments	Amount of water added	Average soil moisture for every 10 days				
		10	20	30	40	Overall
ET60%	322	0.24a	0.24a	0.27a	0.26a	0.25a
ET90%	460.4	0.30bc	0.31b	0.33bc	0.31b	0.31b
ET120%	613.8	0.36d	0.37bc	0.40d	0.39c	0.38c
SM25%	461.5	0.30c	0.32b	0.30b	0.32b	0.31b
SM30%	568	0.33bc	0.35bc	0.35c	0.36c	0.34c
SM35%	521.9	0.36d	0.39c	0.39d	0.39c	0.38d

A comparison of average soil moisture data taken every ten days in the irrigation treatments is shown in table 10. The amount of water added was linearly related to soil moisture content, as shown in Figure 25. Overall, soil moisture content was highest in irrigation treatments, ET120%, and SM35% at 38% and showed no significant difference between the two treatments. Treatments ET90% and SM25% also had the same soil moisture content of 31%. SVWC was lowest in ET60% at 25% and was significantly different from the other treatments.

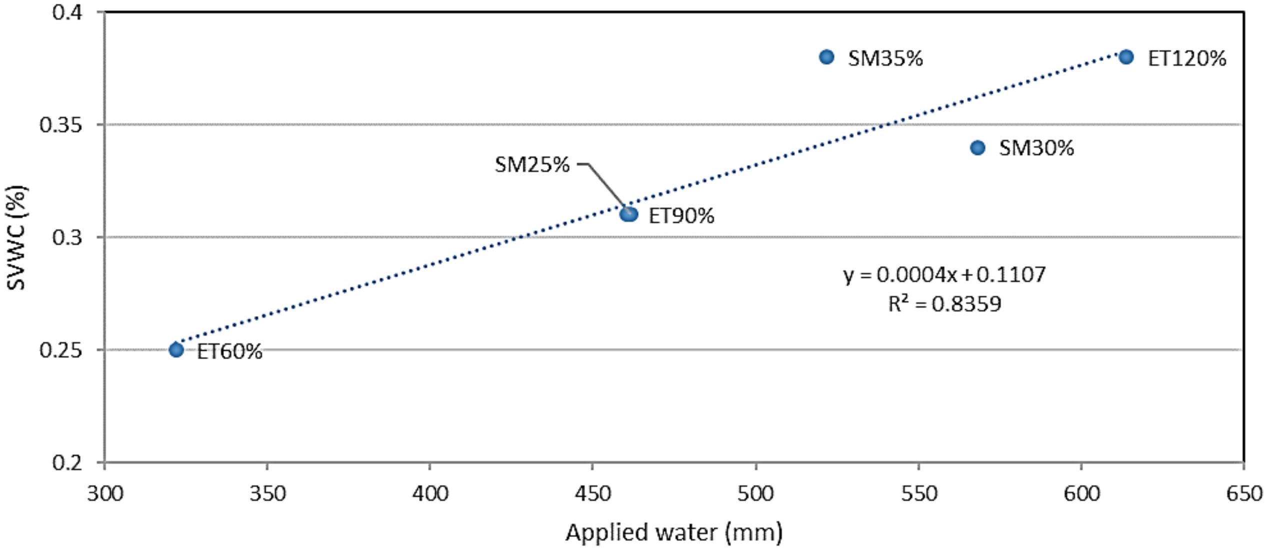


Figure 25. Soil volumetric water content against applied irrigation water.

Table 11. Mean comparisons for shoot height and ear length of field-grown sweet corn at harvest. Within the same columns, means with the same letter are insignificantly different at $P<0.05$ from three replicates (n = 30) based on LSD

Irrigation treatment	Shoot height (cm)	Ear length (cm)
ET60%	151.67a	17.20a
ET90%	195.20b	20.97b
ET120%	203.17c	21.37bc
SM25%	185.83d	19.87d
SM30%	213.00e	21.42bce
SM35%	208.60ce	21.78bce

Shoot height was affected by the irrigation treatments and showed variations. The highest mean in shoot height was in irrigation treatment SM30% at 213 cm and was 30% more than in the lowest/shortest in ET60% at 151cm as shown in Table 11.

The mean ear length was highest in irrigation SM35% but was insignificantly different from that in SM30%, ET120%, and ET90%. Conversely, the least mean ear length was in the ET60% treatment was significantly different from all the other irrigation treatments.

