Integrated weather sensor platform and decision support system for improved sweet potato production

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INTEGRATED WEATHER SENSOR PLATFORM AND DECISION SUPPORT SYSTEM FOR IMPROVED SWEET POTATO PRODUCTION

A Thesis

Submitted to the Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College in partial fulfillment of the requirements for the degree of Master of Science in Biological and Agricultural Engineering

In

The Department of Biological and Agricultural Engineering

By

José Pablo Rojas-Jiménez
B.S. Universidad de Costa Rica, 2006
December, 2011
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ABSTRACT

Water management represents an essential component in all agricultural activities, where significant improvements can be achieved through the implementation of field measuring devices and irrigation scheduling models. The methods that integrate these tools may be based on information regarding the soil, crop, and weather. Evapotranspiration (ET) is one of the most important components of the soil water-balance used in modeling. A number of estimation methods have been developed to determine Reference Evapotranspiration (ET₀) under various types of weather conditions.

In this research, an analysis was conducted between different ET₀ estimation methods and ET₀ calculated from soil water content measurements and a soil-water budget, in Northeast Louisiana during the 2010 sweetpotato growing season. Similarly, the standardize ASCE Penman-Monteith equation was then compared to ET₀ equations using limited weather inputs. Additionally, a Sweetpotato Irrigation Scheduler (SPIS) based on a simple soil-water balance approach was developed to improve irrigation scheduling using weather, crop, and soil data. The model’s predictions were validated, for the critical first 30 Days after Transplanting (DAT) and for the entire growing season, against field data obtained from soil water content probes. A previously developed phenology-driven Bayesian belief network model was used to establish the timing and depth of irrigation.

Some difficulties were found during the assessment of ET₀ and the simulation of the soil-water content under unsaturated soil and dry weather conditions. These circumstances reduced the capacity of the soil to move water appropriately, slowing down some of the processes involved in the soil-water budget, causing a misrepresentation by the ET₀ equations and the irrigation scheduling model.

Key-words: Reference Evapotranspiration, limited data, irrigation scheduling, sweetpotato, Louisiana
CHAPTER 1: VALIDATION OF FOUR REFERENCE EVAPOTRANSPIRATION MODELS USING SOIL WATER CONTENT MONITORING IN NORTHEAST LOUISIANA

1.1 INTRODUCTION

Water availability is a fundamental aspect in agriculture and in general human activities. Crops have water requirements that must be fulfilled to have a healthy crop and abundant harvest. This water can be provided either by precipitation or available subsurface moisture. However when the supply is not met with natural conditions, growers must implement irrigation. For efficient irrigation, they first need to determine the right amount of water depth to meet the evapotranspiration requirement.

Evapotranspiration (ET) is the combined process by which water is converted from liquid to water vapor via evaporation from soil and plant surfaces and via transpiration of water from within plant tissue (Allen et al., 2007; ASCE-EWRI, 2005). ET is very important in many scientific fields in general and irrigation scheduling in particular (Temesgen et al., 2005).

The first process component of ET is evaporation, where energy in needed to change the state of water (Allen et al., 1998); with the primary energy being provided through direct solar radiation. This water state change is achieved due to the difference between water vapor pressure from the surface and the atmosphere. The rate of evaporation decreases as the surrounding air becomes saturated. Variables such as wind become important, since they affect the rate of replacement of the saturated air around a surface, such as a plant’s leaf. When considering soil as the evaporating surface, the percentage of canopy cover and the available water in the soil will affect the rate.

The second process is transpiration, where crops lose water through stomata, which are small
openings on the leaf (Allen et al., 1998). The vapor exchange with the atmosphere is controlled by the stomatal resistance, which is defined as the restriction of the guard cells around the opening of the stomata to the diffusion of water vapor back to the atmosphere (Geiger et al., 2003). Like evaporation, transpiration depends on the amount of energy received, the vapor pressure gradient and wind velocity. The transpiration rate will be affected by factors such as weather parameters, soil water content, conductivity, soil water salinity, crop root characteristics, and environmental and agricultural practices.

Evapotranspiration can be expressed as the amount of energy consumed (latent heat energy, W m⁻² or MJ m⁻² t⁻¹) or the equivalent depth of evaporated water (mm t⁻¹, where t represents a time unit). A loss of 1 mm of water corresponds to a loss of a 10 m³ of water per hectare (Allen et al., 2007).

Several methods are available to measure total daily evapotranspiration, either directly or indirectly. Direct measurements are primarily used to provide data for calibrating weather-based ET models and for monitoring soil water conditions (Allen et al., 2007). The drawbacks for direct methods include the initial equipment cost and the cost of operating and maintaining the instrumentation (Pauwels and Samson, 2005; Farahani et al., 2007).

Some examples of direct methods for ET measurement are the lysimeter, the Bowen Ratio Energy Balance (BREB) model and Eddy covariance (EC) approach. The lysimeter is design to compute the changes in soil moisture either by weight or non-weight techniques (Howell et al., 1991; Watson and Burnett, 1995). Likewise, the Bowen Ratio Energy Balance approach attempts to estimate ET by calculating the positive vertical flux of water vapor from the evaporating surface (Geiger et al., 2003; Payero et al., 2003). The eddy covariance technique provides alternative measures of the latent heat flux equivalent to ET (Pauwels and Samson, 2005; Sun et al., 2007).
Similarly, ET can also be calculated by monitoring the change in soil water content over a given
depth in conjunction with estimates of additional components of the soil-water budget (Farahani et al.,
2007). The soil-water balance technique can be compared to a checkbook, where effective
precipitation, net irrigation and capillary rise from groundwater add to the water budget, while
evapotranspiration and deep percolation represent the water losses.

Care should be taken when interpreting data from direct ET methods (Allen et al., 2007),
because such readings do not represent ET for a large vegetation area. Therefore, the measurements
shouldn’t be done over small groups of spatially isolated plants since this will produce an increase in
the transfer of heat and radiation energy from outside the measured group, thereby misrepresenting
ET.

Given the difficult task of making direct ET measurements, a series of Reference
Evapotranspiration (ET_o) models were developed by researchers and practitioners using historic and
current meteorological data (Itenfisu et al., 2003). These models can be divided into three categories:
temperature based, radiation based and a combination of energy budget and mass transfer models
(Jensen et al., 1990). The widely used Reference ET equations are combination based, including the
original Penman and Penman-Monteith (PM) methods.

The Penman-Monteith equation has been extensively evaluated and compared with measured
lysimeter data under different climatic conditions (Yoder et al., 2004; Amatya et al., 1995). Penman-
Monteith was introduced as a standard model to estimate ET_o (Allen et al., 1998; ASCE-EWRI, 2005).
Unfortunately, the equation considers many meteorological inputs and surface parameters, making it a
more physical representation of ET (Tabari, 2009).

Despite the advantages of the more physically based Penman methods, empirical ET_o equations
are commonly used in cases where data availability is limited. The 1985 Hargreaves-Samani approach requires only data for maximum and minimum temperature, with extraterrestrial radiation calculated as a function of latitude and day of the year (Yoder et al., 2004). The 1972 Priestley-Taylor and the 1961 Turc equations are other frequently used methods requiring only air temperature and solar radiation as inputs.

Few projects have been conducted to evaluate the performance of these ET\textsubscript{o} methods in Louisiana. Fontenot (2004) tested six daily and monthly reference evapotranspiration models (FAO-24 Radiation, FAO-24 Blaney-Criddle, 1985 Hargreaves-Samani, 1972 Priestley-Taylor, 1957 Makkink and 1961 Turc) against values computed with the FAO-56 Penman-Monteith equation (Allen et al., 1998). The results indicated that the 1961 Turc model was the most accurate model in estimating daily and monthly ET\textsubscript{o} in Louisiana. Shah and Edling (2000), evaluated the performance of the Penman-Monteith, FAO-Penman, and 1963 Penman models in Louisiana. However, they focused on one particular location for a short period of time. No published studies have examined the behavior of ET\textsubscript{o} models against observed ET using soil water monitoring probes (Capacitance/Frequency Domain technology) in Louisiana, particularly the northeast part of the state.

In this study, pair-wise comparisons were made between daily ET\textsubscript{o} estimated from four different reference evapotranspiration equations (ASCE-EWRI Penman-Monteith, Priestley-Taylor, Turc, and Hargreaves-Samani) and ET\textsubscript{o} determined from soil volumetric water content measurements. The purpose was to provide helpful information in selecting the appropriate ET\textsubscript{o} equation for the climate in Northeast Louisiana, during the first 30 days after transplanting (DAT) and for the entire growing season of ‘Beauregard’ Sweetpotato. The selected ET\textsubscript{o} equation will then be used as part of a computer-based Decision Support System to assist sweetpotato producers to schedule appropriate
irrigation volumes and timing as well as overall farm profitability (Villordon et al., 2010).

1.2 MATERIALS AND METHODS

1.2-A STUDY AREA

The weather and soil data used in this study were measured on experimental fields which are part of Louisiana State University Agricultural Center Sweetpotato Research Station, situated approximately 8 km (5 miles) south of Winnsboro, LA (Franklin Parish). The sweetpotato transplanting date was set to June 1, 2010.

The site is located at an elevation of 22 m above MSL and lies at latitude 32°06’N and longitude 91°42’W. Franklin Parish has historically long, hot summers due to moist tropical air moving from the Gulf of Mexico. Winters are cool and fairly short. Precipitation is fairly heavy throughout the year and prolonged droughts are rare.

During the summer, precipitation consists mainly of afternoon thundershowers (Martin et al., 1981). According to the United States Historical Climatology Network (USHCN), for Winnsboro, LA from (1980-2009), the average annual precipitation is 1452.23 mm (57.2 in), with 635.31 mm (25 in) or 43.75% of which falls during the growing season (May to October). The sun shines 60 percent of the time in summer and 50 percent during winter. The prevailing wind is from the south with an average high wind speed being 3.57 meters per second (8 miles per hour) during spring.

During the experiment (May to October 2010), the mean temperature was 27.2 °C (80.9 F), mean relative humidity 80 percent, wind speed 1.71 m s⁻¹ (3.83 mph), and a total precipitation of 325.12 mm (12.8 in) during the growing season.

The soils within the experimental area were a relatively homogenous combination of Gigger silt loam (8.2%) and Gigger-Gilbert complex (91.8%). Table 1-1 provides the main properties and qualities
for the soil types found at the site. Additionally, Allen et al. (2007) gives some ranges for physical soil properties for Silt loam soils such as $\theta_{FC}$ (field capacity volumetric water content) of 0.22-0.36 m$^3$ m$^{-3}$ and $\theta_{WP}$ (permanent wilting point volumetric water content) of 0.09 - 0.21 m$^3$ m$^{-3}$.

Table 1-1. Main soil properties and qualities (USDA-NRCS, 2010)

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Slope</th>
<th>Drainage</th>
<th>Depth to water table</th>
<th>Available water capacity</th>
<th>Typical profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gigger silt loam</td>
<td>1 - 3%</td>
<td>Moderately well drained</td>
<td>30 to 76 cm (12 - 30 in)</td>
<td>Moderate 224 mm/m (8.8 in/ft)</td>
<td>0 – 140 cm (0 - 6 in) Silt loam</td>
</tr>
<tr>
<td>Gigger-Gilbert complex</td>
<td>1 - 3%</td>
<td>Moderately well drained</td>
<td>30 to 76 cm (12 - 30 in)</td>
<td>Moderate 226 mm/m (8.9 in/ft)</td>
<td>0 – 125 cm (0 - 5 in) Silt loam</td>
</tr>
<tr>
<td>0 - 1%</td>
<td>Poorly drained</td>
<td>0 to 46 cm (0 to 18 in)</td>
<td>High 305 mm/m (12 in/ft)</td>
<td>0 – 178 cm (0 - 15 in) silt loam</td>
<td></td>
</tr>
</tbody>
</table>

1.2-B DATA MEASUREMENTS

The data set used in this analysis was obtained from an automated weather station measuring weather and soil variables including Air Temperature (T), Wind Speed ($u_2$), Relative Humidity (RH), Solar radiation ($R_s$), Precipitation (P) and Soil volumetric water content (VWC).

The station was equipped with standard measuring devices. Air temperature and relative humidity were measured using a thermoelectric sensor (model: HMP45C – Campbell Scientific, Inc./Vaisala). Wind speed was measured at 2 m height with a RM Young Wind Monitor (model: 05305); solar radiation was determined using a silicon photovoltaic pyranometer (model: LI-COR LI200X – Campbell Scientific Inc.), which measures incoming shortwave (i.e. solar) radiation ($R_s$); precipitation data was obtained using a tipping bucket rain gauge (model: TB4 - Campbell Scientific, Inc.). Finally, soil volumetric water content was measured via a soil moisture sensor (model 5TE – Decagon Devices,
The use of trademarks in this publication does not imply endorsement of the products listed nor criticism of similar products not mentioned.

All the meteorological inputs were sampled at three-second intervals and recorded at 1-minute, 1-hour, and 24-hour averages by a data logger (model: CR-1000 - Campbell Scientific, Inc.). Data was then transmitted to the LSU AgCenter, through the Louisiana Agriculture Information System (LAIS). The LAIS is a statewide network primarily dedicated to collecting meteorological data for use predominately by agriculture and engineering communities and is operated by the Department of Biological and Agricultural Engineering and the LSU Agricultural Center (LAIS, 2010).

A daily 24-hr time step was used for the comparisons, given that most lysimeter data sets and calibrations have been done using daily time steps (Jensen et al., 1990). Additionally under many conditions, the application of the Penman-Monteith equation, including the standardized ASCE-EWRI (2005), employ 24-hour data sets, which produce accurate results when compared to sum-of-hourly ET₀ value (Allen et al., 1998; Itenfisu et al., 2003).

Daily reference evapotranspiration ET (mm day⁻¹) was computed using weather data for all four ET₀ methods during the growing-season. In this study, emphasis was placed on growing-season period comparisons because of its importance to agriculture, particularly sweetpotato. This stage is characterized by active vegetative growth pertaining to the reference ET computation (Itenfisu et al., 2003).

Quality control (QC) and integrity assessment criteria for the weather data sets were performed using guidelines suggested by Allen (1996) and Allen et al. (1998). All weather recordings were corrected manually for outlier values through comparisons with recordings to a nearby LAIS weather station. Additionally, the Double Mass Analysis technique was used, where cumulative sums of a
parameter from the two locations were plotted against one another. A change over time in the slope of the cumulative curve would indicate an instrument malfunction (Allen, 1996). The reliability of this method depends on the distance between the two stations and the variable being analyzed. Thus, for solar radiation over similar vegetation, a good correlation should be achieved over distances of hundreds of km in non-mountainous areas. Relative humidity and air temperature readings should give good correlations on distances between weather stations up to 100 km, as long as there are no abrupt changes in topography, land use, and weather. On the other hand, wind speeds are the least likely to correlate due to local site effects. The approximate distance between the station and the LAIS weather station was 0.6 km (0.4 miles).

