Final Report

Demonstrating tools for improving on-farm irrigation efficiency

Report to:

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Prepared by:

Nithya Rajan, Ph.D.
Assistant Professor (Cropping Systems)
Texas AgriLife Research and Extension Center
Vernon, TX 76385. Email: nrajan@ag.tamu.edu
Phone: 940-552-9941 x 230

Srinivasulu Ale, Ph.D.
Assistant Professor (Spatial Hydrologist)
Texas AgriLife Research and Extension Center
Vernon, TX 76385. Email: sriniale@ag.tamu.edu
Phone: 940-552-9941 x 243

Paul B. Delaune, Ph.D.
Assistant Professor (Environmental Soil Scientist)
Texas AgriLife Research and Extension Center
Vernon, TX 76385. Email: pdelaune@ag.tamu.edu
Phone: 940-552-9941 x 207

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Abbreviations

Abbreviation	Description
CWUE	Crop Water Use Efficiency
ET	Evapotranspiration
ETo	Reference Evapotranspiration
ETc	Crop Evapotranspiration
FC	Field Capacity
k_c	Crop coefficient
$k_{c\ ini}$	Initial- crop coefficient
$k_{c\ mid}$	Mid- crop coefficient
$k_{c\ end}$	End- crop coefficient
$IRRI_{obs}$	Irrigation applied based on the scheduling approach
$IRRIG_{sav}$	Water Savings
IWUE	Irrigation Water Use Efficiency
PWP	Permanent Wilting Point
PAW	Plant Available Water
$RAIN_{eff}$	Seasonal value of effective rainfall

1. Executive Summary

The goal of this project was to demonstrate irrigation scheduling tools that can assist producers in the Texas High Plains and Rolling Plains regions in making irrigation management decisions. With large-scale irrigated agriculture starting in the 1950's, the southern Ogallala Aquifer has experienced a continuous decline with extraction far exceeding recharge. Although more efficient irrigation technologies, such as low-energy precision application and subsurface drip, have been introduced over the past 50 years, these developments have not slowed the depletion of the aquifer, and the aquifer is being mined at an unsustainable rate. In the Texas Rolling Plains, expansion of irrigation while conserving water resources is achievable through the installation of efficient irrigation systems. Currently, majority of the producers in the Texas high Plains and Rolling Plains do not use any objective method for irrigation scheduling. Through the adoption of irrigation scheduling strategies, appreciable increase in water conservation is achievable in these regions.

There are different technologies available for scheduling irrigation. In this project, our goal was to demonstrate tools that are easy-to-use and show the potential for adoption in this region. The four irrigation scheduling tools that were demonstrated in this project are:

(1.) Tensiometers: Tensiometers are used for measuring the soil-water potential, which in turn is related to soil water content. Hence, tensiometers are useful instruments for scheduling irrigation. These are inexpensive and easy to use. A tensiometer reading of 0 indicates saturation. As plants extract water from the soil, the tensiometer reading increases. Previous research has shown that irrigation can start when the soil water tension reaches 10-20 centibars in sandy soils, and 50-70 centibars in clayey soils.

(2.) Crop coefficients: Crop coefficients are used to calculate crop evapotranspiration (ET) from weather data. Crop coefficients are crop-specific and are designed to estimate crop ET under "standard conditions" which represent the upper envelope of crop ET where no limitations are placed on crop growth or ET due to water shortage, crop density, or disease, weed, insect, or salinity pressures. Thus, the current crop coefficients will always predict the maximum crop water use under a given set of environmental conditions.

(3.) Soil Moisture Sensors: Irrigation scheduling using soil moisture sensors is based on measuring soil moisture contents in the root zone of plants. For a given soil, the difference between field capacity and the permanent wilting point represents the maximum amount of water in the soil available to support plant growth. This maximum amount is called the *plant available water.* Measurements of soil volumetric water content using sensors helps in calculating the amount of water required to maintain a certain amount of water in the soil.

(4.) SmartField: These are sensors are commercially available sensors that can continuously measure crop canopy temperature. Crop canopy temperature is a good indicator of stress caused due to water deficits. Through years of scientific research, scientists have determined threshold temperatures for plants. Crop canopy temperature exceeding a pre-determined threshold temperature for extended periods of time (canopy temperature above 82^{o}F for six hours for cotton) can lead to crop water stress. If the crop canopy temperature is below the threshold temperature, then irrigation is not required. When the crop canopy temperature exceeds the threshold temperature for few hours, irrigation can be applied to avoid stress

The demonstration project was established in subsurface drip-irrigated cotton field plots at the Chillicothe Research Station near Vernon, TX. The variable rate irrigation according to the different irrigation scheduling methods (Tensiometer, 75% ET based on crop coefficient, soil moisture, and SmartField) started in July of 2011 and 2012. The amount of rainfall was taken into consideration while determining the irrigation amounts. The greatest amount of irrigation was applied using the SmartField sensors at 100% ET replacement level in both years (23.40 inches in 2011 and 16.39 inches in 2012). In 2011, similar amounts of irrigation were applied based on the 75% ET and soil moisture-based methods (21 inches), while the least amount of irrigation was applied using tensiometer-based irrigation scheduling (19 inches). In 2012, the amount of irrigation applied based on the 75% ET method was 12.50 inches which was one inch lower than the tensiometer-based application (13.55 inches). The least amount of irrigation was applied using soil moisture-based irrigation scheduling in 2012 (11.60 inches). Some of the differences in performance of soil moisture sensors and tensiometers in 2011 and 2012 might be attributed to the placement of sensors relative to the drip emitters.

Outreach activities in the demonstration project were organized to target area producers and county extension agents in order to improve awareness of irrigation water management and scheduling. We feel that, through our efforts over the course of this project, we generated information on irrigation scheduling tools that will be of substantial use and benefit to the producers of the Southern High Plains and Rolling Plains of Texas. To maintain our commitment to getting information to the maximum number of producers and county extension agents, a project website was created that showcases information on all irrigation scheduling methods (http://people.tamu.edu/~nrajan/ irrigationschedulingtools). We believe that linking the project website and showcasing the project results through this website will increase the visibility of the water conservation efforts associated with this project. This will also act as a mechanism to perpetuate the availability of the tools beyond the end of this project.

The estimates of water savings associated with the demonstration project were derived from comparing the water application in the demonstration project to what producers were generally applying in this region. The amount of irrigation producers applied varied from moderate deficit to over- irrigation with many producers falling in the latter category. Hence, producer application was fixed as 100% ET replacement which is considered as full irrigation. Our estimates show that adoption of tensiometer-based irrigation can conserve an average of 4.15 acre-inches of water per growing season compared to full irrigation. The adoption soil-moisture based irrigation can conserve an average of 3.60 acre-inches of water and the adoption of 75% ET replacement irrigation according to the crop coefficient method can conserve an average of 2.62 acre-inches of water. Because we applied full irrigation in demonstration plots with SmartField sensors, it did not result in any water savings.

The demonstration project results show that there are opportunities for conserving water if these methods are adopted on a large scale in the Texas High Plains and Rolling Plains regions. The ET and tensiometer methods are the simplest to implement, and would result in little cost to the producer. Of these two methods, the tensiometer method should be better at representing the actual water demand of individual fields, and thus may be less likely to result in over-irrigation.

A trained producer can interpret the information from the tensiometers to make decisions regarding timing and amount of irrigation. The SmartField and soil moisture-based methods also appear to be suitable for practical use in irrigation scheduling, although each would involve a greater investment by the producer.

2. Introduction

Water is the most limiting factor for agriculture in the Texas High Plains (Groundwater Management Area 1, see Figure 1) and Rolling Plains (Groundwater Management Area 6, see Figure 1). In the heavily irrigated Texas High Plains, the Ogallala Aquifer is the primary source for irrigation water of agricultural crops, but depletion of the aquifer since the 1950's has resulted in a decline in irrigated farm land from more than 6 million acres (2.4 million hectares) to around 4.4 million acres (1.8 million ha) (Stewart, 2003). In some portions of the Texas High Plains, water levels in the Ogallala Aquifer have fallen more than 300 ft (90 m) over this period as a result of pumping for irrigation (TWDB, 2007).

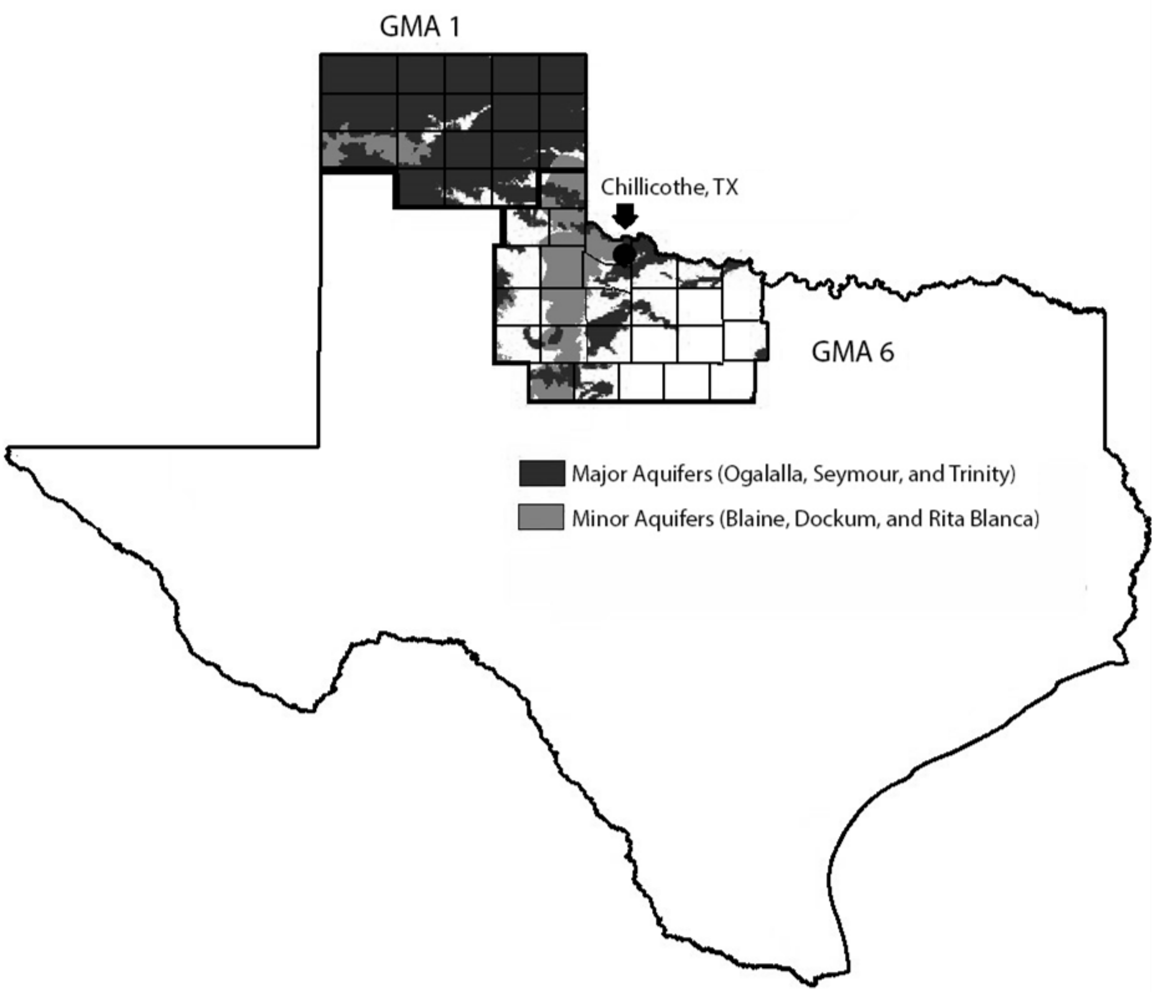

Figure 1: Groundwater Management Areas (GMA) 1 and 6.