Table 12. Mean comparisons for aboveground biomass (fresh and dry weight), root biomass, ear yield (fresh and dry weight) and grain yield of field-grown sweet corn at harvest. Within the same columns, means with the same letter are insignificantly different at P<0.05 from three replicates (n = 30) based on LSD

Irrigation treatment	Aboveground biomass (t/ha)		Root biomass (t/ha)	Ear yield (t/ha)		Grain Yield (t/ha)
	Fresh weight	Dry weight		Fresh weight	Dry weight	
ET60%	26.54a	8.66a	7.17ac	11.92a	5.53a	2.54a
ET90%	39.87b	12.03b	13.00bc	21.81b	6.53b	4.95b
ET120%	48.75c	14.17c	15.39b	26.42c	7.41ce	6.41c
SM25%	44.33bc	13.75c	10.50bc	25.43d	7.58cd	6.08c
SM30%	56.29d	16.14d	13.89bc	33.70e	9.12ce	6.47c
SM35%	50.41cd	13.44bc	11.27abc	23.42d	7.62cd	6.20c

With regards to the fresh weight of aboveground biomass, sweet corn in full irrigation treatments in SM30% accumulated the highest biomass which was significantly different from that in all ET-based irrigation treatments and 13% higher than in treatment ET120%. Irrigation treatments that had an insignificant difference in SVWC showed no significant difference in their fresh weight of aboveground biomass ($P < 0.05$, $F= 7.37$).

This is demonstrated in treatments SM25% and ET90% and valid for treatments SM30% and ET120% as observed in Table 12.

The dry weight of aboveground biomass followed a closely similar pattern as fresh weight aboveground biomass regarding the treatment with the highest and least mean weight. Most distinctive is the high moisture percentage in irrigation treatment SM35% at 72.8%. This was higher than in any other irrigation treatment.

The root biomass showed little variation among the treatments. Although irrigation treatments ET60% had the least mean weight of root biomass at 7.17 t/ha, it was insignificantly different from most of the other treatments at $P < 0.05$.

Sweet corn yields were influenced by mainly soil moisture status and amount of water applied in the different treatments. Previous studies have shown that the highest sweet corn yield came from satisfactory irrigation treatments (Ko & Piccinni, 2009). Amount of applied irrigation water and yield were noticeably related with more water applied, projecting a higher ear yield. (Di Paolo & Rinaldi, 2008). The total water in relation to sweet corn productivity researched to show a positive linear relationship between water use and yield (Kiziloglu et al., 2009; Liu et al., 2017; Medrano et al., 2015). Fresh weight of ear yield increased at a rate of 32 kg/ha per 1 mm of water applied by sweet corn while increasing at a rate of 5.4 kg/ha in the dry weight of ears as shown in Figure 25

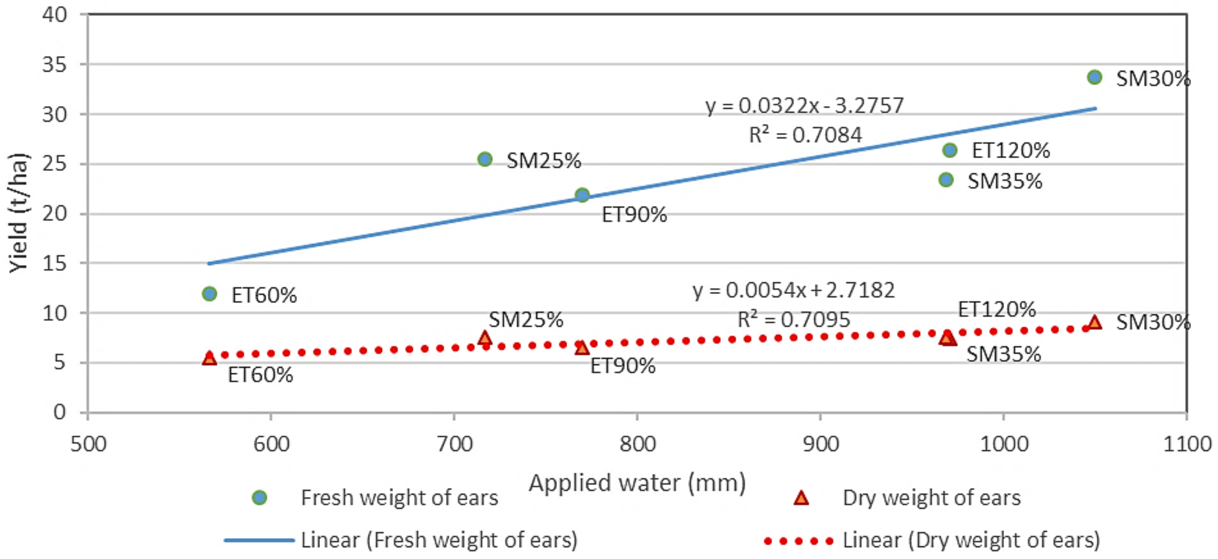


Figure 25. The relationship between water use and fresh weight and dry weight of ears.