For additional reliability, the pyranometer (solar radiation) readings were compared against short wave radiation under clear-sky conditions \( (R_{so}) \) as suggested by Allen et al. (2007). \( R_{so} \) is a function of the time of the year, elevation and the latitude of the station. Overall, the pyranometer measurements fitted the calculated clear-sky tendency. Moreover, the measured net radiation \( (R_n) \) was plotted against \( R_n \) estimated by the Hargreaves radiation formula, which is based on air temperature (Allen et al., 1998).

### 1.2-B-i SOIL WATER CONTENT SENSOR

A soil water probe (model: 5TE Decagon Devices, Inc.) was used to compute the soil volumetric water content. Fig. 1-1 provides a brief description of the components found in the 5TE; it has dimensions of 10 cm x 3.2 cm x 0.7 cm (3.94 in x 1.25 in x 0.28 in) with a prong length of 5.2 cm (2 in). The probe has an \( \varepsilon_a \) (apparent dielectric permittivity) range between 1 and 80 (air and water respectively) and operates at a frequency of 70 MHz. The device converts the raw dielectric permittivity values to volumetric water based on Topp’s Equation (Topp et al., 1980):
Figure 1-1: Decagon 5TE probe components.

\[ VWC = 4.3 \times 10^{-6} \varepsilon_a^3 - 5.5 \times 10^{-4} \varepsilon_a^2 + 2.92 \times 10^{-2} \varepsilon_a - 5.3 \times 10^{-2} \]

Equation 1-1: Topp's equation

where, VWC is the volumetric water content (m$^3$ m$^{-3}$), and $\varepsilon_a$ is the apparent dielectric permittivity.
The sensor is adapted for use with the automated data loggers from Campbell Scientific, Inc., making it possible to document soil volumetric water content variation. Additional information such as resolution, accuracy, measuring time and datalogger compatibility can be found at Decagon (2010) for volumetric water content (VWC), electrical conductivity (bulk) and temperature.

Two depths were chosen to represent the soil water content, 5.08 cm (2 in) and 15.24 cm (6 in). These two depths were proposed by Villordon et al. (2010) based on previous research and the development of a decision support system for sweetpotato production. The soil moisture sensors were installed vertically following the instructions from Decagon (2010); first digging a 10-cm diameter hole up to the previously established depths. The recorded average daily volumetric water content $\theta_i$ ($m^3 m^{-3}$) was then computed for each depth.

1.2-C DIRECT EVAPOTRANSPIRATION MEASUREMENTS USING SOIL WATER CONTENT PROBES

Evapotranspiration can be obtained from either direct field measurements or from estimates based on weather and crop data (Allen et al., 2007). In this study, soil volumetric water content sensors and a soil water balance (evapotranspiration-based) approach were employed to determine the real-time soil water conditions and the evapotranspiration rate. Estimates for irrigation water requirements (IR) are frequently done for short periods. These short term approximations were expressed using a soil water balance equation (Howell et al., 2007; Allen et al., 2007):

$$IR_n = ET_c - P_e - CR - \Delta \theta Z_s$$

Equation 1-2: Soil water balance.

where, $IR_n$ considers the contributions of the change in stored soil water $\Delta \theta$ ($m^3 m^{-3}$). This change was measured with the STE sensor. In this case $Z_s$ was the depth of soil experiencing the change in water content. The $ET_c$ value represented the actual sweetpotato evapotranspiration, which was calculated
by rearranging Equation 1-2 and considering net irrigation (IRn) embedded in the change of soil water content ∆θ.

For the purposes of this study, the following assumptions were made:

- During the growing season the water table was deep, thus there was no significant contribution from groundwater (CR);
- Deep percolation and canopy interception were assumed negligible when compared to precipitation and runoff at this site; and,
- At the end of each day, the water content of the root zone was uniformly distributed.

Reference evapotranspiration was deducted using the ETc previously calculated by means of the following equation:

\[
ET_c = ET_o (K_s K_c)
\]

**Equation 1-3: Reference Crop Evapotranspiration.**

where, \( K_s \) is a crop water stress reduction coefficient to account for the effects of soil water deficit (0-1), and \( K_c \) is the dimensionless crop coefficient function of the crop type and the growth stage. Table 1-2 provides a summarized list of grass-based \( K_c \) values for sweetpotato based on the annual crop development cycle and the crop growth stage length periods (L).

<table>
<thead>
<tr>
<th>Crop</th>
<th>( K_c ) ini</th>
<th>( L ) ini</th>
<th>( K_c ) mid</th>
<th>( L ) mid</th>
<th>( K_c ) end</th>
<th>( L ) end</th>
<th>Total</th>
<th>Plant date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sweetpotato</td>
<td>0.5</td>
<td>20</td>
<td>1.15</td>
<td>60</td>
<td>0.65</td>
<td>40</td>
<td>150</td>
<td>April</td>
</tr>
</tbody>
</table>

Where: \( K_c \): dimensionless crop coefficient; and \( L \): crop growth length period. The first row shows the \( K_c \), while the second row shows the growth stage in days.
The crop stress factor on the other hand was estimated using a logarithmic function (George et al. 2000) such as:

\[
K_s = \frac{\log\left(1 + 100(1 - \frac{D_r}{TAW})\right)}{\log 101}
\]

**Equation 1-4: Crop stress factor.**

where, \(TAW\) is total available soil water in the root zone, mm; and \(D_r\) is the root water depletion, mm.

Effective precipitation is the portion of total rainfall that assists in meeting the consumptive use requirements of growing crops. This precipitation will be intercepted by the leaves and stems and then distributed in relation to the canopy architecture (Howell et al., 2007). According to Allen et al. (2007), the depth of effective rainfall can be determined by subtracting surface runoff and it can be calculated using the USDA-NRCS (Schwab et al., 1993) curve number approach. Once the surface runoff depth was calculated, effective rainfall was determined with the following expression:

\[
P_{ef} = P - RO
\]

**Equation 1-5: Effective rainfall.**

where, \(P_{ef}\) is the effective rainfall (mm); \(P\) is the measured precipitation depth (mm); and \(RO\) is the depth of surface runoff (mm).

**1.2-D REFERENCE EVAPOTRANSPIRATION METHODS**

Four ET\(_o\) approximation models were used to compare reference evapotranspiration estimates to soil water data obtained from volumetric water content probe readings in northeastern Louisiana. The methods utilized were one combination, two radiation based and one temperature-based models. Table 1-3 summarizes the general characteristics and main parameters needed for each method. The weather station used was not located over a clipped grass reference surface (for a distance 100 times
the height of the wind, air temperature and relative humidity sensors in all directions), as recommended by Allen et al. (1998) for Reference Evapotranspiration estimates. The site did have an average wind run of 1000 m (3168 ft).

The estimated ET₀ values for each equation were calculated using a reference crop evapotranspiration calculator know as REF-ET and developed by Allen (2000). The REF-ET program is specifically written to perform reference ET calculations for a variety of commonly used equations. Additionally, the software has the ability to read a variety of data formats and site specifications (Itenfisu et al., 2003; Yoder et al., 2004). The specific methods used to predict net radiation, soil heat flux, aerodynamic and bulk resistances, and other coefficients needed in each method are described in the REF-ET manual (Allen, 2000). Processing all weather data with the same program assures consistency in the calculations.

Table 1-3. Characteristics of methods for estimating ET₀ (Adapted from Amatya et al., 1995)

<table>
<thead>
<tr>
<th>Method</th>
<th>Main parameters required</th>
<th>Recommended time period</th>
<th>Reference Crop</th>
<th>Location developed for</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASCE Penman-Monteith</td>
<td>T, RH, u₂, Rᵣ, rₑ</td>
<td>Hourly, daily, weekly, monthly</td>
<td>Any</td>
<td>All locations</td>
</tr>
<tr>
<td>Priestley-Taylor</td>
<td>T, Rᵣ</td>
<td>10 days, monthly</td>
<td>Rain-fed land</td>
<td>Australia, US</td>
</tr>
<tr>
<td>Turc</td>
<td>T, RH, Rₛ</td>
<td>10 days, monthly</td>
<td>Grass</td>
<td>Cool climate, Europe</td>
</tr>
<tr>
<td>Hargreaves</td>
<td>Tₘₐₓ, Tₘᵢₙ, T, Rₐ</td>
<td>Weekly, monthly</td>
<td>Cool season grass</td>
<td>Semiarid Western US</td>
</tr>
</tbody>
</table>

Where T: temperature (°C), RH: relative humidity (%), u₂: wind (m s⁻¹), Rᵣ: net radiation (MJ m⁻² d⁻¹), Rₛ: solar radiation (MJ m⁻² d⁻¹), rₑ: canopy resistance (s m⁻¹), Tₘₐₓ: max temperature (°C), Tₘᵢₙ: min temperature (°C) and Rₐ: extraterrestrial radiation (MJ m⁻² d⁻¹).
1.2-D-i ASCE-EWRI PENMAN-MONTEITH MODEL

The ASCE-EWRI standardized reference equation is derived from the full-form ASCE Penman-Monteith equation (Jensen et al., 1990). For daily computations a hypothetical short reference crop (grass) is used with a height of 0.12 m, a fixed surface resistance of 70 s m\(^{-1}\) and an albedo of 0.23; closely resembling the evapotranspiration from an extensive surface of green grass cover of uniform height, actively growing and not short of water (Allen et al., 2007). When site vegetation is much taller than the 0.1-0.2 m range, the full ASCE Penman-Monteith equation (Itenfisu et al., 2003) is recommended. The ASCE-EWRI (2005) standardized Penman-Monteith method can be expressed as follows:

\[
ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{C_n}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)}
\]

**Equation 1-6: Standardized Penman-Monteith equation.**

where, \(ET_o\) is the reference evapotranspiration (mm d\(^{-1}\) for daily time steps); \(R_n\) is the net radiation at the crop surface (MJ m\(^{-2}\)d\(^{-1}\)); \(G\) is the soil heat flux density (MJ m\(^{-2}\)d\(^{-1}\)); \(T\) the mean daily air temperature (°C); \(u_2\) the mean daily wind speed at 2-m height (m s\(^{-1}\)); \(e_s\) is the saturation vapor pressure (kPa), calculated for daily time steps as the average of saturation vapor pressure at maximum and minimum air temperature; \(e_a\) is the mean actual vapor pressure at (kPa); \(\Delta\) is the slope of the saturation vapor pressure temperature curve (kPa °C\(^{-1}\)); \(\gamma\) is the psychrometric constant (kPa °C\(^{-1}\)); \(C_n\) is the numerator constant that changes with reference type and calculation time step (K mm s\(^{3}\) Mg\(^{-1}\) d\(^{-1}\)); \(C_d\) is the denominator constant that changes with reference type and calculation step (s m\(^{-1}\)); finally the units for the 0.408 coefficient are m\(^2\) mm M J\(^{-1}\). Detailed descriptions of all the parameters can be found in Allen et al. (1998) and ASCE-EWRI (2005).
For the purposes of this research, $C_n$ and $C_d$ had constant values of 900 and 0.34 respectively, according to the recommendations by ASCE-EWRI (2005) for daily time steps. On daily time steps the nature of the climate system allows for the soil heat flux term $G$, to be disregarded (Allen et al., 1998; ASCE-EWRI, 2005). In this study, the soil heat flux was assumed to be zero.

1.2-D-ii PRIESTLEY-TAYLOR MODEL

The 1972 Priestley-Taylor equation is a shortened version of the original 1948 Penman combination equation (Jensen et al., 1990). It is based on the assumption that the effect of turbulence is small compared to the effect of radiation (Pauwels and Samson, 2005). Such conditions can happen when the air becomes saturated, which leads to an equilibrium evaporation. The Priestley-Taylor equation was described by Jensen et al. (1990) as:

$$
ET_o = \alpha \frac{\Delta}{\Delta + \gamma} \frac{(R_n - G)}{\lambda}
$$

Equation 1-7: Priestley-Taylor equation.

where, $ET_o$ is reference evapotranspiration (mm day$^{-1}$), $\alpha$ is a dimensionless proportionality coefficient to compensate for true equilibrium conditions rarely existing (Priestley and Taylor, 1972), $\Delta$ is the slope of the saturation vapor pressure-temperature curve (kPa°C$^{-1}$); $\gamma$ is the psychrometric constant (kPa °C$^{-1}$); $\lambda$ is latent heat of vaporization (MJ kg$^{-1}$); $R_n$ is the net radiation at the crop surface (MJ m$^{-2}$ d$^{-1}$) and $G$ is the soil heat flux (MJ m$^{-2}$ day$^{-1}$). A value of 1.26 was assigned to the coefficient $\alpha$, which may be modified for different wind and humidity conditions. The constant 1.26 is reasonable across most climates (Fontenot, 2004).

1.2-D-iii TURC MODEL

The Turc reference evapotranspiration model was originally designed for use in the Netherlands
(Turc, 1961). This method ranks second globally for use in the humid climate, following the Penman-Monteith model, and the best among other radiation methods for estimating mean monthly $ET_o$ according to Jensen et al. (1990). Allen (2000) defined the Turc as:

$$ET_o = a_T \times 0.013 \frac{T_{\text{mean}}}{T_{\text{mean}} + 15} \frac{23.8856R_s + 50}{\lambda}$$

**Equation 1-8: Turc equation.**

where, $ET_o$ is reference evapotranspiration (mm day$^{-1}$), $T_{\text{mean}}$ is the mean daily air temperature ($^\circ$C), $R_s$ is the incoming solar radiation (MJ m$^{-2}$ day$^{-1}$), and $\lambda$ is the latent heat of vaporization (MJ kg$^{-1}$). The coefficient $a_T$ is a humidity-based value: if the mean daily relative humidity ($RH_{\text{mean}}$) is greater than or equal to 50%, then $a_T = 1.0$. If the mean daily relative humidity was less than 50% then $a_T$ was determined as follows:

$$a_T = 1 + \frac{50 - RH_{\text{mean}}}{70}$$

**Equation 1-9: Humidity-based coefficient $a_T$ for Turc model.**

### 1.2-D-iv HARGREAVES MODEL

The Hargreaves and Samani equation is a simple, empirical radiation-based approach that has been used in cases where the availability of weather data is limited. Allen et al. (1998) proposed that when sufficient data to solve the FAO-56 Penman-Monteith are not available, then the Hargreaves equation can be used. The equation used is expressed as (Hargreaves and Samani, 1985):

$$ET_o = 0.0023(T_{\text{mean}} + 17.8)(T_{\text{max}} - T_{\text{min}})^{0.5} R_a$$

**Equation 1-10: Hargreaves equation.**

where, $ET_o$ is reference evapotranspiration (mm day$^{-1}$), $R_a$ is the water equivalent of extraterrestrial radiation (mm day$^{-1}$), $T_{\text{mean}}$ is the mean air temperature ($^\circ$C), $T_{\text{max}}$ is the daily maximum temperature...
\( T_{\text{min}} \) \( ^\circ \text{C} \), and \( T_{\text{min}} \) is the daily minimum temperature \( ^\circ \text{C} \).