In recent years, adoption of improved irrigation methods, such as low energy precision application (LEPA) center-pivot systems and sub-surface drip irrigation (SDI), has held the promise of more efficient use of water in growing crops, potentially slowing the rate of aquifer depletion. However, increasing demand for irrigated silage and grain crops to support rapidly growing dairy and biofuel industries in the Texas High Plains has worked against the potential benefits of more efficient irrigation methods by shifting production to crops with higher water demands (corn, forage sorghum, and alfalfa).

In the Texas Rolling Plains, only 5 to 8% of land is irrigated, but the revenue from the irrigated crop production is 3 to 6 times higher than dryland (Sij et al., 2009). Expansion of irrigation in this region while conserving water resources is achievable through the installation of efficient irrigation systems (Colaizzi et al., 2009; Rajan et al., 2010). In addition, improving the efficiency of existing on-farm irrigation systems is possible through effective irrigation scheduling.

Once the farmer has established an irrigation method (LEPA, SDI, etc.) and chosen a crop to grow, the opportunity remains to conserve water resources by scheduling irrigations to match the water demand of the crop without over-irrigating. The two important questions regarding irrigation scheduling are when to turn on/off the irrigation and how much to irrigate. Most producers in the region do not use any objective form of irrigation scheduling. In light of the uncertainty of how much water the crop is actually using, producers usually opt for conservatism and end up applying more irrigation water than is needed. Recently, many of the growers are becoming interested in making irrigation efficiency improvements. The advancements in irrigation scheduling include methods based on weather data, soil moisture measurements, plant temperature measurements, and satellite imaging. The recent advancements also include computer controlled irrigation, but the number of growers using these technologies is limited. Hence the objectives of the proposed project are:

1) Demonstrate the technologies available for conserving water resources associated with irrigated crop production.

2) Promote the adoption of irrigation scheduling technologies through a series of training programs.

The following tasks were developed for achieving the project goals.

Task 1: Equipment purchases and installation

Task 2: Hire research associate and conduct field work

Task 3: Organize and conduct training workshops and field day demonstrations

Task 4: Prepare reports

Deliverables for the project are the following:

a) Project website

b) Annual and final reports

c) Data base on water savings

d) Journal articles

e) Abstracts & presentations.

2.1 Soil and Water

The growth and yield of crops such as cotton in the semiarid Texas Rolling Plains is primarily driven by the amount of water available to the crop through rainfall and irrigation. However, the atmospheric demand for water (Potential Evapotranspiration/ET) considerably exceeds the amount of water supplied by precipitation. In this case, extra water must be supplied by irrigation to maintain a healthy plant cover.

Most plants receive water from the soil upon which they grow. Plants take up water from the soil through their roots to balance the water lost from the plant through their leaves by transpiration. The portion of the soil profile explored by the roots is called the *root zone*. The main soil characteristic that determines how much water the soil can hold, and how easily the plant can extract water from the soil, is *soil texture*. The soil texture determines the amount of gaps, or *pore space*, between the particles when they are packed together in the soil. The total porosity of the soil and the size of the pore spaces in the soil determine how much water the soil can hold. Small pore spaces ("micropores") do not drain easily through the action of gravity like large pore spaces ("macropores"). Figure 2 shows the water occupying the pore spaces of a hypothetical soil. The soil in Figure 2A is at *saturation*, where water completely occupies all the pore spaces in the soil. For soils, this could occur immediately after a substantial rainfall or irrigation, before the gravitational water has drained from the macropores. Figure 2B shows the soil after the gravitational water has drained from the centers of the macropores. A layer (or "skin") of water remains coating the surfaces of the soil particles, held in place by the combination of adhesive and cohesive forces. At this point, the soil is said to be at *field capacity* (FC).

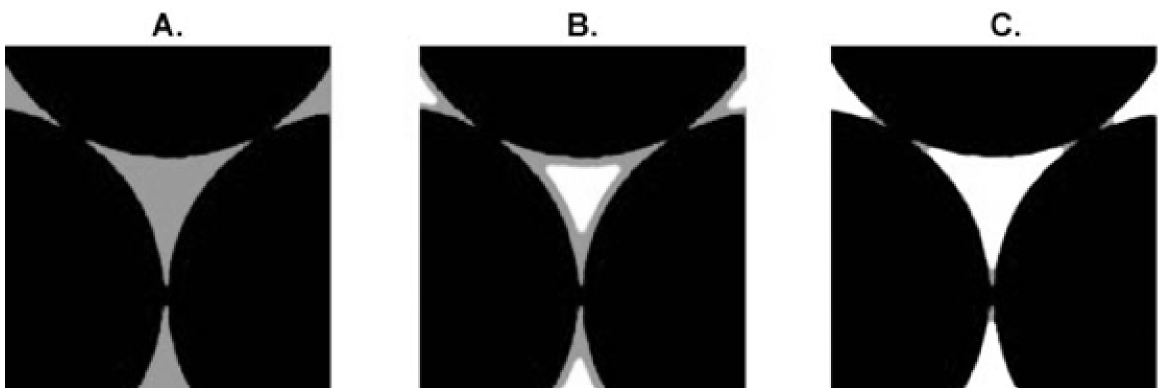

Figure 2: Water occupying the pore spaces of a hypothetical soil (A.) at saturation, (B.) at field capacity, and (C.) at the permanent wilting point.

In the absence of other forces acting upon the water molecules, the soil can theoretically remain at FC for an indefinite length of time, since in this state there is an approximate equilibrium between gravity and the adhesive and cohesive forces. However, the evaporation of water from plant leaves ("transpiration") produces a tension in the water column within the plant xylem stretching from the leaves down to the roots. This tension draws water up from the roots, creating a suction that attempts to pull water from the soil into the roots to maintain the water column. Roots can be very effective in removing water from the soil surrounding the roots. However, the suction created by the roots is not great enough to remove *all* the water from the pore spaces in the soil. In the very small spaces between soil particles, the adhesive forces on the water molecules are greater even than the force of suction produced by the roots. Therefore, roots normally cannot extract all the water from a soil. The point at which the roots have extracted all the water that they can from the soil is called the *permanent wilting point* (PWP). This situation is shown in Figure 2c. It is called the "permanent wilting point" because, at this point, the plant cannot withdraw any more water from the soil, so the water column in the plant xylem cannot be maintained. As a result, turgor is lost, and the plant wilts. Without the addition of more water to the soil, the plant will not recover from this wilting (hence, it is "permanent").

For a given soil, the difference between FC and the PWP represents the maximum amount of water in the soil available to support plant growth. This maximum amount is called the *plant available water* (PAW). In equation form, we can express this as follows,

$$PAW = FC - PWP \qquad [1]$$

Figure 3A shows typical characteristic curves for a sand and a clay soil. The horizontal line in this figure labeled "FC" indicates a soil water tension of -33 kiloPascal/kPa (-336 centimeter/cm), which is associated with field capacity for most soils. Kilopascal (kPa) is a commonly used unit of pressure. Similarly, the horizontal line labeled "PWP" indicates a soil water tension of -1500 kPa (-15,300 cm), which is associated with the permanent wilting point for most soils. The horizontal line labeled "Tensiometer Limit" indicates a soil water tension of -86 kPa (-878 cm), which represents the previously described lower limit to soil water tension that can be measured using a standard tensiometer.

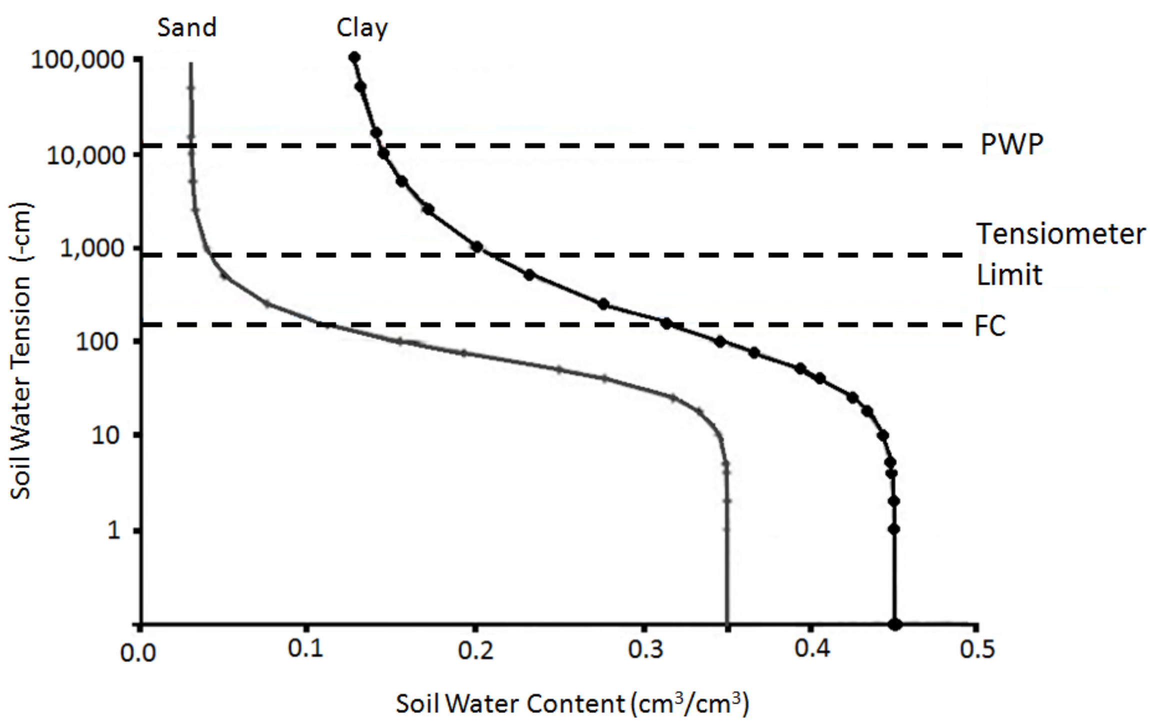

Figure 3A. Characteristic curves for a sand and a clay soil.
(Modified from source: Levitt and Young, 2003)

In Figure 3B, the values for the volumetric soil water content associated with FC and PWP are indicated for each soil. For the sandy soil, the volumetric soil water content at FC is approximately 0.105, while the volumetric soil water content at PWP is approximately 0.03. For the clayey soil, the volumetric soil water content at FC is approximately 0.31, while the volumetric soil water content at PWP is approximately 0.14. For each soil, the difference between the soil water content at FC and PWP represents the PAW. As we would expect, the PAW for the clayey soil is considerably greater than the PAW for the sandy soil.