Sweet corn in irrigation treatment SM30% had the dominant response with the highest above fresh and dry ear yield and grain yield. This can be explained by a high amount of water applied but at the same time an overall equilibrium in air and moisture with MAD of 50% at an average of 34% SVWC. On the contrary, irrigation treatment ET60% had less amount of water applied, and very low soil moisture had the least fresh and dry yield of ears. Irrigation treatments SM35% and ET120% that had very high levels of soil moisture at an average of 38% did not necessarily produce the highest yield. It can, therefore, be argued that both soil water stress and very high levels of soil moisture have a negative effect on yield.

Grain yield data showed little variation and was mostly insignificantly different among irrigation treatments. Applied water has been previously proven not to increase grain yield to any significance (Yildirim et al., 1996) as shown in this study. Prolonged water stress has been highlighted to cause losses in grain yield as high as 40 to 90% with prolonged water stress (Cakir, 2004); as observed in irrigation treatment ET60% which had 64% less yield than in irrigation treatment SM30%.

Water productivity of fresh weight and dry weight of ears, and grain yield in the treatments were compared and compiled in Table 13.

Table 13. Comparisons of applied water and water productivity of sweet corn. Within the same columns, the same letter shows an insignificant difference at $P<0.05$

Irrigation treatment	Water applied (mm)	Water productivity of ears (kg m^{-3})		Grain yield (t m^{-3})
		Fresh weight	Dry weight	
ET60%	566.35	2.70a	2.04a	.83a
ET90%	770.15	3.77b	2.08a	1.14b
ET120%	971.09	3.62bc	1.95a	1.02b
SM25%	717	4.73d	2.56b	1.41c
SM30%	1050	4.28d	2.05a	1.16b
SM35%	969	3.22c	1.85a	1.05b

Previous studies have shown that water productivity in sweet corn increased as the amount of irrigation decreased (Cid et al., 2018; Di Paolo & Rinaldi, 2008; Viswanatha et al., 2002). This was true for all the treatments, except for treatments ET60% and SM30% that had meager and high yields respectively. More so, water productivity in dry weight of ears and grain yield in treatment SM25% that had low amount of applied irrigation water showed significantly higher WP than in other treatments. Overall, WP was not considerably affected by choice of irrigation techniques.

In conclusion, the results of this study agree with other studies that have been conducted on other corn varieties. Water stress has a significant effect on plant height, aboveground biomass, and yield (Cakir, 2004; Cordner, 1942; Vial et al., 2015). Soil moisture data collected also gave a predictable pattern of yield, with treatments that had irrigation below wilting point or more than 50% MAD experiencing stress and hence less yield. More so, the study showed that the highest yields are observed in full irrigation treatments regardless of the irrigation scheduling method. In conclusion, both methods were effective in scheduling irrigation and water saving as observed from the results.

CHAPTER 5

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

5.1.Summary

As water scarcity continues to be exacerbated with increased water needs for agriculture, advanced irrigation scheduling methods will have to be adopted to maintain productivity. Two irrigation scheduling approaches based on soil moisture sensing and ET were assessed in improving water productivity and yield production of sweet corn. The two field experiments were carried out at Agricultural Research and Educational Center (AREC) of the American University of Beirut (AUB) in Lebanon's Beqaa Valley from June 6, 2018, to September 4, 2018.

To compare between ET-based and soil moisture-sensor based irrigation scheduling techniques, sweet corn was subjected to different treatments under those two methods. The ET-based experiment has 3 irrigation treatments, ET60%, ET90%, and ET120% based on percentages of Grass-reference FAO Penman-Monteith (ET_C), while the soil moisture sensor-based irrigation experiment had SM25%, SM30%, and SM35% which were thresholds of soil volumetric water content readings from the CS655 soil moisture sensors at which irrigation was scheduled. Sap flow data was also collected in the soil moisture sensor-based experiment to identify a relationship between the amount of water applied, sap flow transpiration and possibility of using it as an irrigation scheduling method.

There was a significant difference in aboveground biomass, ear yield, and grain yield realized in all treatments. ET120% had the highest fresh ear yield at 26.42 t/ha and was 17% and 55% higher than in treatments ET90% and ET60% respectively. Regardless, there was a positive effect of deficit irrigation on the water productivity of fresh weight of ears with the highest in ET90% at $3.8kg^{-3}$. High water stress due to deficit irrigation in irrigation treatment ET60% caused economic loss as it had less than 50% yield in comparison to full irrigation treatments and recording the lowest water productivity of $2.7Kgm^{-3}$.