### 1.2-E EVALUATION PARAMETERS

Several performance routines can be considered to analyze the relationship of the ET\(_o\) models to the estimates of soil water content from the 5TE probe. In this study, comparisons were made using cumulative graphs as well as the following criteria: mean absolute error (MAE), and the coefficient of efficiency (\( E_f \)). MAE measures the average difference, using the absolute difference thus reducing the sensitivity to extreme differences. MAE is calculated as:

\[
\text{MAE} = k^{-1} \sum_{i=1}^{k} (|P_i - O_i|)
\]

**Equation 1-11: Mean absolute error.**

where, \( \text{MAE} \) is the mean absolute error (mm day\(^{-1}\)); \( O_i \) is the \( i^{th} \) ET observed data, measured by the 5TE probe; \( P_i \) is the \( i^{th} \) estimated data by the ET\(_o\) models; and \( k \) is the total number of observations.

The coefficient of efficiency (\( E_f \)) examines whether the difference between the estimated and measured data is as large as the variability in the measured data. Values range between \([-\infty - 1]\); with higher values indicating better agreement between the estimated and measured data (Yoder *et al.*, 2004). \( E_f \) is calculated as:

\[
E_f = 1 - \frac{\sum_{i=1}^{k} (O_i - P_i)^2}{\sum_{i=1}^{k} (O_i - \bar{O})^2}
\]

**Equation 1-12: Coefficient of efficiency.**

where, \( O_i \) is the \( i^{th} \) ET observed data, measured by the 5TE probe; \( P_i \) is the \( i^{th} \) estimated data by the ET\(_o\) models; \( \bar{O} \) is average of the observed data, and \( k \) is the total number of observations.
1.3 RESULTS

The comparisons and analysis of reference ET equations and measured ET were based considering the DAT of sweetpotato and the depth of the soil water monitoring sensors. In this study emphasis was given to the growing season because of the importance of this period to sweetpotato. Furthermore, according to Villordon et al. (2010) within 20 DAT a relationship exists between agroclimatic variables and U.S#1 sweetpotato yield. U.S. No. 1 grade storage roots consist of elliptical roots 8 to 23 cm in length and 5 to 9 cm diameter, as well as few small or oversized (jumbos) roots (Villordon et al., 2009). The measured volumetric water content against the DAT at both depths is given in Fig. 1-2.

The results of the statistical analysis for each equation against the measured evapotranspiration via the soil monitoring probes are presented in Table 1-4. The best model was selected based primarily on the lowest MAE, followed by the highest coefficient of efficiency for the 2010 growing season of sweetpotato in Northeast Louisiana.

The MAE values obtained for all the models, during the time frames and depths selected, exceeded 1.0 mm d\(^{-1}\), implying that the equations fail to provide an accurate estimate of actual evapotranspiration when compared to the output from the soil moisture probes. An error of only 1 mm d\(^{-1}\) of ET on a 1 ha field accounts for approximately 10 m\(^3\) (2641 gallons) of water per day (Fontenot, 2004).

For the first 30 DAT at a depth of 5 cm (soil water probe), the Turc model showed the lowest MAE 5.13 mm d\(^{-1}\) as well as the highest coefficient of efficiency \(E_f = -0.61\). For interpretation, if \(E_f = 0\), there’s a good estimation from the model regarding the observed ET value. Turc was followed by the ASCE-EWRI Penman-Monteith equation with an MAE of 5.63 mm d\(^{-1}\) and by the Hargreaves-Samani
Figure 1-2: Measured soil water content by 5TE sensors at 5 cm and 15 cm depths.

Table 1-4. Statistical analysis of estimated vs. observed evapotranspiration.

<table>
<thead>
<tr>
<th>Model</th>
<th>Time period</th>
<th>Depth (cm)</th>
<th>MAE (mm day$^{-1}$)</th>
<th>$E_f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASCE-EWRI Penman-Monteith</td>
<td>30 DAT</td>
<td>5</td>
<td>5.63</td>
<td>-0.79</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>5.50</td>
<td>-0.77</td>
</tr>
<tr>
<td></td>
<td>Growing season</td>
<td>5</td>
<td>5.38</td>
<td>-0.37</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>5.00</td>
<td>-1.17</td>
</tr>
<tr>
<td>Hargreaves-Samani</td>
<td>30 DAT</td>
<td>5</td>
<td>5.65</td>
<td>-0.75</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>5.52</td>
<td>-0.73</td>
</tr>
<tr>
<td></td>
<td>Growing season</td>
<td>5</td>
<td>5.67</td>
<td>-0.41</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>5.31</td>
<td>-1.34</td>
</tr>
<tr>
<td>Priestley-Taylor</td>
<td>30 DAT</td>
<td>5</td>
<td>5.65</td>
<td>-0.79</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>5.53</td>
<td>-0.78</td>
</tr>
<tr>
<td></td>
<td>Growing season</td>
<td>5</td>
<td>4.96</td>
<td>-0.28</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>4.58</td>
<td>-0.92</td>
</tr>
<tr>
<td>Turc</td>
<td>30 DAT</td>
<td>5</td>
<td>5.13</td>
<td>-0.61</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>5.04</td>
<td>-0.59</td>
</tr>
<tr>
<td></td>
<td>Growing season</td>
<td>5</td>
<td>4.88</td>
<td>-0.28</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>4.49</td>
<td>-0.86</td>
</tr>
</tbody>
</table>

Where: Depth: STE sensor depth, MAE: mean absolute error, and $E_f$: coefficient of efficiency.
with an $E_f = -0.75$. The least effective model for 30 DAT / 5 cm use is the Priestley-Taylor equation having an MAE of 5.65 mm d$^{-1}$ and $E_f = -0.79$. Fig. 1-3 shows the cumulative behavior of the models and the soil water sensors.

The lowest MAE and highest $E_f$ for 30 DAT and a depth of 15 cm were achieved by the Turc model with 5.04 mm d$^{-1}$ and -0.59, respectively; outperforming the rest of the models. The lowest agreement was made by the Priestley-Taylor with $E_f$=-0.78 and MAE = 5.53 mm d$^{-1}$. The cumulative performance of the models and the soil water sensors 30 DAT and with the sensor installed at 15 cm is given in Fig. 1-4.

The results obtained for the entire growing season showed that all of the models had lower MAE values than at 30 DAT, except for the Hargreaves-Samani. However they were still over 1 mm d$^{-1}$ clearly overestimating $ET_o$. Overall the Turc equation performed better than the rest, with MAE results of 4.49 mm d$^{-1}$ and 4.88 mm d$^{-1}$, at 5 cm and 15 cm depth respectively. It was followed by the Priestley-Taylor model with 4.96 mm d$^{-1}$ (5 cm) and 4.58 mm d$^{-1}$ (15 cm). The Hargreaves-Samani had the greatest MAE values for the growing season. In terms of the coefficient of efficiency, the best equation fit was completed by the Turc model at both depths. Figures 1-5 and 1-6 illustrate the cumulative reference ET during the growing season for 5 cm and 15 cm soil water probe depths respectively.

1-4 DISCUSSION

Based on the obtained MAE values (Table 1-4), all the models failed in general to accurately estimate reference ET when compared to the measured $ET_o$. On average, Turc had the best agreement with the observed daily reference evapotranspiration. These results are in agreement with other studies for humid climate (Jensen et al., 1990; Amatya et al., 1995, Fontenot, 2004).
Figure 1-3: Cumulative $E_{T_o}$ at 30 DAT and 5TE sensor at 5 cm depth.


Figure 1-4: Cumulative $E_{T_o}$ at 30 DAT and 5TE sensor at 15 cm depth.

Figure 1-5: Cumulative $\text{ET}_o$ for the growing season and 5TE sensor at 5 cm depth. Where 5TE: sensor at 5 cm depth, P-M: ASCE Penman-Monteith, Turc: Turc model, Hargr: Hargreaves, and P-T: Priestley-Taylor.

Figure 1-6: Cumulative $\text{ET}_o$ for the growing season and 5TE at 15 cm depth. Where 5TE: sensor at 15 cm depth, P-M: ASCE Penman-Monteith, Turc: Turc model, Hargr: Hargreaves, and P-T: Priestley-Taylor.
On the other hand, the rest of the models presented similar MAE and \( E_f \) values for the time frames and depths selected. The results demonstrated that the Hargreaves-Samani equation had the lowest correlation with measured \( ET_o \); again demonstrating good agreement with previous findings for humid locations (Jensen et al. 1990).

The high MAE and \( E_f \) results obtained for the \( ET_o \) models (Table 1-4), can be attributed in part to the unsaturated soil-water conditions presented in the experimental plots, which were extremely low for the soil type in the area (Fig. 1-2). Unsaturated soil conditions are often complicated and difficult to describe quantitatively, where soil-water is subject to a sub-atmospheric pressure, which is equivalent to a negative pressure potential (Hillel, 2004). These circumstances affect the water flow in the soil, thus diminishing the soil conductivity, making it harder for water to move across the soil matrix and increasing tortuosity. Therefore, processes such as evapotranspiration, which are directly related to water movement across a soil profile, were affected by the lack of wetness and excessive suction in the experimental plots.

In the case of the first 30 DAT, the soil moisture content was far from saturation, having 13% average soil water content at both depths, which is below 50% Field Capacity for this soil type. Following the first 30 DAT, the soil volumetric water content averaged for the monitoring depths of 5 cm and 15 cm, 10.2% and 10.1% respectively, approximately the Permanent Wilting Point for silt loam.

During the 2010 growing season, a total precipitation of 325.1 mm was measured, which represents 51.2% of the historical average reported by the US Historical Climatology Network. Most likely the available soil-water was under great suction, thus being unreachable to the plants.

Additionally, the reference models employed are set to be used over a reference surface with specific characteristics as recommended by Allen et al. (1998), for convenience and reproducibility.
Such features are a dense crop, actively growing, not short of soil water and representing an expanse of at least 100 m (ASCE-EWRI, 2005). However, these conditions weren’t present during the experiment as previously described.

Other sources of error might occur when determining ET over a small area or group of plants with the capacitance STE sensors. According to Allen et al. (2007), calculating ET over a small group of plants will misrepresent ET\textsubscript{o} for a wider area. Furthermore, capacitance sensors are less consistent and show sensitivity to the electrical conductivity and temperature of irrigated soils, even when using soil-specific calibrations (Farahani et al., 2007). Finally, the extraction by deep roots and soil disturbance during sensor placement increases the uncertainty of the calculations. Given all these circumstances, such comparisons between ET\textsubscript{o} models and soil-water content sensors are difficult or not reasonable to perform.

1-5 CONCLUSIONS

Pair-wise comparisons were made between daily ET\textsubscript{o} estimated with four reference ET\textsubscript{o} models, and ET\textsubscript{o} determined from soil water monitoring sensors at two depths, over ‘Beauregard’ sweetpotato plots in Northeast Louisiana. The results indicated that in general, all the models failed to accurately predict ET\textsubscript{o} when compared to the measured ET\textsubscript{o}.

Overall, the 1961 Turc model was the best method for the weather and soil conditions presented in the experimental plots, with MAE values of 5.13 and 5.04 mm day\textsuperscript{-1} for the first 30 DAT and 4.88 and 4.49 mm day\textsuperscript{-1} for the entire growing season, at 5 cm and 15 cm, respectively. The Turc model was followed by the ASCE-EWRI Penman-Monteith equation for the first 30 DAT time frame (5.38 and 5.00 mm day\textsuperscript{-1}) and the Priestley-Taylor method (4.96 and 4.58 mm day\textsuperscript{-1}) for the entire growing season. Low correlation was found between the measured ET\textsubscript{o} and Hargreaves-Samani
The Turc approach is an attractive alternative to more complex methods, which require more input parameters that might not be available in all weather stations.

The unsaturated conditions presented in the field inhibited normal water movement across the soil matrix, slowing down processes such as evapotranspiration. These conditions, in addition to inaccuracies of the capacitance probes measurements, increased the level of uncertainty when representing reference evapotranspiration in the study area.

It is highly recommended that the direct measurement of ET data through the soil-water budget approach should be done considering a bigger experimental area (increase the number of soil VWC sensors) and under the appropriate soil-water conditions, as recommended by Allen et al. (1998) and Allen et al. (2007). Following these suggestions, the ET output will reflect the soil water movement more accurately for the area and conditions been studied.

1-6 REFERENCES


CHAPTER 2: EVALUATION OF DAILYREFERENCE EVAPOTRANSPERSION ET\textsubscript{o}
METHODS AS COMPARED TO THE ASCE-EWRI PENMAN-MONTEITH
EQUATION USING LIMITED WEATHER DATA IN NORTHEAST LOUISIANA

2.1 INTRODUCTION

Evapotranspiration (ET) is the loss of water to the atmosphere by the combined processes of
 evaporation from soil and plant surfaces, and plant transpiration (Temesgen et al., 2004). The rate of
evapotranspiration is based on the atmospheric water demand and the surface characteristics (Itenfisu
et al., 2003); because of the interdependence of these factors and the spatial and temporal variability,
it is basically implausible to develop a model that will fully account for various crops under different
environmental conditions. Consequently, a series of reference ET models have been developed by
researchers and practitioners using historic and current meteorological data.

Reference Evapotranspiration (ET\textsubscript{o}) has been defined as the rate of evapotranspiration from a
hypothetical reference crop as characterized by Allen et al. (1998), having a fixed height, surface
resistance and reflection coefficient. This reference surface is independent of vegetation and soil
characteristics, allowing for the analysis of only meteorological factors, thus simplifying the calculation
of ET (Allen et al., 1998). Accurate estimates of ET\textsubscript{o} are a fundamental part of crop production, water
resources management, and environmental assessments (Trajkovic, 2007).

ET\textsubscript{o} models can be divided into three categories: temperature based, radiation based and
combination based (combines elements of the energy budget and mass transfer models). The
combination Penman-Monteith approach was ranked by Jensen et al. (1990) as the top equation for
estimating daily and monthly reference ET\textsubscript{o} in their lysimeter evaluation; moreover, it was adopted as
the standard method for computation of ET\textsubscript{o} by the Food and Agricultural Organization of the United
Nations FAO (Allen et al., 2007). In addition, the ASCE-EWRI Task committee recommended a standardized Penman-Monteith $E_T_0$ equation for two reference surfaces, along with computational procedures (ASCE-EWRI, 2005).

The mayor limitation for the Penman-Monteith equation is its requirement of numerous meteorological inputs that are often incomplete and/or unavailable (Jabloun and Sahli, 2008). Thus, Allen et al. (1998) recommended some procedures to estimate the missing parameters, such as wind speed and solar radiation.

In the absence of certain weather data, it is recommended to apply empirical $E_T_0$ equations, popular for their simplicity and fewer inputs. The 1985 Hargreaves-Samani approach was proposed by Allen et al. (1998) as an alternative when sufficient data to solve the Penman-Monteith equation are not available. It requires only data for maximum and minimum temperature, with extraterrestrial radiation calculated as a function of latitude and day of the year (Yoder et al., 2004). However, under humid locations this equation generally overestimates $E_T_0$ (Jensen et al., 1990; Amatya et al., 1995; Trajkovic, 2007).

The 1972 Priestley-Taylor and the 1961 Turc equations are other frequently used methods requiring only air temperature and solar irradiance as inputs. The Priestley-Taylor model was designed to be used in very humid areas, where surfaces were usually wet (Jensen et al., 1990); while the Turc equation is ranked second at humid conditions (Jensen et al., 1990; Trajkovic et al., 2009). In earlier studies, the ranking of these empirical methods varied depending on local calibration and conditions (Yoder et al., 2004).