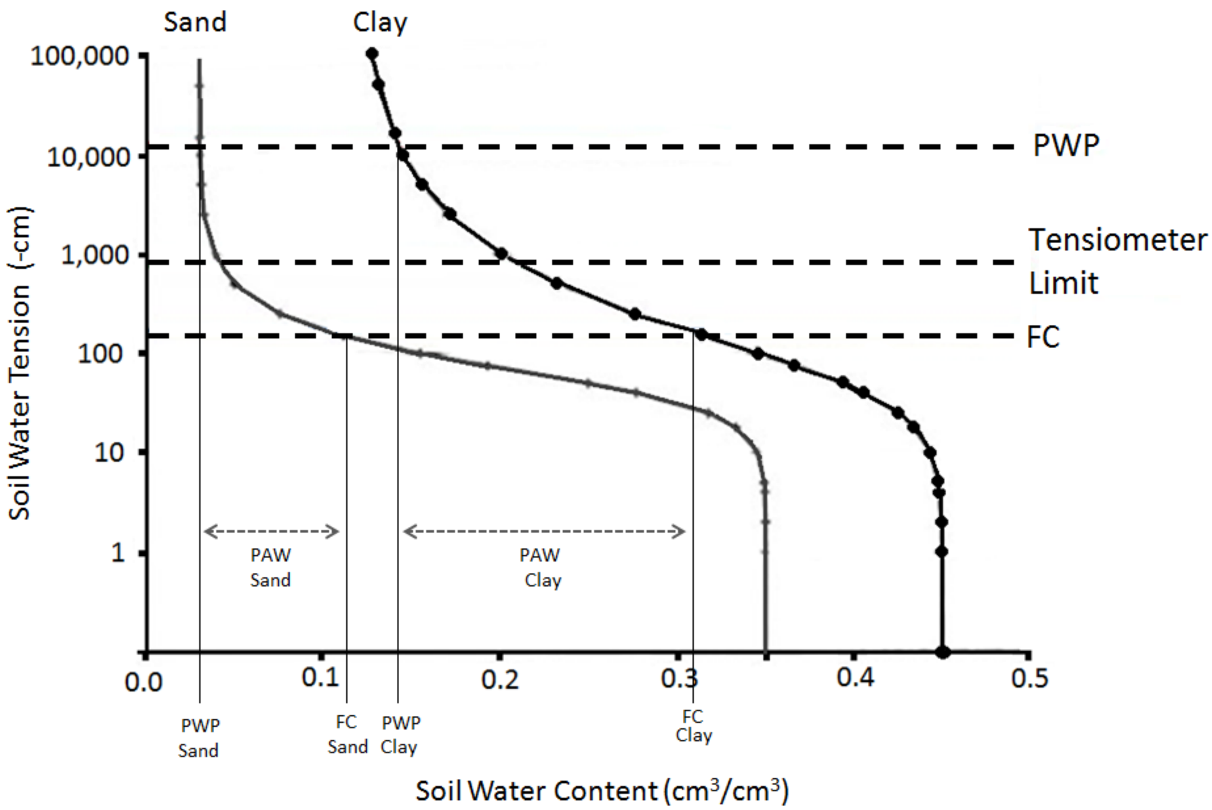

Figure 3B. Soil moisture characteristic curves with field capacity (FC) and permanent wilting point (PWP) shown. (Modified from source: Levitt and Young, 2003)

If we determine the value of PAW midway between the corresponding values of FC and PWP, we get the volumetric soil water content at which half of the PAW in the soil has been depleted. From the characteristic curves, we can determine the values of soil water tension associated with these values of soil water content. For the sandy soil, this turns out to be approximately -49 kPa (-500 cm), while for the clay soil, it is approximately -78 kPa (-800 cm). It is important to note that both of these values are greater than the lower limit for soil water tension measurable by standard tensiometers. Thus, a standard tensiometer should be able to measure when half of the PAW has been depleted in both the sand and the clay soil. Since these two soils represent the extremes in water holding capacity among the conventional soil textural classes, *a standard tensiometer should be effective in measuring when half of the PAW has been depleted in most soils.*

2.2 Irrigation Scheduling Methods

With our knowledge of how the soil holds water, and how plants extract water from soil through transpiration, we can use several approaches for scheduling irrigation. Irrigation techniques generally fall into two classes--

1) Irrigation to meet the transpirational demand
2) Irrigation to maintain the soil water content

In the demonstration project, we have tested four popular irrigation approaches which are described below.

2.2.1. Soil Tensiometers

Soil tensiometers are used for measuring soil water tension. The standard form of a tensiometer is shown in Figure 4. It consists of a tube with a rigid, porous semi-permeable ceramic tip. As shown in the figure, this tube is fit into a hole cut into the ground by a coring tool that allows intimate contact between the porous tip and the surrounding soil. Once the tensiometer is set into the ground, it is filled with water and the top is sealed with a cap. Once in place, water can move in and out of the tensiometer through the porous tip until the tension on the water in the tensiometer column balances the tension of the water held in the surrounding soil. This tension is measured with a vacuum gauge (reading 0 -100) connected to the tensiometer tube. As the soil dries, water moves out of the tensiometer into the surrounding soil in response to the increased soil water tension-- this increase is measured by the vacuum gauge.

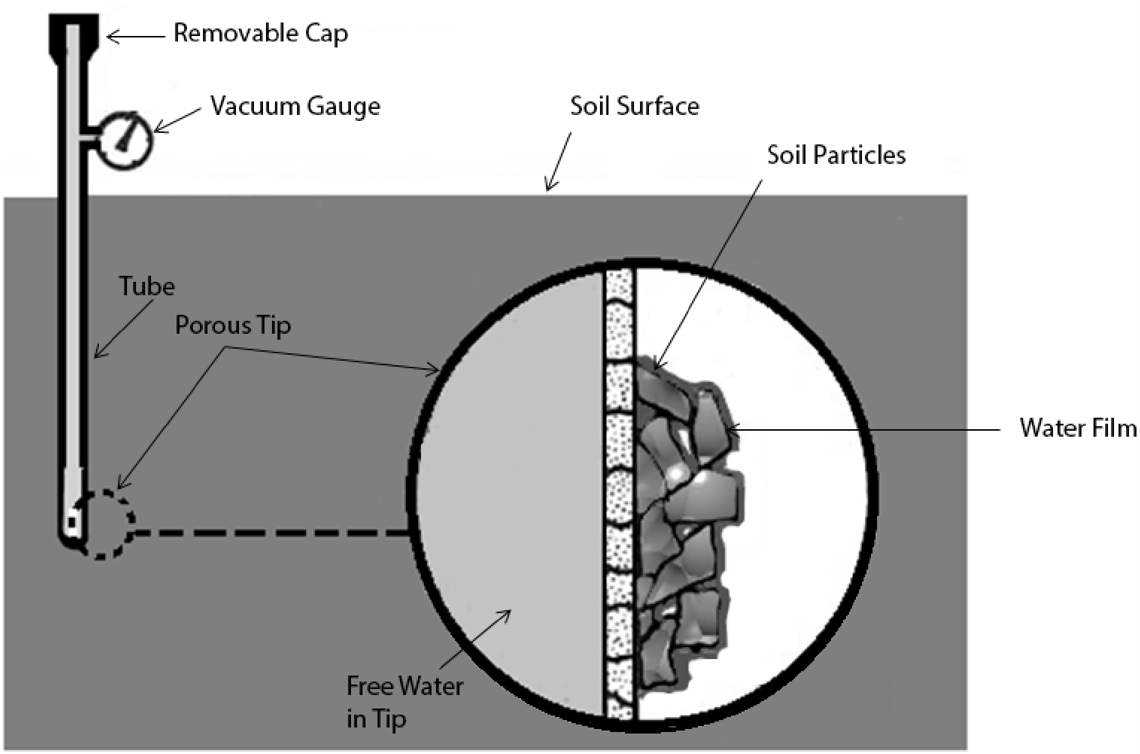

Figure 4. Standard soil tensiometer. (Modified from Risinger and Carver, 2006)

Tensiometers are easy to use and not very expensive. The main limitation of using a tensiometer to measure soil water tension is that they can measure tension only down to a value of around -0.85 atmosphere (-86 kPa, -0.86 bar, or -878 cm). Beyond that point, air begins to enter the porous tip, breaking the tension in the water column in the tensiometer (a process called *cavitation*). FC is generally associated with a soil water tension of -33 kPa, while the PWP is generally associated with a soil water tension of -1500 kPa. While the standard tensiometer can measure FC for most soils (0 – 20 in tensiometer), it is clearly beyond the capability of the standard tensiometer to measure PWP for most soils.

In conclusion, tensiometers really are useful in scheduling irrigation for crops growing on most soils, even though they can't measure the entire range of soil water tension. Other devices, such as time-domain reflectometry (TDR) and granular matrix sensors (like watermark sensors) can be used to determine soil water content as part of an irrigation scheduling program. These sensors generally are more complex than standard tensiometers, require an electrical power source for their operation, and must be read using an electronic device (such as a data logger).

2.2.2. Crop Coefficients

The crop coefficient approach has been widely used by agricultural engineers and irrigation specialists to estimate the water requirements of crops, particularly in regard to their needs for irrigation. In many agricultural regions, networks of weather stations have been established to provide the information needed to calculate reference evapotranspiration (ET_0). One can think of the value of ET as the water used by the crop under optimal conditions (i.e., if the plants were growing without water stress). This is the amount of water the irrigator would have to add to replace what is transpired by the plants-- i.e., the *water demand* of the plants. Additional factors have been developed to account for features such as soil wetness and water stress. The crop coefficient approach can be an effective method for irrigating large areas of relatively uniform vegetation, like agricultural fields.

Equations such as the Penman-Monteith Equation can be used to estimate how much water is necessary to meet the transpirational demand of plants on a given day. However, calculating potential ET using the Penman-Monteith Equation require information on stomatal resistance (something that typically is not easy to measure). A simplification of this procedure for estimating ET is by using ET_0 and crop coefficients. This approach is a way of separating the plant-related influences from the environment-related influences. The basics of the procedure are shown diagrammatically in Figure 5. In its simplest form, the procedure contains two steps. In the first step, the potential ET of a standardized reference surface is calculated based on ambient environmental conditions (solar radiation, air temperature, humidity, and wind speed). The standardized surface is usually considered to be a closely-clipped grass or alfalfa surface with sufficient water to prevent any stress effects. This is similar to the use of the Penman-Monteith Equation to calculate ET. In this approach, however, the values for the plant canopy characteristics (plant height and stomatal resistance) are fixed for the reference surface. The resulting value of potential ET for the reference surface is called the *reference ET* (ET_0). ET_0 is considered to represent a standardized "climatic demand" for water.

In the second step of the procedure, the ET of the plant species we are interested in is calculated by multiplying the reference ET by a parameter called a *crop coefficient* (K_c). The crop coefficient is unique for each plant species, and has a value that varies over the growing season to account for changes in the plant canopy characteristics, such as plant height, stomatal resistance, and ground cover. The crop coefficient converts the value of ET_0 on any day of the growing season into the appropriate value of ET for the plant species we are interested in (i.e., the crop evapotranspiration, ET_c). Once the reference ET has been calculated, then the crop ET can be determined using equation 2.

$$ET_c = K_c\, ET_0 \qquad [2]$$

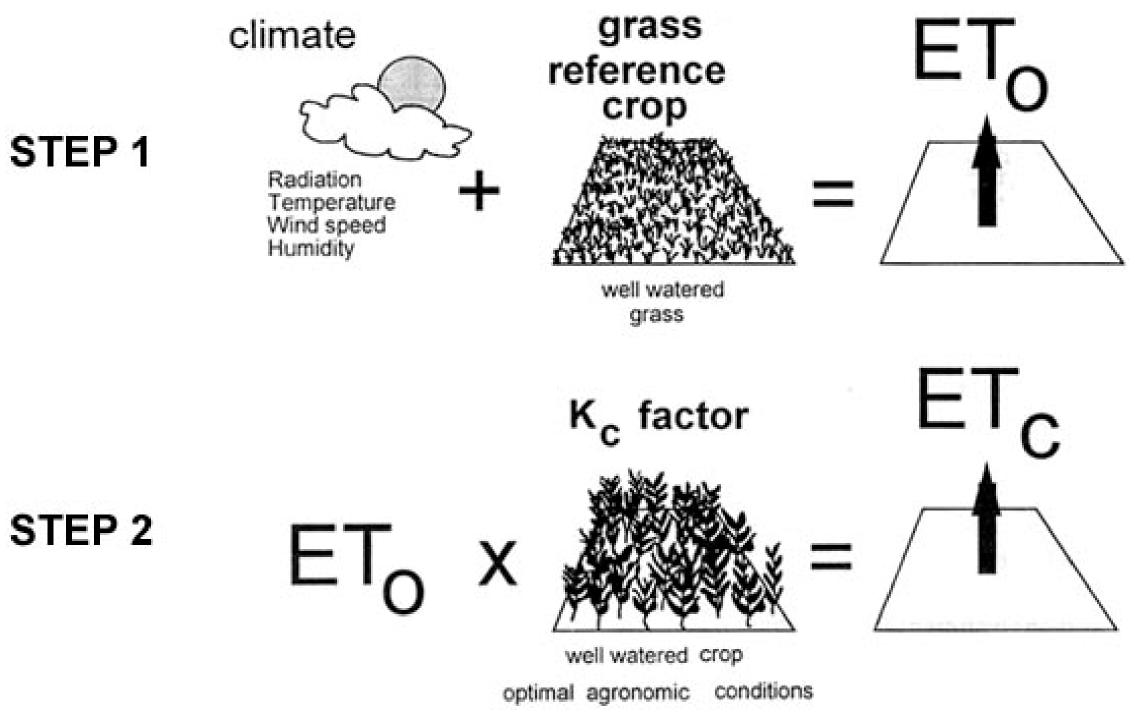

Figure 5. Diagrammatic representation of the estimation of crop ET using the crop coefficient approach. (Source: Allen et al., 1998)

The value of K_c can be greater than 1-- this indicates that the maximum ET for the crop can be greater than the maximum ET for the reference surface. For agricultural crops, the variation in a typical crop coefficient over the growing season depends upon the growth phase of the crop. Values of the crop coefficient at the start of crop growth ($K_{c\ ini}$), the mid-season ($K_{c\ mid}$), and the end of the growing season ($K_{c\ end}$) define the changes in magnitude of the crop coefficient with time. Linear transitions in the value of K_c between these periods complete the shape of the crop coefficient over the growing season. In general, the seasonal variation in the crop coefficient reflects the development and later senescence of the crop canopy.