In the soil moisture sensor-based irrigation experiment, sweet corn shoot height, cob length, and aboveground biomass, yield increased from least soil moisture in SM25% and peaking in SM30% and decreasing in SM35%. The effects of very high soil moisture and low soil moisture contents in treatments SM25% and SM35% showed no significant difference Grain yield and root biomass were insignificantly different in these treatments at an average of 11.27 t/ha and 6.25 t/ha respectively.

In both the ET-based and soil moisture sensor-based experiments, water stress had a negative response shoot height, aboveground biomass, and yield production. On the other hand, more irrigation water application produced a higher yield production at a rate of $32kgha^{-1}$ for fresh ear yield and $5.4kgha^{-1}$ in dry ear yield for every 1mm of irrigation water added. The field experiments also illustrated that water productivity increased by reducing applied irrigation water except in treatment ET60% and SM30% that had exceptionally low and high yields respectively. Additionally, irrigation water can be saved by using deficit irrigation as observed in irrigation treatments ET60%, ET90% and SM25% saving 29% 5%

and 11% respectively of the estimated water for a full irrigation treatment at ET100%. The deficit irrigation in these treatments can also be concurrently observed through the soil moisture sensor data, showing that irrigation was above the recommended 50%MAD. Just like in low soil moisture content, high soil moisture had a negative effect on yield as observed in treatments ET120% and SM35% respectively.

Sap flow data was collected under different soil moisture regimes in the soil moisture sensor-based irrigation experiment. Sap flow had a direct relationship with the depth of applied water in the three irrigation treatments, whereby the highest sap flow rates were in treatments that had more applied irrigation water. The highest sap flow rates were in irrigation treatment SM30% with average peaks at 110cm^3hr, followed by SM35% at 85 cm^3hr^{-1}, and the lowest was in SM25% at 65 cm^3hr^{-1}. Sap flow transpiration generated from sap flow data was close to evapotranspiration applied water and yield. Only treatment SM30% had a higher transpiration rate of 3% more, with others 18% and 9% less than ET for treatments SM25% and SM30% respectively. More so, sap flow transpiration and amount of applied water showed a positive relationship with the highest sap flow rates in treatments that had more water and the reverse being true.

5.2. Conclusion

The goal of this research was to test, compare, and evaluate the two widely known irrigation scheduling systems; ET-based and soil moisture sensor-based irrigation systems.

Water stress in both scheduling methods had a significant effect on plant height, aboveground biomass, and yield. Whereas with increased application of irrigation water, ear yield increased linearly at a rate of 32kg/ha per mm of added irrigation water. On the other hand, deficit irrigation in both the ET-based and soil moisture-sensor based irrigation treatments showed an increase in water productivity, thou severe water stress in irrigation treatment ET60% showed insignificantly low water productivity and yield. Noteworthy too is that very high soil moisture conditions in both irrigation scheduling methods are as unfavorable on yield as water stress conditions in the productivity of sweet corn.

Irrigation water can be saved by using smart while applying deficit irrigation in both irrigation scheduling methods as observed in irrigation treatments ET60%, ET90% and SM25% where 29%, 5% and 11% of irrigation water was saved respectively.

Irrigation scheduling can be greatly improved through automation by using either the ET-based system or the soil moisture sensor-based. From the soil moisture sensor-based irrigation, a clear pattern can be established on when and how long to irrigate to realize good yield. Overall, both smart irrigation techniques proved efficient in scheduling irrigation but with regards to cost, the soil moisture sensor-based irrigation experiment is more expensive since it requires a lot more equipment such as the soil moisture sensors, solar panel, data logger in addition to a controller if it is to be automated and therefore smallholder farmers would be recommended to acquire the cheaper ET-based system.

Sap flow had a direct relationship with the depth of applied water in accordance to different soil moisture regimes, whereby the highest sap flow rates were in treatments that had more applied irrigation water. Sap flow transpiration generated from sap flow data was also closely related to evapotranspiration, and yield.

5.3. Recommendations

It is recommended to:

- Avoid both low and high soil moisture while irrigating as it negatively affects yield. High water deficit causes economic loss in yield and water productivity and therefore should be avoided.
- Farmers with limited water resources can grow sweet corn under deficit irrigation to produce satisfactory yield.
- Conduct a study of sap flow over a longer duration to evaluate a pattern in soil moisture change and sap flow.
- Automation of the soil moisture sensor-based scheduling should be used in future studies to reduce marginal human errors.
- Soil moisture sensors can also be put at soil moisture depth for an entire experiment to evaluate that scheduling method.

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