Few studies have been conducted to evaluate the performance of these $E_T_0$ methods in Louisiana. Fontenot (2004) tested six daily and monthly reference evapotranspiration models (FAO-24
Radiation, FAO-24 Blaney-Criddle, 1985 Hargreaves-Samani, 1972 Priestley-Taylor, 1957 Makkink and 1961 Turc) against values computed with the FAO-56 Penman-Monteith equation. The results indicated that the 1961 Turc model was the most accurate model in estimating daily and monthly ET₀ in Louisiana. Shah and Edling (2000), evaluated the performance to predict rice ET of the Penman-Monteith, FAO-Penman, and 1963 Penman models in Louisiana; however the study focused on one particular location for a short period of time. No published studies have examined the behavior of ET₀ models using limited weather data in Louisiana, particularly the northeast part of the state.

The objective of this study was to examine daily reference evapotranspiration estimates under Northeast Louisiana conditions using limited weather data. This was achieved by evaluating two reduced-set Penman-Monteith approaches, the Hargreaves-Samani, Priestley-Taylor, and Turc models as compared to the full-set ASCE-EWRI Penman-Monteith equation.

2.2 MATERIALS AND METHODS

2.2-A STUDY AREA

The weather data used in this study were measured on experimental fields which are part of Louisiana State University Agricultural Center Sweetpotato Research Station, situated approximately 8 km (5 miles) south of Winnsboro, LA (Franklin Parish).

The site is located at an elevation of 22 m above MSL and lies at latitude 32°06’N and longitude 91°42’W. Franklin Parish historically has long, hot summers due to moist tropical air moving from the Gulf of Mexico; winters are cool and fairly short. Precipitation is fairly heavy throughout the year and prolonged droughts are rare. During the summer, precipitation consists mainly of afternoon thundershowers (Martin et al., 1981). The sun shines 60 percent of the time in summer and 50 percent
during winter. The prevailing wind is from the south with an average high wind speed being 3.57 meters per sec (8 miles per hour) during spring.

During the experiment (May to October 2010), the weather conditions on average had a temperature of 27.2 °C (80.9 F), relative humidity of 80 percent, wind speed 1.71 m s\(^{-1}\) (3.83 mph), and a total precipitation of 325.12 mm (12.8 in) during the growing season.

### 2.2-B DATA MEASUREMENTS

The data sets used in this analysis were obtained from automated weather stations measuring climate variables such as air temperature (T), wind speed (\(u_2\)), relative humidity (RH) and solar irradiance (\(R_s\)). The output information was then used to estimate reference evapotranspiration with different models.

A station labeled HE was equipped with standard measuring devices for \(ET_o\) estimates as indicated by ASCE-EWRI (2005) and Allen \textit{et al.} (1998). Air temperature and relative humidity were measured with a thermoelectric sensor (model: HMP45C – Campbell Scientific, Inc./Vaisala); wind speed was measured at 2 m with an anemometer (model: 05305 - RM Young Wind Monitor); finally solar radiation was determined using a silicon photovoltaic pyranometer (model: LI-COR LI200X – Campbell Scientific, Inc.), which computes incoming shortwave (i.e. solar) radiation (\(R_s\)). The station was powered by a 10-Watt solar panel (model: SP10 - Campbell Scientific, Inc.) and a battery (model: PS100 - Campbell Scientific, Inc.). The use of trademarks in this publication does not imply endorsement of the products listed nor criticism of similar products not mentioned.

In addition, a second station labeled LE was installed with limited weather inputs, namely a thermoelectric air temperature and a relative humidity probe (model: HMP45 – Campbell Scientific,
Inc.), powered with a 10-Watt solar panel (model: SP10 - Campbell Scientific, Inc.) and a battery (model: PS100 - Campbell Scientific, Inc.).

All the meteorological inputs were sampled at three-second intervals and recorded at 1-minute, 1-hour, and 24-hour averages by data loggers (Campbell Scientific, Inc.); model: CR-1000 for Station HE and model: CR-10X for Station LE. Data was then transmitted to the LSU AgCenter, through the Louisiana Agriculture Information System (LAIS). The LAIS is a statewide network primarily dedicated to collecting meteorological data for use predominately by agriculture and engineering communities and is operated by the Department of Biological and Agricultural Engineering part of the Louisiana State University Agricultural Center (LAIS, 2010).

A daily 24-hr time step was used for the comparisons, since under a variety of conditions application of the Penman-Monteith equation, including the standardized ASCE-EWRI (2005), produced accurate results when compared to sum-of-hourly ET<sub>o</sub> values (Allen et al., 1998; Itenfisu et al., 2003).

Daily reference evapotranspiration ET<sub>o</sub> (mm day<sup>-1</sup>) was computed using weather data for all four ET<sub>o</sub> methods during the growing-season stage. In this study, emphasis was placed on the growing-season because of the importance to agriculture, particularly sweetpotato. This period is characterized by active vegetative growth pertaining to the reference ET computation (Itenfisu et al., 2003).

Quality control (QC) and integrity assessment criteria for the weather data sets were performed using guidelines suggested by Allen (1996) and Allen et al. (1998). All weather recordings were corrected manually for outlier values through comparisons to recordings from a nearby station part of the LAIS network. The Double Mass Analysis technique was used, where cumulative sums of a parameter from the two locations were plotted against one another. A change over time in the slope of the cumulative curve would indicate an instrument malfunction (Allen, 1996). The reliability of this
method depends on the distance between the two stations and the variable being analyzed. Thus, for
solar radiation a good correlation can be achieved over hundreds of km above similar vegetation, in
non-mountainous areas. For relative humidity and air temperature distances between weather
stations up to 100 km, should provide good correlations, as long as there are no abrupt changes in
topography, land use, and weather. On the other hand, wind speed is the least likely to correlate due
to local site effects and conditions. The approximate distance between the stations and the LAIS
weather station was 0.6 km (0.4 miles).

For additional reliability, the pyranometer (solar radiation) readings were compared against
short wave radiation under clear-sky conditions \(R_{so}\) as suggested by Allen et al. (2007). \(R_{so}\) is a
function of the time of the year, elevation and the latitude of the station. Overall, the pyranometer
measurements fitted the calculated clear-sky tendency. Moreover, the measured net radiation \(R_n\) was
plotted against \(R_n\) estimated by the Hargreaves radiation formula, which is based on air temperature
(Allen et al., 1998).

### 2.2-C Reference Evapotranspiration Methods

Two radiation based \(E\)\(_{t0}\) models (1972 Priestley-Taylor and 1961 Turc), one temperature-based
method (1985 Hargreaves-Samani) and two reduced data-set ASCE-EWRI Penman-Monteith
approaches were used to compare daily reference evapotranspiration to the full data-set ASCE-EWRI
Penman-Monteith model (2005). \(E\)\(_{t0}\) was calculated using limited weather data (only temperature and
relative humidity as measured inputs) and complete weather data (temperature, relative humidity,
solar radiation and wind speed) in Northeast Louisiana.

Table 2-1 summarizes the general characteristics and main parameters needed for each
method. The weather stations used were not located over a clipped grass reference surface (for a
distance 100 times the height of the wind, air temperature and relative humidity sensors in all
directions), as recommended by Allen et al. (1998) for Reference Evapotranspiration estimates.

The estimated ET<sub>o</sub> values for each model were determined using a reference crop
evapotranspiration calculator known as REF-ET and developed by Allen (2000). The REF-ET software
was specifically written to perform reference ET calculations for a variety of commonly used equations.
Additionally, it has the ability to read a variety of data formats and site specifications (Itenfisu et al.,
2003; Yoder et al., 2004). The specific methods used to predict net radiation, soil heat flux,
aerodynamic and bulk resistances, and other coefficients needed in each method are described in the
REF-ET manual (Allen, 2000). Processing all weather data with the same program helped to assure
consistency in calculations.

Table 2-1. Characteristics of methods for estimating ET<sub>o</sub> (Adapted from Amatya et al., 1995).

<table>
<thead>
<tr>
<th>Method</th>
<th>Main parameters required</th>
<th>Recommended time period</th>
<th>Reference Crop</th>
<th>Location developed for</th>
</tr>
</thead>
<tbody>
<tr>
<td>Penman-Monteith</td>
<td>T, RH, u&lt;sub&gt;2&lt;/sub&gt;, R&lt;sub&gt;n&lt;/sub&gt;, r&lt;sub&gt;c&lt;/sub&gt;</td>
<td>Hourly, daily, weekly, monthly</td>
<td>Any</td>
<td>All locations</td>
</tr>
<tr>
<td>Priestley-Taylor</td>
<td>T, R&lt;sub&gt;n&lt;/sub&gt;</td>
<td>10 days, monthly</td>
<td>Rain-fed land</td>
<td>Australia, US</td>
</tr>
<tr>
<td>Turc</td>
<td>T, RH, R&lt;sub&gt;s&lt;/sub&gt;</td>
<td>10 days, monthly</td>
<td>Grass</td>
<td>Cool climate, Europe</td>
</tr>
<tr>
<td>Hargreaves</td>
<td>T&lt;sub&gt;max&lt;/sub&gt;, T&lt;sub&gt;min&lt;/sub&gt;, T, R&lt;sub&gt;a&lt;/sub&gt;</td>
<td>Weekly, monthly</td>
<td>Cool season grass</td>
<td>Semiarid Western US</td>
</tr>
</tbody>
</table>

Where T: temperature (°C), RH: relative humidity (%), u<sub>2</sub>: wind (m s<sup>-1</sup>), R<sub>n</sub>: net radiation (MJ m<sup>-2</sup>d<sup>-1</sup>), R<sub>s</sub>: solar radiation (MJ m<sup>-2</sup>d<sup>-1</sup>), r<sub>c</sub>: canopy resistance (s m<sup>-1</sup>), T<sub>max</sub>: max temperature (°C), T<sub>min</sub>: min temperature (°C) and R<sub>a</sub>: extraterrestrial radiation (MJ m<sup>-2</sup>d<sup>-1</sup>).
2.2-C-i PROCEDURES FOR ESTIMATING MISSING DATA

The main shortcoming of the ASCE-EWRI Penman-Monteith equation is that it requires several weather inputs that frequently are not available for many locations (Trajkovic and Kolakovic, 2009). As mentioned before, Allen et al. (1998) recommended procedures to estimate missing weather data. In the absence of radiation measurements via pyranometers and net radiometers, solar radiation can be estimated using the difference between the maximum and minimum air temperature as an indicator of the fraction of extraterrestrial radiation reaching the surface (Allen et al., 1998; Allen 2000). This relationship is known as the Hargreaves’ radiation formula:

\[ R_s = k_{RS} \sqrt{(T_{max} - T_{min})R_a} \]

Equation 2-1: Hargreaves radiation equation.

where, \( R_s \) is the solar radiation (MJm\(^{-2}\)d\(^{-1}\)); \( R_a \) is extraterrestrial radiation (MJm\(^{-2}\)d\(^{-1}\)); \( T_{max} \) and \( T_{min} \) are maximum and minimum air temperature (°C), respectively; and \( k_{RS} \) is an adjustment coefficient. Allen et al. (1998) recommended using a value for \( k_{RS} \) equal to 0.16 for interior locations.

Two approaches to estimate wind speed were utilized; the first approach used wind data imported from a nearby LAIS station, specifically the Sweetpotato weather station (LAIS, 2010). The second method consisted on using the global default wind speed of 2 m s\(^{-1}\) (Allen et al., 1998; Allen, 2000). This value is the average of over 2000 weather stations around the globe (Jabloun and Sahli, 2008).

2.2-C-ii ASCE-EWRI PENMAN-MONTEITH MODEL

The ASCE-EWRI standardized reference equation is derived from the full-form ASCE Penman-Monteith (Jensen et al., 1990). For daily computations a hypothetical short reference crop (grass) is used with a height of 0.12 m, a fixed surface resistance of 70 s m\(^{-1}\) and an albedo of 0.23; closely
resembling the evapotranspiration from an extensive surface of green grass cover of uniform height, actively growing and not short of water (Allen et al., 2007). On the other hand, for grass/forage or alfalfa reference (ET$_{rs}$) the height is fixed at 0.5 m and the surface resistance is equal to 45 s m$^{-1}$ for daily calculation. The ASCE-EWRI (2005) standardized Penman-Monteith method can be expressed as follows:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{C_n}{T + 273}u_2(e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)}$$


where, $ET_o$ is the reference evapotranspiration (mm d$^{-1}$); $R_n$ is the net radiation at the crop surface (MJ m$^{-2}$d$^{-1}$); $G$ is the soil heat flux density (MJ m$^{-2}$d$^{-1}$); $T$ the mean daily air temperature (°C); $u_2$ the mean daily wind speed (m s$^{-1}$); $e_s$ is the saturation vapor pressure (kPa), calculated for daily time steps as the average of saturation vapor pressure at maximum and minimum air temperature; $e_a$ is the mean actual vapor pressure at (kPa); $\Delta$ is the slope of the saturation vapor pressure temperature curve (kPa°C$^{-1}$); $\gamma$ is the psychrometric constant (kPa °C$^{-1}$); $C_n$ is the numerator constant that changes with reference type and calculation time step (K mm s$^{-3}$ Mg$^{-1}$ d$^{-1}$); $C_d$ is the denominator constant that changes with reference type and calculation step (s m$^{-1}$); finally the units for the 0.408 coefficient are m$^2$ mm MJ$^{-1}$.

For the purposes of this research, $C_n$ and $C_d$ will have constant values of 900 and 0.34 respectively according to the recommendations by ASCE-EWRI (2005) for daily time steps. On daily time steps the nature of the climate system allows for the soil heat flux term, $G$ to be disregarded (Allen et al., 1998; ASCE-EWRI, 2005). In this study the soil heat flux was assumed to be zero. The measurement height for the temperature and humidity sensors is expected to be in the range of 1.5 to
2.5 m, while the wind measurement is set at 2 m height. Detailed descriptions of all the parameters can be found in Allen et al. (1998) and ASCE-EWRI (2005).

Besides using the full data-set ASCE P-M equation, two limited data-set approaches were considered. The first method (ASCE PM_{SP}) used Equation 2-1 to calculate net radiation (R_n) and utilized wind speed data imported from the LAIS-Sweetpotato weather station, approximately 0.6 km (0.4 miles) away from the experimental site. A second approach (ASCE PM_{W2}) employed Equation 2-1 for net radiation (R_n) and used the global wind speed average (2 m s^{-1}).