Figure 6 shows values of K_c for cotton, corn and grain sorghum in the Texas Rolling Plains. These values were obtained from the Texas ET network website (http://texaset.tamu.edu/). The water requirement of grain sorghum and corn is higher early in the growing season compared to cotton as the crop coefficient values of grain sorghum and corn are higher compared to cotton. At the peak of the growing season, K_c increase to maximum value of 1.3 for corn, 1.1 for grain sorghum, and 1.1 for cotton. High K_c values represent high water demand. For grain sorghum, there are 17 days during the growing season when the K_c values exceed 1. For cotton, the number of days when K_c values exceed 1 is 33. For corn, the number of days when K_c values exceed 1 is 75.

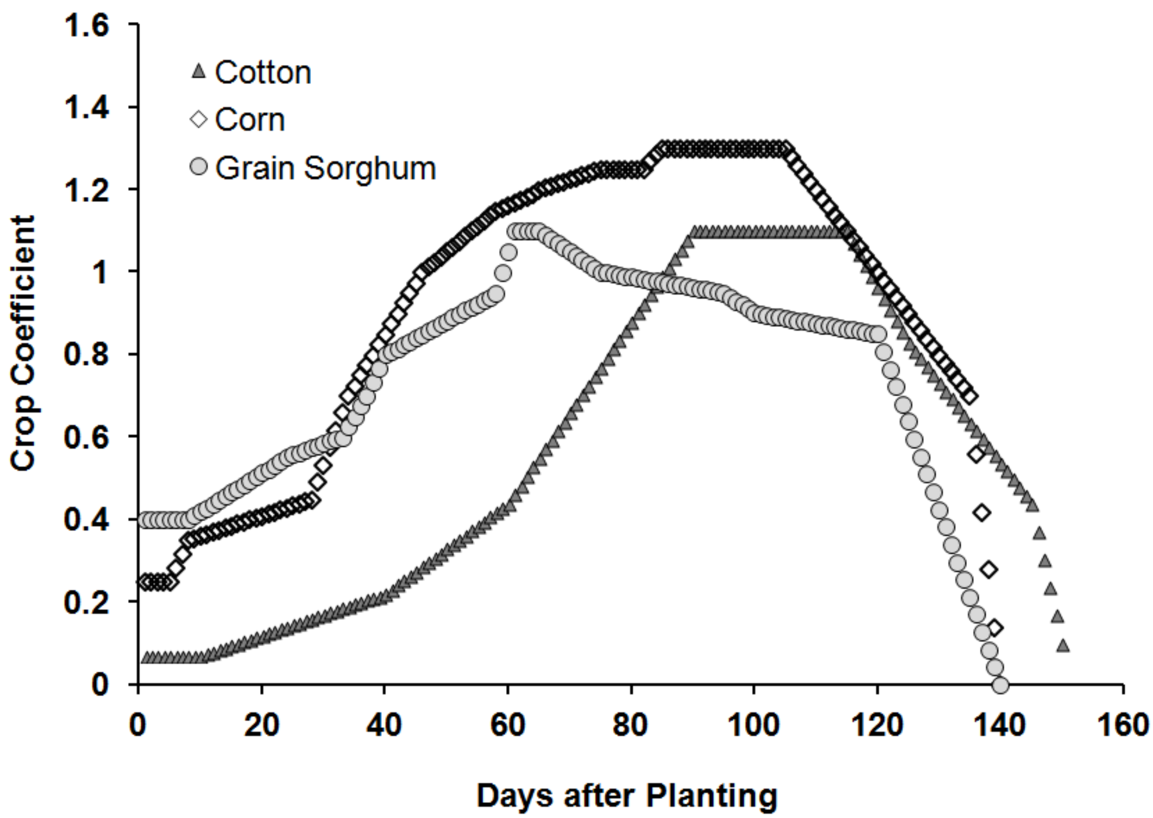

Figure 6. Crop coefficient curves for corn, cotton and grain sorghum.
Source: Adapted from Fipps: Texas ET Network. Available at: http://texaset.tamu.edu/.

2.2.3. Soil Moisture Sensors

One way to schedule irrigation is to keep track of the soil moisture in the rooting zone using soil moisture sensors. As soil moisture depletes in the root zone, irrigation can be applied to refill the rooting zone. To effectively schedule irrigation, we must put the water where it can be used by the plants. This means putting the irrigation water in the root zone (i.e., the portion of the soil profile occupied by plant roots). We normally don't want to let the soil moisture in the root zone to be depleted below half of PAW. Thus, half of PAW represents a rough estimate of the amount of water that can be transpired by the plants before we need to apply irrigation.

Why is a value of one-half PAW important to irrigation scheduling? Starting irrigation when half of the PAW in the plant root zone has been depleted is a common recommendation. Results of field experiments relating plant growth rate to soil moisture content has shown that the transpiration rate of sorghum and cotton plants falls below the maximum level when the soil moisture is depleted below around 30 percent of PAW. This decrease in transpiration rate results from closing of the leaf stomata, a process that also should affect the photosynthesis rate. Leaf extension rate of sorghum and cotton plants falls below the maximum level when the soil moisture is depleted below around 50 percent of PAW. This decrease in leaf extension rate results from a decrease in cell expansion in young leaves. Similar results have been reported for other plant species. These decreases in plant growth rate characteristically occur at soil moisture values below one-half PAW. Therefore, *if we begin irrigating when the value of soil moisture falls to half of PAW, then we should avoid significant stress effects on plant growth.*

2.2.4. SmartField

SmartField sensors are commercially available sensors that can be installed at different locations in the field (Figure 7). These sensors continuously measure crop canopy temperature. Crop canopy temperature is a good indicator of stress caused due to water deficits. Through years of scientific research, scientists have determined threshold temperatures for plants. Crop canopy temperature exceeding a pre-determined threshold temperature for extended periods of time can lead to crop water stress. If the crop canopy temperature is below the threshold temperature, then irrigation is not required. When the crop canopy temperature exceeds the threshold temperature for few hours, irrigation can be applied to avoid stress (Upchurch et al., 1996).

Figure 7: SmartField sensor in the demonstration field. (*Photo by Nithya Rajan*)

The crop canopy temperature information measured by the SmartField sensors will be relayed to a base station. The base station then relays the data to a local cellular tower which uploads the information onto the SmartField server. The information is updated every 15 minutes. These data can be accessed on the website *http://www.cropinsight. com/* using a username and password. A screen shot of this website with examples of real-time information is shown in Figure 8. The critical temperature and time threshold were set at 82^{o}F (28^{o}C) and 360 minutes, respectively. When the crop is water stressed (i.e., canopy temperature above 82^{o}F for six hours), the base station will send an email or text to the field operator with an "irrigate" recommendation to turn on the irrigation system. The base station also serves as a data logger and stores 15-minute average crop canopy temperature data for later analysis. The base station also has a rain gauge which records the rainfall at the field.

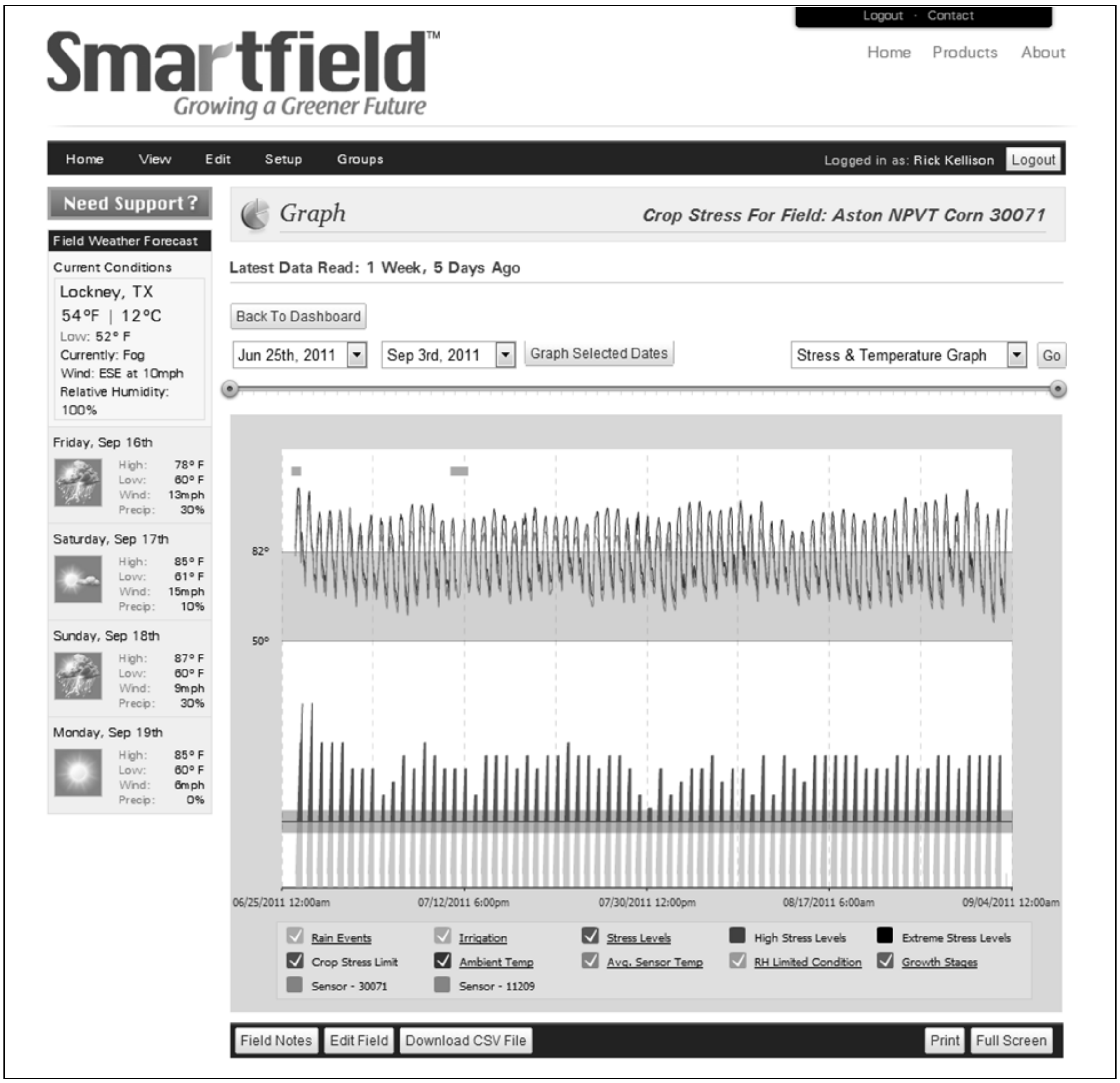

Figure 8: A screen shot of the real-time SmartField crop canopy temperature data from a demonstration site accessed from the website http://www.cropinsight.com/.

3. Methods and Results

3.1 Field Demonstrations

The demonstration project was established in subsurface drip-irrigated cotton field plots at the Chillicothe Research Station near Vernon, TX (Figure 9). This site has the capability of regulating and monitoring the amount of irrigation applied to various portions of the field. The soil type was Abilene clay loam. The total area of the demonstration site was 2.5 acres which was divided into 12 blocks. Each block was 150 ft long and 50 ft wide. Three blocks each were dedicated to variable amounts of irrigation based on one of the four proposed irrigation scheduling method (Tensiometer, crop coefficients, soil moisture sensors and SmartField).

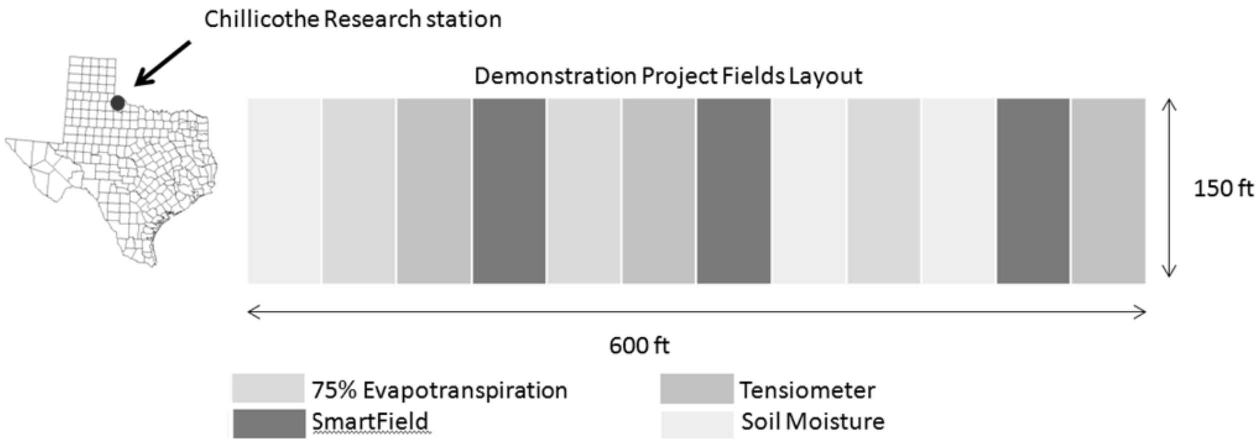

Figure 9: Location of demonstration project fields in the Texas Rolling Plains.

Cotton was planted on 23 May in 2011 and 2012. The variety planted was Deltapine 0912 (DP0912). This variety was chosen from a pool of varieties based on their fiber maturity and perceived drought tolerance. The seeding rate was 3 plants/ft of row and row spacing was 40 inches. The cotton emergence in all demonstration fields was good. Fertilizer rate was determined based on soil test nitrate nitrogen levels. Our plan was to apply fertilizer in two split applications, one at pre-planting and the second application at the first-square stage. All plots received a total of 140 lbs of nitrogen per acre. Nitrogen was knifed in as liquid fertilizer (28-0-0). All other agronomic practices were performed according to best management practice recommendations.

All blocks received a pre-plant irrigation of 3 inches 2011 and 1 inches 2012. All plots were irrigated uniformly from emergence to first square at a rate of 0.2 inches per day. Irrigation treatments started on 1 July in both years. In 2011, because of extreme drought and high temperatures, we continued irrigation after the post-cutout stage to ensure the availability of enough soil moisture reserves for cotton bolls to fully mature. The irrigation termination date was 14 September in 2011. In 2012, irrigation was terminated on 27August. The middle eight rows of each block were harvested in early November using a cotton stripper for yield measurements. Lint samples were ginned at the Texas A&M AgriLife Research Center in Lubbock, and samples were analyzed for quality at the International Textiles Center in Lubbock.

1. Tensiometers

Tensiometers (12 in, 18 in, and 36 in) were purchased from Irromerter Inc. (http://www.irrometer. com) for the demonstration project. Before installing in the field, tensiometers were kept in a bucket of water for several days for saturating the ceramic cup with water. This was done to avoid air bubbles entering the ceramic plate, thereby obstructing water flow through the ceramic plate. After letting the ceramic plate saturate with water, tensiometers were taken to the demonstration site and installed at 12, 24, and 36 inches depths (Figure 10). The tensiometers were installed such that the ceramic plate was in firm contact with the soil in the root zone.

Figure 10: (Top) Tensiometers installed at the demonstration site. (Bottom) Vacuum gauge of the tensiometer. A values of 50 indicates the need for irrigation and a value of 20 indicates saturated conditions.

The irrigation amount was determined from the tensiometer reading. Irrigation was started when the average tensiometer readings installed at 12, 24, and 36 inches depths was 50. Approximately 0.2 acre-inches per foot depth of irrigation was required to maintain a tensiometer reading of 20, which represents FC for the Abilene clay loam soil. Amounts of actual irrigation water applied based on the tensiometer method and rainfall received at the project sites are presented in Table 1.

Table 1: Tensiometer-based irrigation and precipitation data for 2011 and 2012 at the demonstration project site

Year	Pre-plant irrigation (inches)	Rain* (23 May – 30 September)	Tensiometer based Irrigation (inches)	Total Water Received* (Pre-plant + Rain+ Irrigation)
2011	3.00	3.62	19.00	25.62
2012	1.00	15.81	13.55	30.36

*Data shown are in inches.

2. Crop Coefficients (75% ET replacement)

The ET replacement was based on the crop ET demand calculated from weather data. These data were accessed from the High Plains ET network. Water was applied at 2-3 days intervals based on the previous day's ET data. The crop water/ET demand in 2012 was less compared to the crop water demand in 2011 on most days during the growing season (Figure 11). Amounts of irrigation water applied based on the 75% ET replacement method are presented in Table 2.

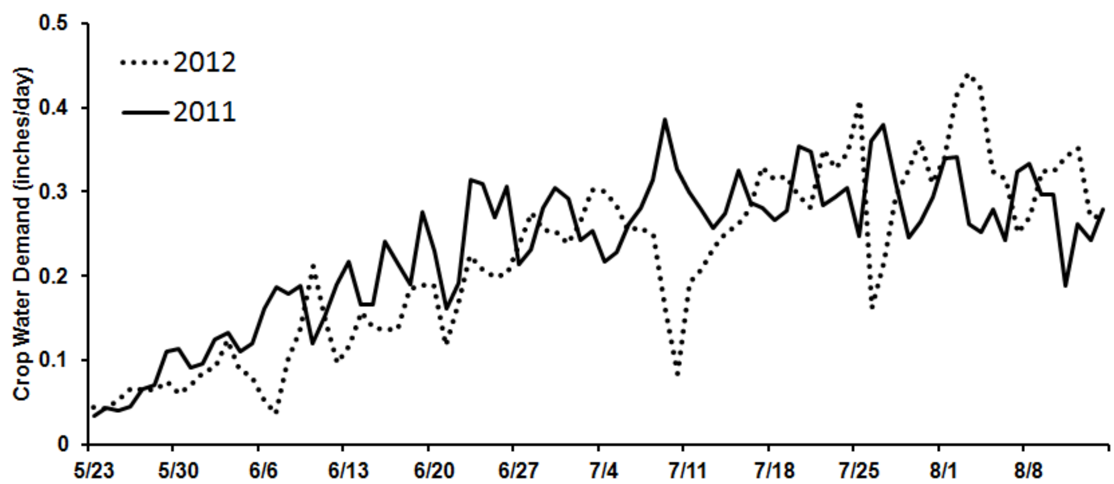

Figure 11: Crop water demand (ET) calculated using weather data from the Texas High Plains ET network station in Chillicothe (Porter et al., 2005).

Table 2: Crop coefficient-based irrigation (75% ET replacement) and precipitation data for 2011 and 2012 at the demonstration project site

Year	Pre-plant irrigation (inches)	Rain* (23 May – 30 September)	75% ET replacement based Irrigation (inches)	Total Water Received* (Pre-plant + Rain+ Irrigation)
2011	3.00	3.62	21.00	27.62
2012	1.00	15.81	12.50	29.31

*Data shown are in inches.

3. Soil Moisture Sensors

Our team initially approached the soil moisture monitoring company Aquaspy (http://www.aquaspy. com/) for installing moisture sensors at the demonstration site. Because of a large demand for these sensors in Texas and several states, the Aquaspy team was not able to install the moisture sensors on time for the demonstration project. So, our team purchased 24 Time Domain Reflectometry soil moisture sensors from Campbell Scientific Inc. (www.campbellsci. com). These sensors measure the electrical properties of a given volume of soil which in turn is related to volumetric water content of the soil. Hence, these sensors can accurately measure soil moisture content of the soil. The sensors were installed at 0-12 inch and 12-24 inch depths at several locations in the demonstration field. The measurements from these sensors were read using a data logger. Before installing in the field, these sensors were calibrated for the soil type (Abilene clay loam) at the demonstration site (Figure 12).

The amount of irrigation water application was determined based on soil moisture readings as described in section 2.2.3. The objective was to replenish half of the PAW. Water was applied at 2-3 days intervals. Amounts of irrigation water applied based on the soil moisture method are presented in Table 2.

Figure 12: (Left) Calibration of TDR sensors (Right) TDR sensors installed in the field.

Table 3: Soil moisture-based irrigation and precipitation data for 2011 and 2012 at the demonstration project site

Year	Pre-plant irrigation (inches)	Rain* (23 May – 30 September)	Soil moisture-based Irrigation (inches)	Total Water Received* (Pre-plant + Rain+ Irrigation)
2011	3.00	3.62	21.00	27.62
2012	1.00	15.81	11.60	28.41

*Data shown are in inches.

4. SmartField Sensors

SmartField sensors and a base station were purchased and installed in the field (Figure 13). These sensors continuously measured crop canopy temperature using an infrared thermometer and relayed the information to the base station. The information was updated every 15 minutes, and was accessed on the website *http://www.cropinsight.com/* using a username and password. The critical temperature and time thresholds were set at 82^{o}F and 360 minutes, which are the recommended values for cotton. The base station also served as a data logger and stored 15 minute average crop canopy temperature data. In addition, the base station also had a rain gauge and recorded the rainfall at the demonstration site.

Because of the extreme heat conditions at the demonstration project, canopy temperature stayed above 82^{o}F even after full irrigation. Hence, we encountered practical difficulties in scheduling irrigation using SmartField sensors. Irrigation was applied at 100% ET replacement level in demonstration plots where SmartField sensors were installed. Amounts of irrigation water applied based on this method are presented in Table 4.