### 2.2-C-iii PRIESTLEY-TAYLOR MODEL

The 1972 Priestley-Taylor (P-T) equation is a shortened version of the original 1948 Penman combination equation (Jensen et al., 1990). It is based on the assumption that the effect of atmospheric turbulence is small compared to the effect of radiation (Pauwels and Samson, 2005). Such conditions can happen when the air becomes saturated, which leads to an equilibrium evaporation. The P-T equation was described by Jensen et al. (1990) as:

\[
ET_o = \alpha \frac{\Delta}{\Delta + \gamma} \left( \frac{R_n - G}{\lambda} \right)
\]

**Equation 2-3: Priestley-Taylor equation.**

where \( ET_o \) is reference evapotranspiration (mm day^{-1}), \( \alpha \) is a dimensionless proportionality coefficient to compensate for the fact that true equilibrium conditions rarely exist (Priestley and Taylor, 1972; Jensen et al., 1990), \( \Delta \) is the slope of the saturation vapor pressure-temperature curve (kPa°C^{-1}); \( \gamma \) is the psychrometric constant (kPa °C^{-1}); \( \lambda \) is latent heat of vaporization (MJ kg^{-1}); \( R_n \) is the net radiation at the crop surface (MJ m^{-2}d^{-1}) and \( G \) is the soil heat flux (MJ m^{-2} day^{-1}). The constant 1.26 was assigned to the coefficient \( \alpha \), which may be modified for different wind and humidity conditions; 1.26 is reasonable across most climates (Fontenot, 2004).
2.2-C-iv TURC MODEL

The Turc reference evapotranspiration model (Turc, 1961) was originally designed for use in the Netherlands. Allen (2000) defined the Turc equation for operational use as:

\[ ET_o = a_T \cdot \frac{0.013}{T_{\text{mean}}} \left( \frac{T_{\text{mean}} + 15}{23.8856R_s + 50} \right) \lambda \]

**Equation 2-4: Turc equation.**

Where, \( ET_o \) is reference evapotranspiration (mm day\(^{-1}\)), \( T_{\text{mean}} \) is the mean daily air temperature (°C), \( R_s \) is the incoming solar radiation (MJ m\(^{-2}\) day\(^{-1}\)), and \( \lambda \) is the latent heat of vaporization (MJ kg\(^{-1}\)). The coefficient \( a_T \) is a humidity-based value where if the mean daily relative humidity (\( RH_{\text{mean}} \)) is greater than or equal to 50%, then \( a_T = 1.0 \). If the mean daily relative humidity was less than 50% then \( a_T \) was determined as follows:

\[ a_T = 1 + \frac{50 - RH_{\text{mean}}}{70} \]

**Equation 2-5: Humidity-based coefficient \( a_T \) for Turc model.**

2.2-C-v HARGREAVES MODEL

The 1985 Hargreaves and Samani equation is a simple, empirical radiation-based approach that has been used in cases where the availability of weather data is limited. The Hargreaves model equation used is expressed as (Hargreaves and Samani, 1985):

\[ ET_o = 0.0023(T_{\text{mean}} + 17.8)(T_{\text{max}} - T_{\text{min}})^{0.5}R_a \]

**Equation 2-6: Hargreaves equation.**

where, \( ET_o \) is reference evapotranspiration (mm day\(^{-1}\)), \( R_a \) is the water equivalent of extraterrestrial radiation (mm day\(^{-1}\)), \( T_{\text{mean}} \) is the mean air temperature (°C), \( T_{\text{max}} \) is the daily maximum temperature (°C), and \( T_{\text{min}} \) is the daily minimum temperature (°C).
2.2-D EVALUATION PARAMETERS

Several statistical routines were considered to analyze the relationship between the ET\(_{o}\) models and the standardized ASCE-EWRI PM (2005) equation. The ASCE PM was chosen as a benchmark for comparison because of its well-recognized accuracy to estimate ET under reference conditions and most locations. Pair-wise comparisons were made using graphics and simple linear regression, as well as the following criteria: root mean squared error (RMSE), mean absolute error (MAE), mean ratio, and the coefficient of determination (R\(^2\)). RMSE is defined as:

\[
RMSE = \left[ k^{-1} \sum_{i=1}^{k} (P_i - O_i)^2 \right]^{1/2}
\]

Equation 2-7: Root mean squared error.

where, \(RMSE\) is the root-mean squared error (mm day\(^{-1}\)); \(O_i\) is the \(i^{th}\) observed data estimated by the ASCE Penman-Monteith equation; \(P_i\) is the \(i^{th}\) estimated data by the ET\(_{o}\) model; and \(k\) is the total number of observations. RMSE is the main parameter for evaluating the reliability of methods in predicting reference evapotranspiration; it indicates the goodness-of-fit of ET\(_{o}\) as compared to the values obtained from the ASCE-PM (Amatya et al., 1995; Trajkovic and Kolakovic, 2009; Tabari, 2009). However, according to Fontenot (2004), RMSE is sensitive to extreme values, thus altering the evaluation of a model. On the other hand, the Mean Ratio provides a measure of model bias (Itenfisu et al., 2003). The Mean ratio is calculated as:

\[
MeanRatio = k^{-1} \sum_{i=1}^{k} \frac{P_i}{O_i}
\]

Equation 2-8: Mean Ratio between ET\(_{o}\) models.

MAE (mm d\(^{-1}\)) measures the average difference between estimates using the absolute difference, thus reducing the sensitivity to extreme differences (Fontenot, 2004). MAE is calculated as:
\[ MAE = k^{-1} \sum_{i=1}^{k} (|P_i - O_i|) \]

Equation 2-9: Mean absolute error.

Finally, the coefficient of determination \((R^2)\) is determined as follows:

\[
R^2 = \left[ \frac{\sum_{i=1}^{k} (P_i - \bar{P})(O_i - \bar{O})^2}{\sum_{i=1}^{k} (P_i - \bar{P}) \sum_{i=1}^{k} (O_i - \bar{O})} \right]
\]

Equation 2-10: Coefficient of determination.

where, \(R^2\) is the coefficient of determination, \(\bar{P}\) is the average value for \(P_i\), and \(\bar{O}\) is the average value for \(O_i\).

### 2.3 RESULTS

The reduced data-set ASCE PM approaches, Hargreaves, Priestley-Taylor, and Turc equations were compared to the full data-set ASCE PM method using weather data from Northeast Louisiana. Emphasis is given to the 2010 growing season because of the importance of these periods to sweetpotato. The results of the statistical analysis for each equation are given in Table 2-2. The best model was selected based primarily on the lowest RMSE and MAE, highest coefficient of determination \(R^2\), and the Mean Ratio closest to 1.0.

The MAE values obtained for all the models never exceeded 1.0 mm d\(^{-1}\), suggesting that the equations provided good estimates of reference evapotranspiration when compared to the full-set ASCE PM. An error of only 1 mm d\(^{-1}\) of \(\text{ET}_o\) on a 1 ha field accounts to approximately 10 m\(^3\) (2641 gallons) of water per day (Fontenot, 2004). Likewise, higher \(R^2\) values and Mean Ratios close to 1, describes the usefulness of the model to estimate \(\text{ET}_o\) under limited data conditions.

The reduced data-set ASCE Penman-Monteith estimates were in closest agreement with the full data-set ASCE Penman-Monteith (Table 2-2). The ASCE PM\(_{SP}\) had the lowest mean absolute difference.
Table 2-2. Statistical summary of Reference Evapotranspiration estimates. All parameters are based on comparisons to the full data-set ASCE Penman-Monteith equation.

<table>
<thead>
<tr>
<th>Model</th>
<th>$R^2$</th>
<th>RMSE (mm day$^{-1}$)</th>
<th>Mean ratio</th>
<th>MAE (mm day$^{-1}$)</th>
<th>Average (mm/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASCE P-M$_{sp}$ Wind: LAIS Sweetpotato</td>
<td>0.638</td>
<td>0.67</td>
<td>0.98</td>
<td>0.56</td>
<td>5.06</td>
</tr>
<tr>
<td>ASCE P-M$_{w2}$ Wind speed: 2 m s$^{-1}$</td>
<td>0.570</td>
<td>0.75</td>
<td>1.07</td>
<td>0.59</td>
<td>5.52</td>
</tr>
<tr>
<td>Hargreaves-Samani</td>
<td>0.595</td>
<td>0.75</td>
<td>1.08</td>
<td>0.60</td>
<td>5.54</td>
</tr>
<tr>
<td>Priestley-Taylor</td>
<td>0.504</td>
<td>0.93</td>
<td>0.92</td>
<td>0.78</td>
<td>4.74</td>
</tr>
<tr>
<td>Turc</td>
<td>0.554</td>
<td>0.99</td>
<td>0.90</td>
<td>0.83</td>
<td>4.59</td>
</tr>
</tbody>
</table>

Where: $R^2$: coefficient of determination, RMSE: root mean square error, MAE: mean absolute error.

(0.56 mm day$^{-1}$), the lowest root mean square error (0.67 mm day$^{-1}$) and the highest coefficient of determination (0.64). The ASCE P-M$_{sp}$ equation was followed by the ASCE P-M$_{w2}$ approach as the best method to estimate $ET_o$. In the case of the models requiring fewer weather inputs, the Hargreaves equation had the best performance. The radiation-based methods, Priestley-Taylor and Turc, presented the worst estimates of $ET_o$ when compared to the full ASCE PM.

Table 2-2 includes a statistical summary of ratios between the different models and the full-set ASCE PM model. The ASCE P-M$_{sp}$ had a mean ratio of 0.98, meaning that the values calculated using this model were on average, 2 % lower than the results obtained with the full ASCE PM equation. Similarly, the ASCE P-M$_{w2}$ method had a value of 1.07, where the values acquired were on average, 7% higher than the benchmark equation. On the other hand, the Hargreaves estimate tended to be higher (8%), while the Priestley-Taylor and Turc had a tendency to be lower (8% and 10%, respectively) than the full ASCE PM $ET_o$.  

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The relationships between ET\(_o\) estimated by the models and the ET\(_o\) values obtained by the full ASCE PM are shown in Figures 2-1 to 2-5. The ASCE PM\(_{sp}\) equation presented the best results at the experimental site with R\(^2\) equal to 0.64 (Figure 2-2). Conversely, the Priestley-Taylor method had the lowest performance with an R\(^2\) of 0.50. The use of empirical equations to determine some parameters, such as solar radiation, in addition to the condition of the wind sensor from the LAIS station, contributed to the weak correlation found between the models and the ASCE PM.

Figure 2-6 presents the cumulative performance of the models during the entire growing season. In general, the ASCE PM\(_{sp}\) outperformed all other models when compared to the full data-set ASCE Penman-Monteith equation, while the Hargreaves and ASCE PM\(_{w2}\) equations over predicted ET\(_o\). In contrast, the Turc and Priestley-Taylor methods clearly underestimated ET\(_o\). Additionally, Figure 2-7 illustrates the performance of the models for the first 30 days after transplanting the sweetpotato. The results obtained were similar to the entire growing season, however for this period of time the ASCE PM\(_{w2}\) outperformed the rest of the models. Overall, the equations underestimated ET\(_o\), except for the Hargreaves approach.

2-4 DISCUSSION

In general, all the models estimated daily reference ET accurately using limited weather inputs, given that the MAE values were all below 1.0 (Table 2-2). However, low correlations (R\(^2\)) were found between the equations. This can likely be explained by the use of estimated data using empirical formulas for wind speed and solar radiation, when compared to a model utilizing measured weather inputs.

The reduced data-set ASCE PM\(_{sp}\), had the closest agreement overall with the full ASCE Penman-Monteith; it was followed in performance by the ASCE PM\(_{w2}\). This is not surprising considering that the
Figure 2-1: Daily ET₀ for the reduced data-set ASCE PMₕ vs. the full data-set ASCE PM

Figure 2-2: Daily ET₀ for the reduced data-set ASCE PMₚ vs. the full data-set ASCE PM.
Figure 2-3: Daily ET₀ for Hargreaves vs. the full data-set ASCE PM.

Figure 2-4: Daily ET₀ for Priestley-Taylor vs. the full data-set ASCE PM.
Figure 2-5: Daily ET₀ for Turc vs. the full data-set ASCE PM.
**Figure 2-6: Cumulative ET₀ for all the models during the entire growing season.**
Where ASCE PM_{FULL}: full ASCE PM, ASCE PM_{SP}: limited data ASCE PM wind speed = nearby station, ASCE PM_{W2}: limited data ASCE PM wind speed = 2 m s⁻¹, Turc: Turc model, Hargreaves: Hargreaves model, and P-T: Priestley-Taylor model.
**Figure 2-7: Cumulative ET₀ for all the models during the first 30 DAT.**

equations are modified versions of the full standardized form ASCE PM.

These two alternatives provided by Allen et al. (1998) were considered given that wind speed and solar radiation are not always available as weather inputs for ASCE PM ET₀ estimation. When using the first approach \((W_2 = 2 \text{ m s}^{-1})\), the results showed that the RMSE and MAE values were larger than those achieved when using wind speed data imported from a weather station located close to the experimental site. Overall, results indicate that when wind speed measurements are not available, the differences between ASCE PM full-set and a reduced-set ASCE PM generally decreased by using local wind speed data, instead of a global wind speed value. These results are in agreement with other studies regarding ET₀ calculations without wind speed data (Jabloun and Sahli, 2008; Trajkovic and Kolakovic, 2009).

In the case of the equations requiring less weather inputs, model performance appears to be dependent on model type i.e. radiation or temperature based. The radiation-based equations tended to underestimate ET₀ as much as 10% (Table 2-2), while the temperature-based Hargreaves model overestimated ET₀ by 8%. The low RMSE, MAE and highest \(R^2\) for the Hargreaves equation indicates a greater agreement with the full-set ASCE PM. Furthermore, this overestimation of ET₀ by the Hargreaves model is in conformity with the data reported by Jensen et al. (1990) and Amatya et al. (1995) for humid locations. Temesgen et al. (2004) reported that when lower wind speeds combined with high relative humidity conditions are registered, such as those found during the study (mean \(u_2\): 1.71 m s\(^{-1}\) and mean RH: 80%), results in higher values for the Hargreaves equation.

The radiation-based equations had low RMSE and MAE values despite using the empirically computed solar radiation. This suggests that it is appropriate to compute ET₀ when estimating \(R_s\) with Equation 2-1. Nevertheless, according to Fontenot (2004) the Turc method is the best equation for
humid climate conditions (inland) in Louisiana; meaning that the empirical determination of solar radiation might produce a misrepresentation of ET$_{o}$ as presented by the R$^2$ results. Several researchers indicated that the Truc model performs well in humid climates such as those found in Iran (Tabari, 2009) and Serbia (Trajkovic and Kolakovic, 2009). The same situation is presented with the Priestley-Taylor approach since it uses the estimated solar radiation to calculate net radiation R$_{n}$. Amatya et al. (1995) ranked the Priestley-Taylor method second, following the Turc equation for humid regions. Moreover, the fact that it was designed for very humid locations where the surface was normally wet, could be another aspect that affects the Priestley-Taylor equation results, given that the settings of the experimental site were not under these particular conditions.

2-5 CONCLUSIONS

Five methods were applied to estimate reference evapotranspiration during the sweetpotato growing season using weather data from an experimental site in northeast Louisiana. The equations used during the experiment were: three combination methods, the full data-set ASCE Penman-Monteith and two modified versions of the full data-set ASCE PM (ASCE PM$_{SP}$ and ASCE PM$_{w2}$); two radiation-based equations, Turc and Priestley-Taylor; and a temperature-based approach, Hargreaves-Samani. The standardized ASCE Penman-Monteith approach was established as the benchmark for comparing ET$_{o}$ estimates with the rest of the methods, which utilized limited data inputs. Daily pairwise comparisons were the basis of the evaluation between ET$_{o}$ models.

In general, the results indicated that the reduced data-set ASCE PM$_{SP}$ is the best method for the humid conditions presented in the area (RMSE: 0.67 mm d$^{-1}$, Mean ratio: 0.98, MAE: 0.56 mm d$^{-1}$ and R$^2$: 0.64); followed by the reduced ASCE PM$_{w2}$ equation, Hargreaves, Turc and the Priestley-Taylor models.
The ASCE $PM_{SP}$, Turc and Priestley-Taylor equations were found to underestimate $ET_o$ up to 10%, while the ASCE $PM_{W2}$ and Hargreaves models overestimated $ET_o$ a maximum of 8%. An overall low correlation was found between all the $ET_o$ models using missing data and the full set Penman-Monteith $ET_o$ model, due to the utilization of empirical formulas to determine wind speed and solar radiation. In the case of the reduced Penman-Monteith methods, the use of imported wind speed data from a nearby weather station yielded accurate estimates of $ET_o$; alternatively, the global default wind speed should be used with caution, nevertheless for the conditions presented in the area, it gave accurate values for $ET_o$.

Further research is required to evaluate the effect of using limited weather data inputs for daily $ET_o$ estimates in Northeast Louisiana. It is recommended to perform a study over an adequate standard reference surface and soil water-content conditions, as recommended by Allen et al. (1998) and ASCE-EWRI (2005), in order to enhance reproducibility and accuracy of the estimates. Additionally, the $ET_o$ calculations should be made for an entire year period with the purpose of making an assessment of the different variations of parameters such as wind speed, air temperature, relative humidity and solar radiation, and its effect over $ET_o$ estimation.

### 2.6 REFERENCES


LAIS. 2010. Louisiana Agroclimatic Information System. Available at: http://weather.lsuagcenter.com


3.1 INTRODUCTION

In recent years, the declining availability of water resources and the increased competition for good water quality among different users has resulted in improvements in irrigated agriculture. Irrigation uses large volumes of water when compared to domestic, municipal, industrial and environmental purposes (Prajamwong et al., 1997). Therefore, it is recognized that most increasing water demands can be met by using the existing resources more efficiently, leading to substantial benefits in terms of water management and addressing many environmental concerns. However, without the proper field measurements and analytical tools, the implementation of appropriate management practices becomes difficult, especially those that will boost a system’s performance. In agriculture, significant improvements can be achieved through the development and implementation of computer-based irrigation scheduling techniques (George et al., 2000).

Irrigation scheduling involves answering two main questions: when and how much to irrigate (George et al., 2000). Irrigation scheduling is an essential part of daily water management practices and represents a useful tool for growers when it comes to consuming water and energy efficiently, while maintaining crop quality. The strategies that integrate irrigation scheduling may be based on historic weather and soil data for average conditions or the use of real-time information collected in the field. In both cases, information about the soil, crop, climate and management-user objectives must be considered to build scheduling procedures for specific situations (Martin et al., 1990).
Irrigation scheduling methods can be based on soil water-balance techniques for root zone water budgeting (Howell et al., 2007). The soil water-balance accounts for water moving into (capillary rise and precipitation) and out (crop evapotranspiration and deep percolation) of the soil. As soil water reserves are used, a deficit develops and increases as water is removed from the soil. When the water depletion reaches a predetermined level, an irrigation event is recommended. Water is then applied to the root zone, refilling the soil profile and resetting the deficit to the desired water content (Fisher and Pringle III, 2010).

Crop evapotranspiration is a critical component of the soil water-balance, where estimations of reference evapotranspiration ($ET_o$) are needed. A variety of models for $ET_o$ have been developed and range from simple empirical equations to highly sophisticated physical models (Itenfisu et al., 2003; Fisher and Pringle III, 2010). Despite the advantages of the more physically based methods, empirical $ET_o$ equations are commonly used especially in cases where data availability is limited. The 1961 Turc equation is frequently used, requiring only air temperature and solar irradiance as inputs (Amatya et al., 1995).

Over the years researchers have developed different irrigation scheduling models, such as the CROPWAT model that was created by the Food and Agriculture Organization (FAO) Land and Water Development Division (Smith and Kivumbi, 2000). It includes a simple water-balance approach that simulates crop water needs and irrigation requirements based on soil, weather and crop data inputs. Other examples of computer-based methods are the Arkansas Irrigation scheduler, an application that has been used in the Mississippi Delta region for over twenty years (Cahoon et al., 1990; Vories and Tacker, 2006) and ISAREG a soil-water balance model developed for growing conditions in Portugal (Liu et al., 1997).
Irrigation scheduling techniques for the humid mid-South are more complicated than those for arid regions, due to variable climate conditions such as cloudy weather, rainfall and temperature swings caused by the movement of weather fronts (Vories and Tacker, 2006). Consequently, the daily evaporative demand in the mid-southern region is highly variable (Cahoon et al., 1990). In addition, the water storage capacity of many soils in the region is low, so frequent irrigations might be necessary during peak water use periods.

Simulation models require appropriate validation to the conditions where they will be applied (Liu et al., 1997). For sweetpotatoes, it has been documented that management and environmental variables influence the critical adventitious root cambium stages within the first 20 days after transplanting (DAT), which in turn affects the yield (Togari, 1950). Lignification renders an adventitious root incapable of becoming a storage root, thus affecting the storage number which is directly related to the expected yield (Villordon et al. 2009).

Villordon et al. (2010), through a Bayesian network model, represented the relationship between agroclimatic variables measured within 20 DAT and U.S. #1 sweetpotato yield from experimental plots; establishing an ideal timing and amount of irrigation water for ‘Beauregard’ sweetpotato in Northeast Louisiana during the growing season. U.S. No. 1 grade storage roots consist of elliptical roots 8 to 23 cm in length and 5 to 9 cm diameter, as well as few small or oversized (jumbos) roots (Villordon et al., 2009). Additionally, Constantin et al. (1974) documented that soil volumetric water content (VWC) in the range of 10-20% was optimal for the growth of sweetpotato in Louisiana.

In this study, a soil water-balance irrigation scheduling model was developed based on the recommendations established by Villordon et al. (2010) for ‘Beauregard’ sweetpotatoes in Northeast
Louisiana, with the primary goal of achieving the irrigation requirements for maximizing U.S. #1 yield. The simulations were tested against field measurements and the FAO CROPWAT model (Smith and Kivumbi, 2000) during the critical first 30 DAT and for the entire growing season of 2010. Comparisons were made analyzing the measured and predicted soil water content and water depletion output. The objective of this study was to develop a comprehensive irrigation simulation model intended to perform predictions for the timing and irrigation depth of sweetpotatoes under the weather and soil conditions of Northeast Louisiana. The long term goal is to provide a tool for improving water use during the growing season, while maintaining suitable soil water content conditions for U.S. #1 sweetpotato yield.

3.2 MATERIALS AND METHODS

3.2-A STUDY AREA AND FIELD EXPERIMENTS

The weather and soil data used in this study was measured on experimental fields which are part of Louisiana State University Agricultural Center Sweetpotato Research Station, situated approximately 8 km (5 miles) south of Winnsboro, LA (Franklin Parish).

The site is located at an elevation of 22 m above MSL and lies at latitude 32°06’N and longitude 91°42’W. Franklin Parish has historically long, hot summers due to moist tropical air moving from the Gulf of Mexico; winters are cool and fairly short. Precipitation is fairly heavy throughout the year and prolonged droughts are rare. During the summer, precipitation consists mainly of afternoon thundershowers (Martin et al., 1981). According to the United States Historical Climatology Network (USHCN), for Winnsboro, LA from (1980 to 2009) the average annual precipitation is 1452.23 mm (57.2 in), with 635.31 mm (25 in), 43.75% of which falls during the growing season (May to October). The sun
shines 60 percent of the time in summer and 50 percent during winter. The prevailing wind is from the south with an average high wind speed being 3.57 meters per second (8 mph) during spring.

During the experiment (May to October 2010), the weather conditions had an average temperature of 27.2 °C (80.9 F), an average relative humidity of 80 percent, wind speed 1.71 m s⁻¹ (3.83 mph), and a total precipitation of 325.12 mm (12.8 in) during the growing season.

The soils within the experimental area were a relatively homogenous combination of Gigger silt loam (8.2%) and Gigger-Gilbert complex (91.8%). Table 3-1 provides the main properties for the soil types found at the site. Additionally, Allen et al. (2007) gives some ranges for physical properties for silt loam soils such as $\theta_{FC}$ (Field Capacity volumetric water content) of 0.22-0.36 m³ m⁻³ and $\theta_{WP}$ (Permanent wilting point volumetric water content) of 0.09 - 0.21 m³ m⁻³.

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Slope</th>
<th>Drainage</th>
<th>Depth to water table</th>
<th>Available water capacity</th>
<th>Typical profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gigger silt loam</td>
<td>1 - 3%</td>
<td>Moderately well drained</td>
<td>30 to 76 cm (12 - 30 in)</td>
<td>Moderate 224 mm/m (8.8 in/ft)</td>
<td>0 – 140 cm (0 - 6 in) Silt loam</td>
</tr>
<tr>
<td>Gigger-Gilbert complex</td>
<td>1 - 3%</td>
<td>Moderately well drained</td>
<td>30 to 76 cm (12 - 30 in)</td>
<td>Moderate 226 mm/m (8.9 in/ft)</td>
<td>0 – 125 cm (0 - 5 in) Silt loam</td>
</tr>
<tr>
<td>0 - 1%</td>
<td>Poorly drained</td>
<td>0 to 46 cm (0 to 18 in)</td>
<td>High 305 mm/m (12 in/ft)</td>
<td>0 – 178 cm (0 - 15 in) silt loam</td>
<td></td>
</tr>
</tbody>
</table>

3.2-A-i SWEETPOTATO PLOTS

The planting dates for the study ranged from May 12 to June 9 2010, with June 1st been set as the transplanting date for the simulations. ‘Beauregard’ G1 plant beds were used as source of planting materials for the experimental plots. Following the procedure established by Villordon et al. (2010), uniform transplants were set (in row spacing of 8, 12, 16 in) and watered with approximately 0.18 liters
(6 fl oz). If a rainfall event did not occur during the first 30 DAT and soil VWC approached 10%, irrigation was supplied to bring VWC up to 50% field capacity using traveling un irrigation. After 30 DAT, additional irrigation was initially supplied via traveling irrigation gun and then by furrow irrigation towards the latter part of the season, to a maximum of 2-3 times during the growing season. All irrigation events were stopped at 70 DAT even if soil moisture dropped below 10% VWC. For the soil type used in the study, a VWC in the range of 10-20% was documented as ideal for sweetpotato (Constantin et al., 1974; Villordon et al., 2010).

3.2-B DATA MEASUREMENTS

The data set used in this analysis was obtained from an automated weather station measuring limited weather and soil variables such as air temperature (T), relative humidity (RH), and soil volumetric water content (VWC).

A station labeled LE was equipped with standard measuring devices. Air temperature and relative humidity were measured using a thermoelectric sensor (model: HMP45C - Campbell Scientific, Inc. / Vaisala), while soil volumetric water content was measured via a soil moisture sensor (model: 5TE, Decagon Devices Inc.). Precipitation data was obtained from a weather station (labeled HE) located next to station LE using a tipping bucket rain gauge (model: TB4 - Campbell Scientific, Inc.). The use of trademarks in this publication does not imply endorsement of the products listed nor criticism of similar products not mentioned.

All the meteorological inputs were sampled at three-second intervals and recorded at 1-minute, 1-hour, and 24-hour averages by a data logger (model: CR-1000 - Campbell Scientific, Inc.). Data was then transmitted to the LSU AgCenter, through the Louisiana Agriculture Information System (LAIS). The LAIS is a statewide network primarily dedicated to collecting meteorological data for use
predominately by agriculture and engineering communities and is operated by the Department of Biological and Agricultural Engineering and the LSU AgCenter (LAIS, 2010).

A daily 24-hr time step was used for the analysis of the agroclimatic data, which was collected during the sweetpotato growing-season. Additionally, these meteorological inputs are considered relevant to the potential root storage number formation within the first 20 days after transplanting (Togari, 1950; Villordon et al., 2010).

Quality control (QC) and integrity assessment criteria for the weather data sets were performed using guidelines suggested by Allen (1996) and Allen et al. (1998). All weather recordings were corrected manually for outlier values and compared to recordings from a nearby station which was part of the LAIS network. The Double Mass Analysis technique was used, where cumulative sums of a parameter from the two locations were plotted against one another. A change over time in the slope of the cumulative curve would indicate an instrument malfunction (Allen, 1996). The reliability of this method depends on the distance between the two stations and the variable being analyzed. Thus, for relative humidity and air temperature a distance up to 100 km, between weather stations, should provide good correlations, as long as there are no abrupt changes in topography and weather. The approximate distance between station LE and the LAIS weather station was 0.6 km (0.4 miles).

In addition, for relative humidity and air temperature data, duplicated signal sensors were employed. The readings yielded similar signals, demonstrating that the probes were working properly.

3.2-B-i SOIL WATER CONTENT MONITORING

A soil water probe (model: 5TE – Decagon Devices, Inc.) was used to compute the soil volumetric water content. Fig. 3-1 provides a brief description of the components found in the 5TE; it
Figure 3-1: Decagon 5TE probe components.
has dimensions of 10 cm x 3.2 cm x 0.7 cm (3.94 in x 1.25 in x 0.28 in) with a prong length of 5.2 cm (2 in). The probe has an \( \varepsilon_a \) (apparent dielectric permittivity) range between 1 and 80 (air and water, respectively) and operates at a frequency of 70 MHz. The device converted the raw dielectric permittivity values to volumetric water content (VWC) based on Topp’s Equation (Topp et al., 1980):

\[
VWC = 4.3 \times 10^{-6} \varepsilon_a^3 - 5.5 \times 10^{-4} \varepsilon_a^2 + 2.92 \times 10^{-2} \varepsilon_a - 5.3 \times 10^{-2}
\]

Equation 3-1: Topp's equation.

where, VWC is the volumetric water content \((\text{m}^3 \text{ m}^{-3})\), and \( \varepsilon_a \) is the apparent dielectric permittivity.

The sensor is adapted for use with the automated data loggers from Campbell Scientific, Inc., making it possible to document soil volumetric water content variation. Additional information such as resolution, accuracy, measuring time and datalogger compatibility can be found at Decagon (2010) for volumetric water content, electrical conductivity (bulk) and temperature.

Two depths were chosen to represent the soil water content, 5.08 cm (2 in) and 15.24 cm (6 in). These two depths were proposed by Villordon et al. (2010) based on previous research and the development of a Decision Support System for Sweetpotato production. The soil-water sensors were installed vertically following the instructions from Decagon (2010); first digging a 10-cm diameter hole up to the previously established depths. The average daily volumetric water content \( \theta_i \) \((\text{m}^3 \text{ m}^{-3})\) was then computed for each depth.