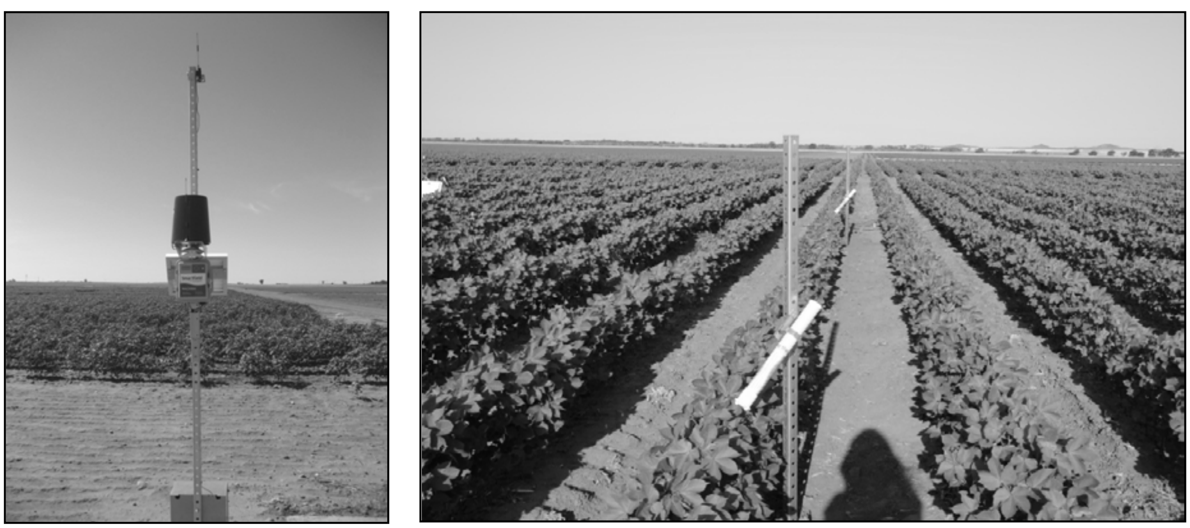

Figure 13: SmartField base station and sensors at the demonstration site.

Table 4: SmartField-based irrigation and precipitation data for 2011 and 2012 at the demonstration project site

Year	Pre-plant irrigation (inches)	Rain* (23 May – 30 September)	SmartField (100% ET replacement) based Irrigation (inches)	Total Water Received * (Pre-plant + Rain+ Irrigation)
2011	3.00	3.62	23.40	30.02
2012	1.00	15.81	16.39	33.20

*Data shown are in inches.

3.2 Outreach Activities

Outreach activities in the demonstration project were organized to target area producers and county extension agents in order to improve awareness of irrigation water management and scheduling. A field day was conducted at the Chillicothe Research Station on 17 July 2012 (see Appendix A for handout). The number of participants in the field day was approximately 30. Participants included county extension agents, area producers, NRCS personnel, and research scientists. Dr. Rajan also attended producer meetings organized by county extension agents and demonstrated the use of tensiometers and soil moisture sensors for scheduling irrigation (see Appendix B and C for presentations). The producer meeting in Turkey, TX was attended by approximately 40 area producers, and the meeting in Munday, TX was attended by approximately 20 area producers.

Data from the project were presented at a scientific conference in San Antonio, TX (see Appendix D for presentation and see Appendix E for abstract). A scientific article is currently being prepared targeting the popular international journal Agricultural Water Management. Popular media were also used to spread awareness of irrigation scheduling methods. The article "*Soil moisture monitoring tools will pay off*" was well-received (Appendix E).

We feel that, through our efforts over the course of this project, we generated information on irrigation scheduling tools that will be of substantial use and benefit to the producers of the Southern High Plains and Rolling Plains of Texas. To maintain our commitment to getting information to maximum number of producers and county extension agents, a project website was created that showcases information on all irrigation scheduling methods except SmartField sensors (http://people.tamu.edu/~nrajan/ irrigationschedulingtools). SmartField sensors were not included because of the difficulty in scheduling irrigation using these sensors in the warmer Texas Rolling Plains climate, as previously described. The project website is also linked from the Texas A&M AgriLife –Vernon website. This Texas A&M AgriLife –Vernon website has numerous visitors each day. We believe that linking the project website and showcasing the project results through this website will increase the visibility of the water conservation efforts associated with this project. This will also act as a mechanism to perpetuate the availability of the tools beyond the end of this project.

Dr. Rajan's current research addresses agricultural water management and conservation, and outreach efforts will be continued to spread awareness on irrigation water management and scheduling in the region.

3.3 Water Savings

The estimates of water savings associated with the demonstration project were derived from comparing the water application in the demonstration project to what producers were generally applying in this region. Producer application was determined after talking to several area producers in the region. Many producers in the region did not use any objective irrigation scheduling tools. The amount of irrigation producers applied varied from moderate deficit to over- irrigation with many producers falling in the latter category. Hence, producer application was fixed as 100% ET replacement.

The actual irrigation applied to fields in the demonstration project over the growing season provided an estimate of the irrigation and was considered as "optimally" managed irrigation. The optimally managed irrigation estimate ($IRRIG_{opt}$) for the growing season was calculated as follows,

$$IRRIG_{opt} = [\ (IRRIG_{obs}) - (RAIN_{eff})\ ] / EFF_{app} \qquad [3]$$

in which $IRRIG_{obs}$ is the irrigation applied based on the scheduling approach, $RAIN_{eff}$ is the seasonal value of effective rainfall, and EFF_{app} is the application efficiency for efficient irrigation systems. Water savings ($IRRIG_{sav}$) was calculated as:

$$IRRIG_{sav} = \text{Producer Application} - IRRIG_{opt} \qquad [4]$$

Irrigation Water Use Efficiency (IWUE) was calculated as:

$$IWUE = \text{Lint Yield} / \text{Irrigation} \qquad [5]$$

Crop Water Use Efficiency (CWUE) was calculated as:

$$CWUE = \text{Lint Yield} / (\text{Irrigation} + \text{Precipitation}) \qquad [6]$$

The values of IWUE, CWUE, and water savings are presented in Tables 5 and 6.

Table 5: Water use efficiency and water savings data for 2011 at the demonstration project sites

Irrigation scheduling method	2011						
	Area (acres)	Irrigation Application (inches)	Rain (inches)	Lint Yield (pounds/ acre)	IWUE (pounds/ acre/inch)	CWUE (pounds/ acre/inch)	IRRIGsav (acre-inches)
Tensiometer	0.60	22.00	3.62	559.07	25.40	21.80	4.40
75% ET	0.60	24.00	3.62	659.95	27.50	23.90	2.40
Soil Moisture	0.60	24.00	3.62	716.00	29.80	25.90	2.40
SmartField (at 100% ET)	0.60	26.40	3.62	917.07	34.70	30.50	0.00

Table 6: Water use efficiency and water savings data for 2012 at the demonstration project sites

Irrigation scheduling method	2012						
	Area (acres)	Irrigation Application (inches)	Rain (inches)	Lint Yield (pounds/ acre)	IWUE (pounds/ acre/inch)	CWUE (pounds/ acre/inch)	IRRIGsav (acre-inches)
Tensiometer	0.60	13.50	15.81	1337.39	99.07	45.60	3.89
75% ET	0.60	14.55	15.81	1281.82	88.10	42.20	2.84
Soil Moisture	0.60	12.60	15.81	1187.64	94.30	41.80	4.79
SmartField (at 100% ET)	0.60	17.39	15.81	1326.08	76.30	39.90	0.00

4. Discussion

The year 2011 was the most extreme drought year in modern records for the region. Climatologists have called 2011 the "worst one-year drought since 1895". The 2001-2010 average precipitation recorded at the Texas High Plains ET network station in Chillicothe was 24 inches. The corresponding recorded precipitation for 2011 at this weather station was only 8.1 inches. Precipitation data from 2011 and 2012 are summarized in Figure 14. As seen in Figure 14, the rainfall in 2012 was similar to the average values expected for the region.

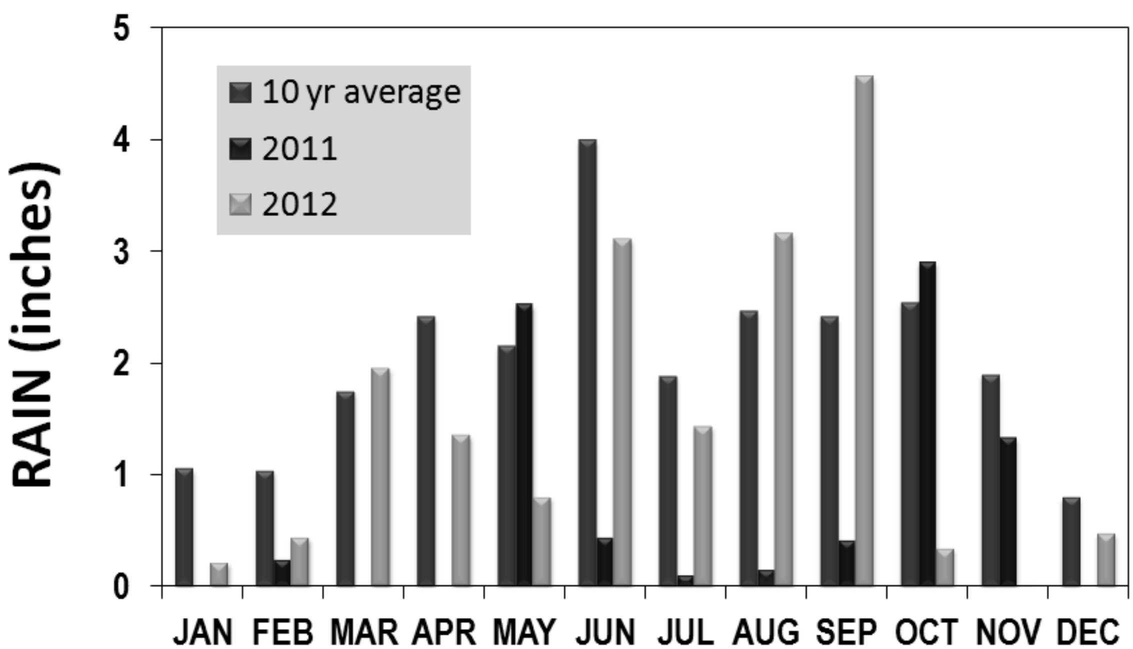

Figure 14: Precipitation data from the Texas High Plains ET network station in Chillicothe.

The lack of rainfall in 2011 was coupled with record high temperatures and, earlier in the growing season, high winds. The maximum air temperatures were above average in 2011. During most of the crop growing season, the maximum air temperatures were above 90°F. In the peak crop growth months of June, July and August, maximum air temperatures were above 100°F, a 20°F increase compared to the average air temperature of 80°F recorded for 2010. Figure 15 presents the 2011monthly average air temperature data compared to the average monthly maximum air temperature recorded in 2012. The average air temperature in 2012 was similar to the average values expected for the region. In the peak crop growth months of June, July, and August, average air temperatures were between 80 and 85°F, a 5-10°F decrease compared to the average air temperature recorded for 2011.

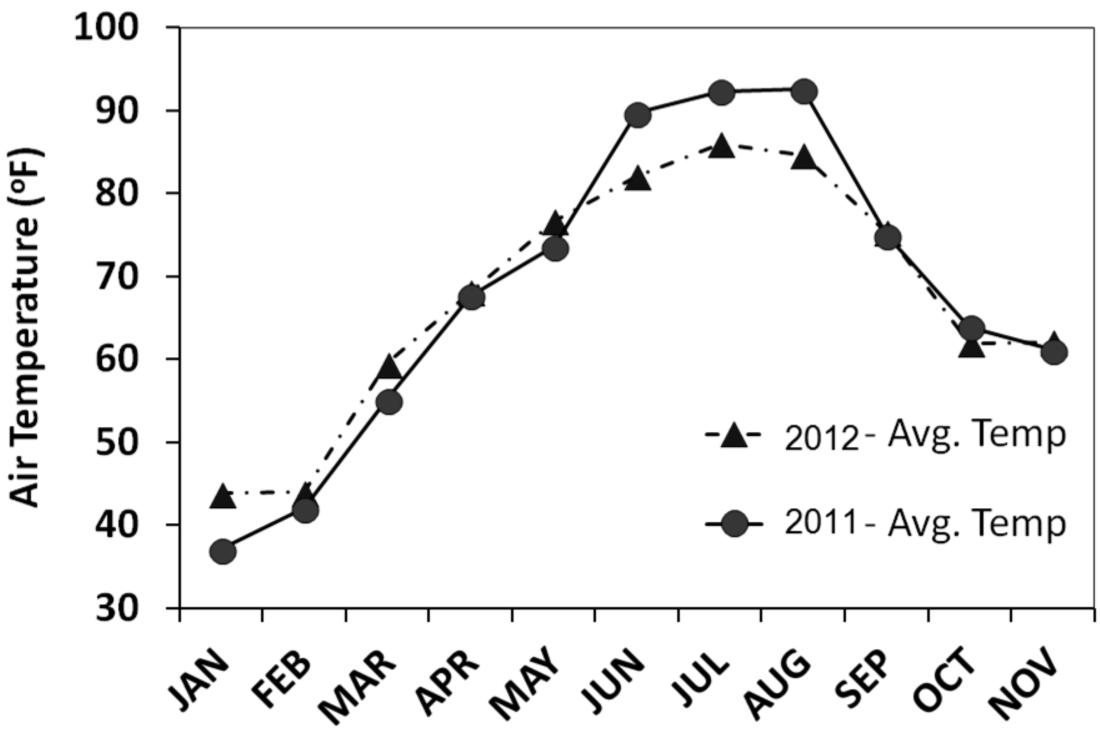

Figure 15: Maximum air temperature data from the Texas High Plains ET network station in Chillicothe.

The scant rainfall and high temperatures in 2011 led to a combination of extreme water stress and heat stress for most of the growing season for cotton plants in the demonstration area region. The daily accumulated heat units for normal cotton development in the region range from 1389 to 1444 from planting to 100% maturity. In 2011, the daily accumulated heat units were above 2000 units, as shown in figure 16. In 2012, plants in the demonstration project fields did not show any symptoms of heat stress.

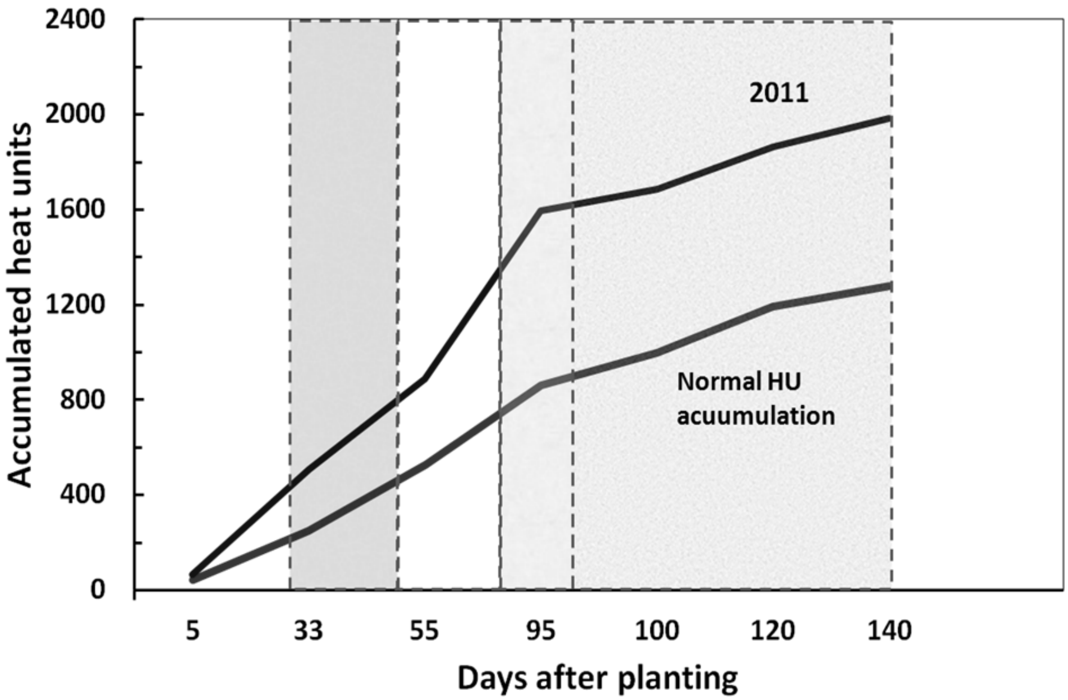

Figure 16: Accumulated heat units for cotton in the demonstration project region.

The variable rate irrigation for the different irrigation scheduling methods started in July. The amount of rainfall was taken into consideration while determining the irrigation amounts. The high temperatures and drought in 2011 presented a unique situation involving the use of SmartField sensors for scheduling irrigation. Because of high air temperatures, full irrigation at the 100% ET replacement level was ineffective in bringing the canopy temperature below 82^{o}F on all days during the growing season, and the crop canopy temperature remained above 82^{o}F for several hours (i.e., canopy temperature above 82^{o}F for six hours) each day. Due to the high sensible heat flux from the atmosphere to the crop canopy as a result of the extremely high daytime air temperatures, the added irrigations were not effective in bringing the canopy temperature back down below the upper threshold temperature used by the SmartField system as the indicator of water stress. Thus, the use of the current versions of SmartField sensors in regions with high air temperatures could potentially result in over-irrigation of the crop.

The greatest amount of irrigation was applied using the SmartField sensors at 100% ET replacement level in both years. In 2011, similar amounts of irrigation were applied based on the 75% ET and soil moisture-based methods, while the least amount of irrigation was applied using tensiometer-based irrigation scheduling. In 2012, the amount of irrigation applied based on the 75% ET method was an inch higher than the tensiometer-based application. The least amount of irrigation was applied using soil moisture-based irrigation scheduling. The differences in performance of soil moisture sensors and tensiometers in 2011 and 2012 might be attributed to the placement of sensors relative to the drip emitters.

In semi-arid regions like the Texas Rolling Plains, water is the most important factor affecting crop yield. The timing and amount of precipitation and irrigation play a major role in determining crop growth and yield. Seasonal precipitation in 2011 was only 3.62 inches. Normally, the dryland and deficit-irrigated cropping systems in the region depend on soil moisture accumulated during the winter and early spring to support early growth. However, the limited precipitation following the 2010 growing season resulted in little soil moisture reserves for the start of the 2011 growing season. We applied 3 inches of pre-plant irrigation at the demonstration project site. The summer of 2011 also exhibited extremely high temperatures and crop water demand was high compared to 2012. The extreme temperatures caused heat stress and considerable yield loss at the demonstration project sites even with full irrigation. Many commercial cotton fields were abandoned during the growing season in the region when insufficient water was available to fully irrigate the crop.

> "*In most of the cotton producing regions, current temperatures are already close to or above the optimum temperature for its growth and yield, particularly during flowering and boll growth period. Therefore, any increase in mean temperature or episodes of heat stress will further decrease yields*" (Singh et al., 2007).

2012 was a productive year in the Texas Rolling Plains. A seasonal rainfall of 15.81 inches was received at the project site. Of the four irrigation scheduling methods, the 75% ET replacement method resulted in the highest irrigation water use efficiency (99 pounds per acre-inch), followed by the soil moisture-based and tensiometer-based methods (94.3 pounds per acre-inch and 88.1 pounds per acre-inch, respectively). The highest amount of irrigation was applied on the 100% ET replacement sites. However, the irrigation water use efficiency was the lowest at these sites (76.3 pounds per acre-inch). The ET-based irrigation recommendation method uses a crop coefficient approach for estimating crop water demand. This crop coefficient corresponds to average well-watered field conditions and is generally not adjusted for conditions occurring in specific fields. This could lead to over-estimation of crop water demand and subsequent over-irrigation of the crop. This suggests that irrigation at 100% ET replacement could lead to over-irrigation and reduced water use efficiency. Deficit irrigation at the 75% ET replacement level resulted in an irrigation water use efficiency of 99 pounds per acre-inch, which is the upper limit of irrigation water use efficiency observed for cotton in this region (http://www.cottoninc.com/fiber/AgriculturalDisciplines/Engineering/Irrigation-Management/Why-Irrigate-Cotton/).

5. Conclusions

Evaluation of four different irrigation scheduling methods (Tensiometer, ET, SmartField, and Soil moisture) reveals that these methods have the potential to improve irrigation efficiency, although the use of each method may result in varying amounts of recommended irrigation. The ET-based irrigation recommendation method uses a crop coefficient approach for estimating crop water demand and uses weather data currently available from established weather monitoring networks in the region. This crop coefficient corresponds to average well-watered field conditions and is generally not adjusted for conditions occurring in specific fields. However, procedures exist to adjust irrigation recommendations to the actual crop growth conditions in specific fields. The use of SmartField sensors, which make irrigation scheduling recommendations based on measured crop canopy temperature, can be challenging in years with high air temperatures, as was the case for this study. Due to the high sensible heat flux from the atmosphere to the crop canopy as a result of the extremely high daytime air temperatures, the added irrigations were not effective in bringing the canopy temperature back down below the upper threshold temperature used by the SmartField system as the indicator of water stress. Thus, the use of the current versions of SmartField sensors in years with extremely high air temperatures could potentially result in over-irrigation of the crop. The tensiometers and soil moisture-based sensors are effective in monitoring soil moisture conditions in the field. A producer can use this information for scheduling irrigation by tracking the real-time soil tension or moisture conditions in a given field.

Our estimates show that adoption of tensiometer-based irrigation can conserve average 4.15 acre-inches of water per growing season compared to full irrigation. The adoption soil-moisture based irrigation can conserve an average of 3.60 acre-inches of water and the adoption of 75% ET replacement irrigation according to the crop coefficient method can conserve an average of 2.62 acre-inches of water. Because we applied full irrigation in demonstration plots with SmartField sensors, it did not result in any water savings.

In conclusion, the use of any of the four methods investigated in this study for scheduling irrigations is likely to be superior to the use of no objective method, in terms of protecting the crop from stress and avoiding over-irrigation. The ET and tensiometer methods are the simplest to implement, and would result in little cost to the producer. Of these two methods, the tensiometer method should be better at representing the actual water demand of individual fields, and thus may be less likely to result in over-irrigation. A trained producer can interpret the information from the tensiometers to make decisions regarding timing and amount of irrigation. The SmartField and soil moisture-based methods also appear to be suitable for practical use in irrigation scheduling, although each would involve a greater investment by the producer.

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7. Appendices

Appendix A

Irrigation Scheduling Tools

Principal Investigator: Nithya Rajan

Funded by: Texas Water Development Board (TWDB)

The two important questions involved in making irrigation recommendations are:

- WHEN?
- HOW MUCH?

Crop water requirements are different at different growth stages

There are several irrigation scheduling methods…but which one to choose?

Adoption by stakeholders is affected by three major factors:

- Cost
- Simplicity
- Awareness

The overall goal of the demonstration project is to provide the producers in our area with the best objective information available to help them manage irrigation water efficiently

Tensiometers

These are commercially available sensors that can be used to monitor soil water potential at various depths. Tensiometers offer producers a reliable, inexpensive soil moisture measurement option for irrigation scheduling. Tensiometers consist of a ceramic cup connected to a vacuum gauge through a tube. As the water moves out from the tensiometer, a partial vacuum is created in the tensiometer tube which creates a reading on the vacuum gauge. This reading is a direct indication of the energy that would be needed by the plant roots to extract moisture from the soil.