### 3.2-C SOIL WATER-BALANCE SCHEDULING MODEL

A simple soil water-balance scheduling technique, referred to as the Sweetpotato Irrigation Scheduler (SPIS) was developed using an excel spreadsheet. The model was based on determining water inputs and outputs, expressing the water content in the root zone in terms of net depletion. According to Cahoon et al. (1990), the water-balance method can be compared to a checkbook, where
effective precipitation, irrigation, and capillary rise of groundwater add to the water budget in the root zone, while evapotranspiration (ET, crop and soil water use) and deep percolation represent the losses in the amount of water, increasing depletion in the root zone. This relationship is widely accepted for practical use (Prajamwong et al., 1997) and was defined as:

$$D_{r,i} = D_{r,i-1} - P_e - IR_{ni} - CR_i - ET_{ci} + DP_i$$

Equation 3-2: Soil water-balance.

where, $D_r$ is the soil water content depletion over the root zone depth and is defined as the difference between total soil water content stored in the root zone at field capacity and the current moisture status (mm); $P_e$ is the effective rainfall (mm); $IR_n$ represents the net irrigation depth (mm); $CR$ is the capillary rise contribution to crop use from the groundwater table (mm); $ET_c$ is the actual crop evapotranspiration (mm); $DP$ is the deep percolation (mm) and, $i$ equals the day time index.

The main purpose was to maintain a minimum amount of soil-water content, especially during the first 30 DAT, in order to avoid conditions that negatively impact storage root initiation and reduce potential yield in sweetpotatoes. Exceeding the maximum allowable soil-water content will represent an unnecessary loss of water resources i.e. runoff and deep percolation (Howell et al., 2007; Allen et al., 2007) The excess soil water deficit represented the amount of water needed in the root zone calculated to reach the required water content (Martin et al., 1990).

For the purposes of this research, the following assumptions were made:

- During the growing season the water table was deep, thus there was no significant contribution from groundwater;
- Deep percolation is assumed negligible relative to the other terms in Equation 3-2 in situations of non-zero deficit ($D_{r,i-1} > 0$). This assumption is based on the low hydraulic conductivities
associated with the soils typical to the humid mid-south sweetpotato production area (Cahoon et al., 1990; Vories and Tacker, 2006). However, in situations where effective precipitation exceeded \( D_{r,i-1} \), the difference between \( P_e \) and \( D_{r,i-1} \) was established as deep percolation for day \( i \);

- Deep percolation and canopy interception were assumed negligible when compared to precipitation and runoff at this site; and,

- At the end of each day, the water content of the root zone was uniformly distributed.

To begin the soil water-balance, an initial depletion \( D_{r,i-1} \) was determined from measured soil water content using the following equation (Allen et al., 2007):

\[
D_{r,i-1} = 1000(\theta_{i-1} - \theta_{FC})Z_r
\]

**Equation 3-3: Initial soil water depletion.**

where, \( \theta_{i-1} \) is the average soil water content at the end of day \( i-1 \) (\( m^3 \ m^{-3} \)), \( \theta_{FC} \) is the water content at field capacity (\( m^3 \ m^{-3} \)), and, \( Z_r \) is the rooting depth (m).

Crop evapotranspiration (\( ET_c \)) was determined using the reference ET and crop coefficient approach, calculated as:

\[
ET_c = (K_cK_s)ET_o
\]

**Equation 3-4: Crop Evapotranspiration.**

where, \( ET_c \) is the crop evapotranspiration (mm d\(^{-1}\)), \( ET_o \) is the reference evapotranspiration (mm d\(^{-1}\)), \( K_c \) is the crop coefficient which is a function of the crop type and growth stage (dimensionless), and, \( K_s \) is a dimensionless crop water stress coefficient (Howell et al., 2007).

Considering the weather conditions for Northeast Louisiana, reference evapotranspiration (\( ET_o \)) was calculated using the radiation-based Turc equation as recommend by Amatya et al., (1995) for
humid locations. Due to the limited data inputs, a reduced-set approach was considered following the suggestions by Allen et al. (1998) for missing radiation data. Allen (2000) defined the Turc equation for operational use as:

\[
ET_o = a_T 0.013 \frac{T_{\text{mean}}}{T_{\text{mean}} + 15} \frac{23.8856R_s + 50}{\lambda}
\]

**Equation 3-5: Turc model.**

where, \( ET_o \) is reference evapotranspiration (mm day\(^{-1}\)), \( T_{\text{mean}} \) is the mean daily air temperature (°C), \( R_s \) is the incoming solar radiation (MJ m\(^{-2}\) day\(^{-1}\)), and, \( \lambda \) is the latent heat of vaporization (MJ kg\(^{-1}\)). The coefficient \( a_T \) is a humidity-based value, where, if the mean daily relative humidity (\( RH_{\text{mean}} \)) is greater than or equal to 50%, then \( a_T = 1.0 \). If the mean daily relative humidity was less than 50%, then \( a_T \) was determined as:

\[
a_T = 1 + \frac{50 - RH_{\text{mean}}}{70}
\]

**Equation 3-6: Humidity-based coefficient \( a_T \) for Turc model.**

Missing net radiation \( R_n \) was estimated using Hargreaves’ radiation formula (Allen et al., 1998; Allen, 2000):

\[
R_s = k_{RS} \sqrt{(T_{\text{max}} - T_{\text{min}})R_a}
\]

**Equation 3-7: Hargreaves radiation equation.**

where, \( R_s \) is the solar radiation (MJm\(^{-2}\)d\(^{-1}\)), \( R_a \) is extraterrestrial radiation (MJm\(^{-2}\)d\(^{-1}\)), \( T_{\text{max}} \) and \( T_{\text{min}} \) are maximum and minimum air temperature (°C), respectively, and, \( k_{RS} \) is an adjustment coefficient. Allen et al. (1998) recommended using a value for \( k_{RS} \) equal to 0.16 for interior locations.

The crop coefficient represents the ratio of Actual Crop Evapotranspiration to Reference Evapotranspiration (Kar et al., 2005). Table 3-2 provides a summarized list of sweetpotato crop
coefficient values (Allen et al., 1998), based on the annual crop development cycle. The table provides the crop growth stage length periods (L), $K_c$ values and plant date.

Table 3-2. Sweetpotato $K_c$ values and length (L) of typical growth stage (days) with planting dates and their regions. Adapted from Allen et al. (1998).

<table>
<thead>
<tr>
<th>Crop</th>
<th>$K_c$ ini</th>
<th>$K_c$ mid</th>
<th>$K_c$ end</th>
<th>Total</th>
<th>Plant date</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L initial</td>
<td>L dev</td>
<td>L mid</td>
<td>L end</td>
<td>April</td>
</tr>
<tr>
<td>Sweetpotato</td>
<td>0.5</td>
<td>1.15</td>
<td>0.65</td>
<td>20 30 60 40 150</td>
<td></td>
</tr>
</tbody>
</table>

Where: $K_c$: dimensionless crop coefficient; and L: crop growth length period. The first row shows the $K_c$, while the second row shows the growth stage in days.

The crop water stress coefficient $K_s$, is an adjustment to the potential crop water use to account for limiting deficits (Hess, 1996). It was estimated using a logarithmic function as provided by George et al. (2000):

$$K_s = \log\left[1 + 100\left(1 - \frac{D_{r-1}}{TAW}\right)\right]$$

**Equation 3-8: Logarithmic function for $K_s$.**

where, TAW is total available soil water in the root zone (mm), and $D_{r-1}$ is the root water depletion on day $i-1$ (mm). The total available water (TAW) was estimated for the soil as the difference between soil water content at field capacity and wilting point with the following equation:

$$TAW = 1000\left(\theta_{FC} - \theta_{WP}\right)Z_r$$

**Equation 3-9: Total available water.**

where, $\theta_{FC}$ is the soil water content at field capacity (m$^3$ m$^{-3}$), $\theta_{WP}$ is the water content at wilting point (m$^3$ m$^{-3}$), and, $Z_r$ is the rooting depth (m). The magnitude of TAW depends on the type of soil and the rooting depth.
The estimation of the vertical root depth was only considered when SPIS was compared to FAO CROPWAT, otherwise it was kept constant at 5 and 15 cm in order to assess soil-water movement at the specific sensor installation depths. Root depth was approximated using the following method described by Martin et al. (1990):

\[ Z_r = Z_{\text{min}} + (Z_{\text{max}} - Z_{\text{min}})R_f \]

**Equation 3-10: Rooting depth function.**

where, \( Z_r \) is the root zone depth (m), \( Z_{\text{min}} \) is the minimum rooting depth (m), \( Z_{\text{max}} \) is the maximum effective depth of the root zone (m), and, \( R_f \) is the root growth factor. \( R_f \) was determined as the fraction of days from germination to the number of days to reach the maximum effective root depth.

For both the SPIS and CROPWAT, the crop rooting depth was considered for the profile ranging from 5 cm (\( Z_{\text{min}} \)) to 15 cm (\( Z_{\text{max}} \)).

Effective rainfall is the portion of total rainfall that assists in meeting the consumptive use requirements of growing crops (Patwardhan et al., 1990). According to Allen et al. (2007), the depth of effective rainfall can be determined by subtracting surface runoff and it can be calculated using the USDA-SCS curve number approach (Schwab et al., 1993). Once the surface runoff depth was calculated, the effective rainfall was determined with the following expression:

\[ P_e = P - RO \]

**Equation 3-11: Effective rainfall.**

where, \( P_e \) is the effective rainfall (mm), \( P \) is the measured precipitation depth (mm), and, \( RO \) is the depth of surface runoff (mm).

When all the components of the soil water-balance model were integrated, the soil-water status in the crop root zone was simulated to predict the time and amount of irrigation needed using
the following procedure (same for all simulations). The daily soil-water depletion ($D_{ri}$) was updated by taking the previous day’s soil-water deficit ($D_{ri-1}$), subtracting $P_e$ and adding $ET_c$ and $DP$ (if $D_{ri-1} = 0$). During the first 30 DAT, if the $D_{ri}$ obtained was more than zero, it was compared to the allowable deficit, represented by a soil water content equal to or less than 0.10 m$^3$ m$^{-3}$ (10%). In case the $D_{ri}$ results were greater than the allowable deficit, an irrigation was scheduled for the following day. The effective irrigation depth was established to bring the soil water content up to 50% of field capacity, approximately, or 0.145 m$^3$ m$^{-3}$ soil water content for these soils. Between 30 DAT and 70 DAT, irrigation events where limited to 3 following the same procedure; after 70 DAT no more irrigation events were scheduled. The timing and depth of irrigations was based on the allowed soil water depletion and the crop requirements set by Villordon et al. (2010) for ‘Beauregard’ sweetpotato in Northeast Louisiana.

Having found the net irrigation depth required for sweetpotato, the gross irrigation ($IR_g$) depth was determined and totaled. Net irrigation was defined as the amount of water that ultimately reaches the sweetpotato root zone (Martin et al., 1990; Allen et al., 2007). The gross irrigation depth was derived from the net irrigation water requirement and was approximated using the following formula:

$$IR_n = \frac{E_a IR_g}{100}$$

*Equation 3-12: Net irrigation.*

where $E_a$ is the system application efficiency (%) and $IR_g$ is the gross depth of water applied (mm). The system application efficiency where estimated using suggested values found on Martin et al. (1990).

**3.2-D MODEL VALIDATION**

The SPIS model simulated the daily water balance for sweetpotato during the first 30 DAT and a complete growing season using weather input data and the parameters described above. Average soil
characteristics for the area such as field capacity, permanent wilting point, and infiltration rate were used in the study. The 5TE soil probe measurements at 5 cm and 15 cm were utilized to determine the average soil volumetric water content (m$^3$ m$^{-3}$) at each particular depth. Additionally, FAO CROPWAT model was used to predict the average daily soil moisture profile (limited from 5 cm to 15 cm). The proposed model gave soil moisture depletion values that were employed for estimating daily available soil water in terms of VWC. The performance of SPIS was then tested comparing the simulated soil water content, with the values obtained at both 5TE measurement depths and within the selected soil profile (CROPWAT).

The Mean Absolute Relative Error (MARE) routine was used to determine the model’s predictive performance when compared to the measured soil volumetric content from the 5TE probes and the predicted values obtained with the CROPWAT model. MARE was calculated as:

$$MARE = k^{-1} \sum_{i=1}^{k} \left( \frac{|Simulated_i - Observed_i|}{Observed_i} \right)$$

Equation 3-13: Mean Absolute Relative Error.

In addition, a regression analysis of soil moisture was performed between the SPIS’ simulated values and those obtained from the CROPWAT model. The coefficient of regression was calculated as:

$$R^2 = \frac{\sum_{i=1}^{k} (P_i - \bar{P})(O_i - \bar{O})^2}{\sum_{i=1}^{k} (P_i - \bar{P})^2 \sum_{i=1}^{k} (O_i - \bar{O})^2}$$

Equation 3-14: Coefficient of determination.

where $R^2$ is the coefficient of determination, $P$ is the average value for $P_i$, and $O$ is the average value for $O_i$. 
3.3 RESULTS

3.3-A SIMULATION OF SOIL WATER CONTENT AND DEPLETION AT 5 CM DEPTH

A comparison of simulated and measured soil water at a sensor depth of 5 cm for the first 30 DAT is shown in Fig. 3-2. During the first stages of the growing season, Villordon et al. (2010) attempted to maintain the soil water content within a range of 10-20% VWC, supplying irrigation when the water content reached approximately 10% and up to 50% field capacity (approximately 14.5% VWC). The average soil water content during this period for the irrigation scheduling model (SPIS) was 13.9%, while for the observed data it was 13.4%. The MARE value obtained for 30 DAT was 28.88%.

The output of the soil water-balance in terms of soil water deficit for sweetpotato is presented in Fig. 3-3. The solid line represents the total available water (TAW), whereas the dash lines the readily available water (RAW). If the daily depletion calculated reached the TAW line, an irrigation event was programmed for the next day (VWC ≤ 10%). The amount of net irrigation determined was calculated in order to be enough to bring the soil water deficit back to the dash line, 50% field capacity. During this stage, a total of 24.31 mm were estimated as net irrigation; assuming a system application efficiency of 70%, 34.73 mm were approximated as gross irrigation.

During the entire growing season, the simulated and observed soil water content at 5 cm depth had an average soil-water content for the SPIS approaching 11.9% (Fig. 3-4), while the measured VWC using the 5TE probes was 10.9%. The MARE value obtained was 42.39%. Fig. 3-5 depicts the soil water balance in terms of soil water deficit. In this case, the depletion determined from the soil water content measurements is illustrated with a solid line. During the entire growing season, a total net irrigation of 37.98 mm was computed. Again, using an irrigation system application efficiency of 70%, 54.26 mm were approximated as gross irrigation.
3.3-B SIMULATION OF SOIL WATER CONTENT AND DEPLETION AT 15 CM DEPTH

During the first 30 DAT, the simulated soil water content for a sensor depth of 15 cm (Fig. 3-6) followed the same procedure regarding the timing and amount of water supplied. The effective precipitation used in this case was determined as the excess rainfall depth that infiltrated the soil beyond the 5 cm (2 in) measurement depth, known as deep percolation, and assuming the soil water was distributed uniformly daily up to 15 cm (6 in) depth. SPIS’ average soil water content during this period and depth was 12.0%, while for the observed data it was 13.3%. The MARE value obtained for 30 DAT was 21.27%. The output of the soil water-balance in terms of soil water deficit for sweetpotato is presented in Fig. 3-7. The total amount of net irrigation determined was 28.05 mm, while the gross irrigation was computed at 40.07 mm.

The average soil water content during the growing season at 15 cm depth for both the SPIS model and the measured data was 10.8%. The simulated and observed soil water contents are given in
Figure 3-3: Simulated and observed soil water depletion at 5 cm sensor depth for the first 30 DAT. Where TAW: Total available water and RAW: Readably available water.

Figure 3-4: Effective precipitation, simulated, and observed values of soil VWC at 5 cm sensor depth for the growing season.
Figure 3-5: Simulated and observed soil water depletion at 5 cm for the growing season. Where TAW: Total available water and RAW: Readably available water.

Figure 3-6: Simulated and observed values of soil VWC at 15 cm sensor depth for the first 30 DAT. Where: Simulated water content profile is based on predicted irrigation events.
Figure 3-7: Simulated and observed soil water depletion at 15 cm for the first 30 DAT.
Where TAW: Total available water and RAW: Readably available water.

Fig. 3-8, where the MARE value obtained was 19.61%. In Fig 3-9 the depletion determined from the soil water content measurements, is illustrated with the solid line. During the growing season, a total net irrigation of 51.16 mm was computed and the required gross irrigation was determined at 54.26 mm.

3.3-C COMPARISON BETWEEN SPIS AND CROPWAT FOR A SOIL PROFILE 5 CM – 15 CM

Using the same agro-climatic data over the growing season, daily soil water content and water depletion were simulated by SPIS and CROPWAT for a soil profile (Fig. 3-10). The average VWC for SPIS was 13.8%, while CROPWAT estimated an average of 17.0%. The MARE obtained between the models was 19.67% and the coefficient of determination ($R^2$) was equal to 0.44. Due to modeling restrictions imposed by CROPWAT, it was assumed that the maximum rooting depth ($Z_{r,\text{max}} = 15.24$ cm) for the soil profile, was achieved at 50 DAT. During this period, SPIS computed a total net irrigation of 35.85 mm
and 51.21 mm of total gross irrigation, assuming 70% irrigation system efficiency. On the other hand, CROPWAT calculated 211.90 mm and 302.80 mm, total net and gross irrigation respectively.

**Figure 3-8:** Effective precipitation, simulated and observed values of soil VWC at 15 cm sensor depth for the growing season.

Finally, the average soil water content obtained during the first 30 DAT for SPIS was 13.8%, while for CROPWAT it was 16.2%. The comparison of predicted soil water content by both models is given in Fig. 3-12. The MARE value between models was 18.93% and $R^2$ equal to 0.30. Net irrigation during this stage for SPIS had a total of 20.25 mm and 28.93 mm were approximated as gross irrigation. In the case of CROPWAT, 37.10 mm and 53.0 mm, net irrigation and gross irrigation respectively.

### 3-4 DISCUSSION

Throughout the critical first 30 DAT at depths of 5 cm and 15 cm, the irrigation goal was to maintain the soil water content between a range of 10% and 20% at 5 cm and 15 cm as it favors the optimal growth for ‘Beauregard’ sweetpotato adventitious roots (Villordon *et al.*, 2010). Based on
Figure 3-9: Simulated and observed soil water depletion at 15 cm for the growing season. Where TAW: Total available water and RAW: Readably available water.

Figure 3-10: Predicted VWC using SPIS and CROPWAT for a soil profile (5-15 cm) during the growing season.
Figure 3-11: Simulated soil water depletion for a soil profile using SPIS and CROPWAT for the growing season.

Where TAW: Total available water and RAW: Readably available water.

Figure 3-12: Simulated soil VWC for SPIS and CROPWAT during the first 30 DAT.
these conditions, the SPIS model was able to predict at both depths the average soil water content, keeping the average between the selected range. However, the differences (Fig. 3-2 and Fig. 3-6) obtained as well as the MARE results, suggest that the SPIS model failed to predict the actual water movement across the soil matrix, either overestimating or underestimating the soil water content and water depletion, including certain days where the predicted values went below the established 10% threshold.

In general, unsaturated conditions were present in the experimental plots during the growing season, due to the soil, weather and irrigation management practices of ‘Beauregard’ sweetpotato in this particular region. An average 13.4% VWC (5 cm) and 13.3% (15 cm) where found during the study for the first 30 DAT, which is less than 50% field capacity for the soil type (silt loam). Whilst for the entire growing season, the observed values were 10.9% and 10.8% respectively.
Unsaturated soil conditions are often complicated and difficult to describe quantitatively, where soil-water is subject to a sub-atmospheric pressure, which is equivalent to a negative pressure potential (Hillel, 2004). These circumstances affect the water flow in the soil, thus diminishing the hydraulic conductivity, making it harder for water to move across the soil matrix and increasing tortuosity. Therefore, processes such as evapotranspiration, which are directly related to water movement across a soil profile, were affected by the lack of wetness and excessive suction in the experimental plots. Based on this, the water movement over time (Fig. 3-2 and Fig. 3-6) was more gradual when compared to the simulated water-balance, where steep drops and increases of the soil water content were predicted.

After 70 DAT, the decline in hydraulic conductivity due to an increase in matric suction under increasing unsaturated conditions, affected the overall soil-water dynamics. Under saturated conditions, the processes take place faster, such as infiltration that moves more rapid when compared to evaporation, that typically transfers water through a drying soil profile. Such an effect is illustrated on Fig. 3-4 and Fig. 3-8, when after 70 DAT no water was applied to the field and soil water content was kept below 10%, which is the Permanent wilting point for this soil type. After this point, high suctions were present in the soil, resulting in low water movement. On the other hand, when a rainfall event replenished the soil matrix, the slope of the soil VWC was steeper than when depletion was occurring in the soil.

The high MARE values calculated for the entire growing season and for the first 30 DAT confirm the difficulty of simulating water movement under unsaturated conditions based on deficit irrigation practices. In addition, Prajamwong et al. (1997) mentions that the crop ET is distributed within the soil layers as a function of root density and soil water availability in each layer. This adjustment represents
the potential ET extraction distributed for each soil level, using weighting factors. Moreover, the variable weather conditions for the humid mid-South make the attempt to develop irrigation scheduling tools more complicated than arid regions (Cahoon et al., 1990). This variability needs to be accounted for, however these types of modifications are not commonly considered when developing a simple soil water-balance model.

The simulated output by SPIS and CROPWAT had similar performance for soil water content and water depletion during the first 30 DAT (Fig. 3-12 and Fig 3-13). However, CROPWAT overestimated the average VWC and exceeded the established requirement (50% Field Capacity) proposed by Villordon et al. (2010). For the duration of this period, CROWAT estimated 83% more gross irrigation compared to SPIS. This translates into unnecessary irrigation and management costs while maintaining the same potential root quality, according to the water requirements of sweetpotato and the conditions presented in the field.

When considering the entire growing season and bearing in mind that after 70 DAT no more irrigations were needed, it’s important to note that CROPWAT continued scheduling irrigation events. At this point, all irrigation supplied will be a misuse of water resources without producing any potential increase in root quality. According to the CROPWAT program, a total of 302.80 mm of gross water are needed in order to fulfill the specifications of the crop, clearly overestimating the irrigation depth when compared to the SPIS model, 51.21 mm. The software used by CROPWAT was unable to adjust to some of the irrigation requirements, in this case the irrigation timing.

The discrepancies found between the CROPWAT and SPIS models might be caused by different rooting functions, effective rainfall, crop water stress coefficient calculation methods and ET₀ estimation equations (CROPWAT used the Penman-Monteith approach, while SPIS used the Turc
equation). The SPIS model provided flexibility in selecting such parameters, including the timing and depth of irrigation required. This flexibility allowed SPIS to produce predictions closer to real irrigation management practices of ‘Beauregard’ sweetpotato, under the conditions presented in the field.

3-5 CONCLUSIONS

A Sweetpotato Irrigation scheduling model (SPIS) based on a simple soil-water balance method, was developed in order to simulate the timing and depth of irrigation events during the 2010 growing season of ‘Beauregard’ sweetpotato in Northeast Louisiana. The predictions for the soil water content and water deficit were made initially during the first 30 DAT and then for the entire growing season. The model calculations were compared against field data obtained at two predetermined depths (5 cm and 15 cm, respectively) and to the outcome of the FAO CROPWAT model for a soil profile ranging from 5 cm to 15 cm depth.

The high Mean Absolute Relative Error (MARE) values indicated that in general, the simulation and qualitative analysis of unsaturated soil conditions turned out to be complex, primarily due to the low soil water contents presented in the field. During the first 30 DAT, MARE values of 28.88% and 21.27% at 5 cm and 15 cm respectively, were obtained; whilst for the growing season 42.39% (5 cm) and 19.61% (15 cm).

The low hydraulic conductivity consequence of the deficient soil water contents found in the field, reduced the capacity of the soil to move water appropriately and slowed down the processes involved in the water balance, such as evapotranspiration. Moreover, the inconsistent weather conditions presented in the region induced a highly variable evaporative demand. Both SPIS and CROPWAT failed to account for all these factors during the simulations and the time frames chosen. However, the soil water contents predicted by the SPIS model (30 DAT: 13.8%; Growing season: 13.8%)
were closer to the field measurements (30 DAT: 13.4%; Growing season: 10.9%), while the CROPWAT approach (30 DAT: 16.2%; Growing season: 17.0%) over estimated the soil-water conditions.

Based on the results, the SPIS model requires additional adjustments to include the settings of deficit irrigation on sweetpotato and the variable weather conditions (evaporative demand) of Northeast Louisiana. Nevertheless, the flexibility of the model allows further improvements that could assist producers and researchers to predict more accurately the soil water content and irrigation scheduling needs.

3-6 REFERENCES


CHAPTER 4: THESIS CONCLUSIONS AND IMPROVEMENTS

4.1 THESIS CONCLUSIONS

An irrigation scheduling model (SPIs) was developed using a Reference Evapotranspiration (ET\(_o\)) based soil-water balance, with the purpose of simulating the timing and depth of irrigation events during the 2010 growing season of ‘Beauregard’ sweetpotato. In addition, recommendations were made for daily ET\(_o\) via four different models as compared to ET\(_o\) calculated from soil-water monitoring sensors and daily ET\(_o\) estimated utilizing limited data inputs for the conditions in Northeast Louisiana.

Firstly, all the ET\(_o\) models failed to accurately predict ET\(_o\) when compared to the directly measured ET\(_o\). The 1961 Turc model was the best method for the conditions presented in the experimental site, with MAE values of 5.13 and 5.04 mm day\(^{-1}\) for the first 30 DAT and 4.88 and 4.49 mm day\(^{-1}\) for the entire growing season, at 5 cm and 15 cm soil depths, respectively. The Turc model was followed by the ASCE-EWRI Penman-Monteith equation for the first 30 DAT period and the Priestley-Taylor method for the entire growing season. Low correlation was found when using the Hargreaves-Samani approach.

Secondly, five methods were applied to estimate ET\(_o\) using limited weather data, where the standardized full data-set ASCE Penman-Monteith approach was established as the benchmark for the comparisons. In general, the reduced data-set ASCE PM\(_{SP}\) was the best method (RMSE: 0.67 mm d\(^{-1}\), Mean ratio: 0.98, MAE: 0.56 mm d\(^{-1}\) and \(R^2\): 0.64), followed by the reduced ASCE PM\(_{W2}\) equation, Hargreaves, Turc and the Priestley-Taylor models. The ASCE PM\(_{SP}\), Turc and Priestley-Taylor equations were found to underestimate ET\(_o\) up to a 10%, while the ASCE PM\(_{W2}\) and Hargreaves models overestimated ET\(_o\) a maximum of 8%. An overall low correlation was found between all the ET\(_o\) models...
using limited data and the benchmark model, due to the utilization of empirical methods to determine wind speed and solar radiation.

Finally, the SPIS model predicted soil water content for the first 30 DAT and for the entire growing season. The model simulations were compared against field data obtained at depths of 5 cm and 15 cm, respectively, and to the computations of the FAO CROPWAT model for a soil profile ranging from 5 cm to 15 cm depth.

Overall, the SPIS model managed to maintain the soil water content within the expected ranged (10%-20%), however the high Mean Absolute Relative Errors (MARE) indicated a low correlation between the daily predictions and the observed data, mainly because of the unsaturated soil conditions presented in the field and the highly variable evaporative demand of the humid South. MARE values equal to 28.88% and 21.27% at 5 cm and 15 cm respectively, were obtained during the first 30 DAT; whilst for the growing season 42.39% and 19.61%. In addition, the soil water contents predicted by the SPIS model (30 DAT: 13.8%; Growing season: 13.8%) were closer to the field measurements (30 DAT: 13.4%; Growing season: 10.9%), while in general the CROPWAT approach (30 DAT: 16.2%; Growing season: 17.0%) tended to overestimate the soil-water conditions.

The low hydraulic conductivity consequence of the deficient irrigation and dry weather conditions found during the study, reduced the capacity of the soil to move water appropriately and slowed down the processes involved in the water balance, such as evapotranspiration. Hence, SPIS was unable to accurately simulate the soil water content in the field during the experiment since the simple soil-water balance method used is not designed to manage these types of conditions.
4.2 IMPROVEMENTS AND RECOMMENDATIONS

4.1-A REFERENCE EVAPOTRANSPIRATION ESTIMATES

When estimating reference evapotranspiration, two weather stations were installed next to the sweetpotato field. The first station followed the ASCE-EWRI (2005) recommended set up for the ASCE Penman-Monteith equation, while the second station included only air temperature and relative humidity as input parameters. The surface and soil-water conditions of the experimental site were not appropriate for standard ET\textsubscript{o} estimation, based on the established settings by Allen \textit{et al.} (1998) and ASCE-EWRI (2005). In order to enhance reproducibility and accuracy, future studies for ET\textsubscript{o} determination in Louisiana should be performed over a well irrigated reference surface such as grass. Additionally, a complete year of data is recommended in order to asset the different variations of the input parameters and its effect over ET\textsubscript{o}.

The comparisons made between modeled and observed ET\textsubscript{o} where based on monitoring the soil water content and derived from a simple soil-water budget. The direct measurements of ET were done over a small group of plants; however, Allen \textit{et al.} (2007) recommended performing the calculations considering a larger experimental area. Hence, an increase is needed in the number of soil water sensors across the field in order to avoid the misrepresentation of ET\textsubscript{o}.

4.1-B IRRIGATION SCHEDULING

The SPIS irrigation scheduling model was determined with a simple ET\textsubscript{o} based soil-water balance, using limited weather, soil and crop data to simulate the movement of water across the soil profile. The unsaturated soil and dry weather conditions presented in the field affected the predictions of the water content, where variables of the soil-water balance such as ET\textsubscript{o} where slowed down and the model wasn’t able to accurately characterize what was happening. It’s recommended to
incorporate settings to account for deficit irrigation and drought weather, such as a variable that includes soil conductivity, which will influence some of the parameters in the water budget and the ability of the model to represent actual water movement across the soil.

4.3 REFERENCES


VITA

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