Soil tension reading between *0* and *20*: Adequate soil moisture
Soil tension reading above *40* or *50*: Start irrigating

Evapotranspiration (ET)

- This method is based on the crop evapotranspiration demand calculated from weather data.
- The best practical tool available for regional producers is "TAWC Solutions"
- Calculates ET using weather data from the West Texas Mesonet
- Includes a Soil Water Balance to track current soil moisture conditions
- Allows the user to modify input information (rainfall, irrigation, crop growth stage, etc.) to match conditions in the field

Soil Moisture Sensors

- Direct soil moisture measurements
- Several commercially available soil moisture probes are available that can be used to detect soil moisture conditions at various depths.
- Producers can access this information from the website.
- When the soil moisture content falls below a pre-determined level, the producer can

Hydrosense is a soil moisture sensor with a hand-held device that can be used to measure soil moisture up to 1 ft depth. (www.CampbellSci.com)

Canopy Temperature Sensors

- These are commercially available sensors that can be installed at different locations in the field. An example is the *SmartField* sensor.
- These sensors measure crop canopy temperature.
- When the crop is water stressed, these sensors will send a signal to the base controller in the form of an "irrigate" signal to turn on the irrigation system.
- A producer can monitor this operation in the form of text messages to his/her cell phone.

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Texas AgriLife Research and Extension Center
110708 Highway 70S, Vernon, TX 76384
P. O. Box 1658, Vernon, TX 76385
Phone: (940) 552-9941 x 230
Email: ***nrajan@ag.tamu.edu***

Project participants:
Paul DeLaune
Srinivasulu Ale

Appendix B

Tools to Aid Irrigation Efficiency

NITHYA RAJAN
Agronomist
Texas AgriLife Research
Vernon, TX

1

Irrigation Recommendations

The two important questions involved in making irrigation recommendations are —

- WHEN?
- HOW MUCH?

Irrigation Scheduling Tools

Crop water requirements are different at different growth stages

Figure 1. Growth stages of the cotton plant

3

Irrigation Scheduling Tools

There are several irrigation scheduling methods…but which one to choose?

4

Irrigation Scheduling Tools

As in the case of any technology, its adoption by stakeholders is affected by three major factors:

- Cost
- Simplicity
- Awareness

5

1 :Tensiometers

6

7

Install at different depths

6”
12”
18”
24”
36”

8

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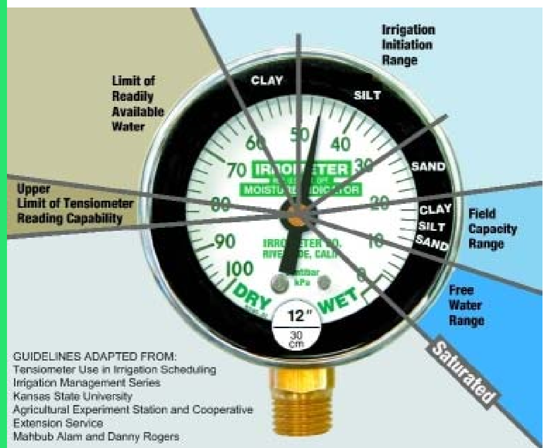

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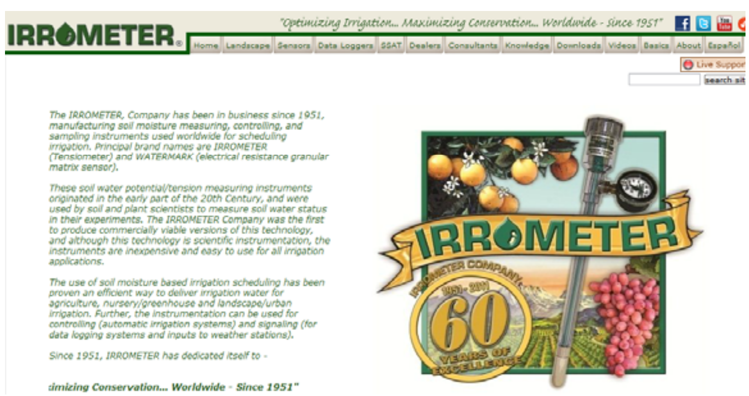

10

Tensiometers

- ➢Simple tool
- ➢Inexpensive

Some drawbacks….

- Constant maintenance
- Good contact between soil and tensiometer
- Sub-surface drip: Several tensiometers are necessary

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2: Soil moisture sensors

- ➢ Direct soil moisture measurements
- ➢ Majority of these sensors are highly technical
- ➢ **Handheld devices**

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HydroSense®
Soil Water Measurement System (CD620, CS620)

CAMPBELL SCIENTIFIC
WHEN MEASUREMENTS MATTER

The HydroSense system combines a compact, hand-held display (CD620) and a sophisticated soil water sensing probe (CS620) in a portable package to provide quick and reliable soil water content measurements. Each measurement takes less than one second and is obtained by inserting the probe rods into the soil and pressing a single button on the display unit. A choice of 12- or 20-cm long probe rods makes HydroSense a versatile tool for monitoring and managing soil water in a wide range of conditions.

The microprocessor-controlled circuitry and two-line readout are contained in a splash-proof enclosure that includes two integral membrane buttons used to operate the system. A 5-ft coiled cable connects the display to the probe. The 5 mm diameter stainless steel rods are an integral part of the electronic circuitry encapsulated in the epoxy probe head. The parallel rods constitute a driven transmission line which is sensitive to dielectric permittivity and consequently water content.

The HydroSense has two modes of operation. The water content measurement mode uses standard laboratory calibrations to provide percent volumetric water content in the range from air dry to saturated.

In the water deficit mode, HydroSense measurements are taken at lower and upper water contents as specified by the user and stored in memory as reference values. The reference values are then applied to subsequent measurements to determine the amount of water that must be added to bring the soil to the upper water content.

The Hydrosense system consists of the CS620 sensor (left), the CD620 display (right), and two rods.

13

3: SmartField

- Crop canopy temperature-based.
- ‘Irrigate signal’

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SmartField

- Access the data online
- cropinsight.com

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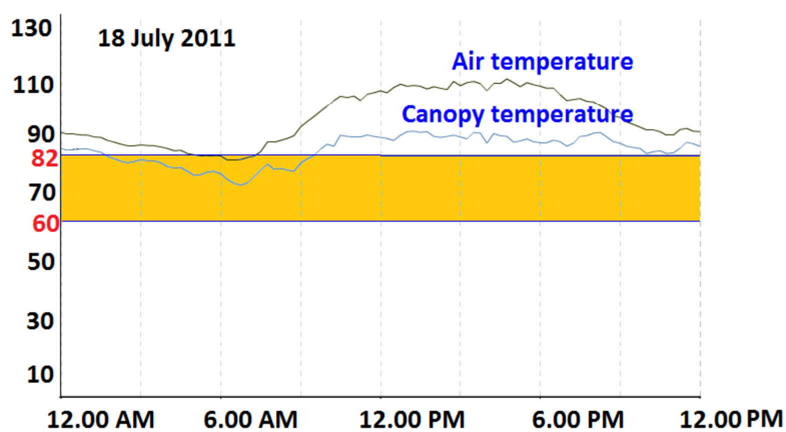
SmartField



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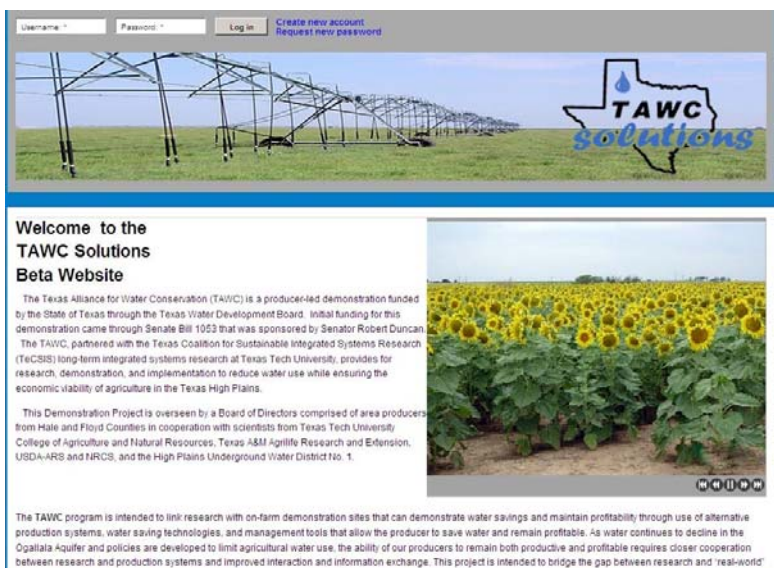
4: Crop Evapotranspiration

17

TAWC Solutions Irrigation Scheduling Tool



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TAWC Solutions Irrigation Scheduling Tool

- Calculates Reference ET from the West Texas Mesonet
- Includes a Soil Water Balance to track current soil moisture conditions
- Allows the user to modify input information (rainfall, irrigation, crop growth stage, etc.) to match conditions in the field

19

5: Next-Generation TAWC Solutions Irrigation Scheduling Tool

- Advanced version of the current tool
- Under development and testing for release for the 2012 growing season
- Will include a number of advanced features that will provide more information and options to the user
- Will build on the knowledge gained from the previous 7 years of the TAWC Project

20

Next-Generation TAWC Solutions
Irrigation Scheduling Tool

21

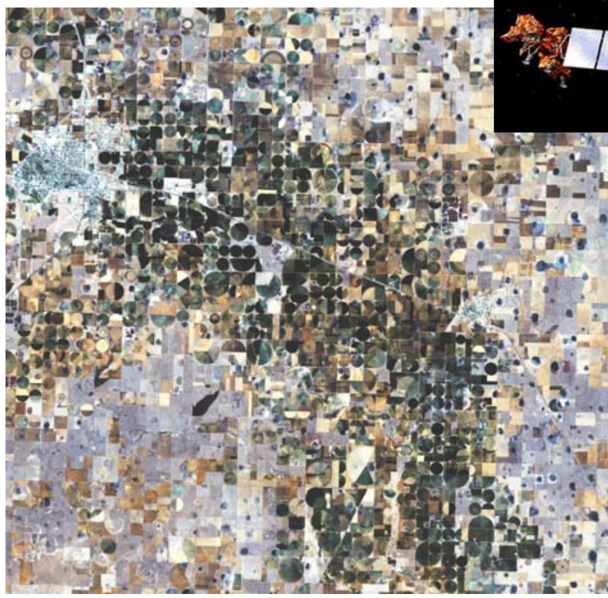
Crop Coefficients

The next-generation irrigation scheduling tool will use crop coefficients developed from satellite observations.

"Spectral Crop Coefficients"

22

Crop Coefficients



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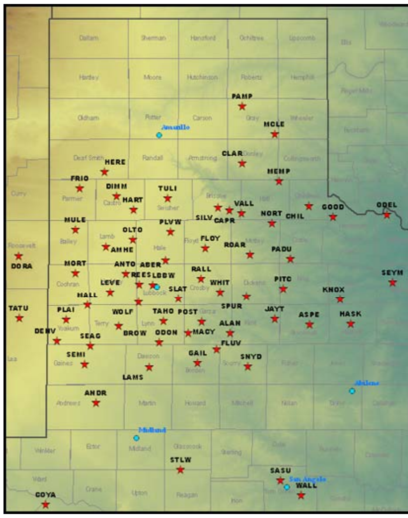
Crop Coefficients

Crop coefficients used in the next-generation tool will be specific to each individual field.

The goal of the next-generation tool is not to estimate crop water use for the "optimum field in the region", or for a "typical field in the region", but to estimate the crop water use for <u>your field</u>.

24

The next-generation TAWC irrigation scheduling tool will continue to use weather observations from the West Texas Mesonet.



25

Irrigation Recommendations

The next-generation TAWC irrigation scheduling tool will provide the following information—

- **How many days from the current day will it take for the crop to start being water stressed.**

  — this gives the user lead time to set up an irrigation.

- **How much water must be applied (by irrigation or rainfall) to avoid stress and maintain the soil moisture at an optimum level.**

  — the user can use the default values for the optimum soil moisture level already in the tool, or they can define their own values.

26

Overall Goal

The overall goal is to provide the producers in our area with the best objective information available to help them manage their crops.

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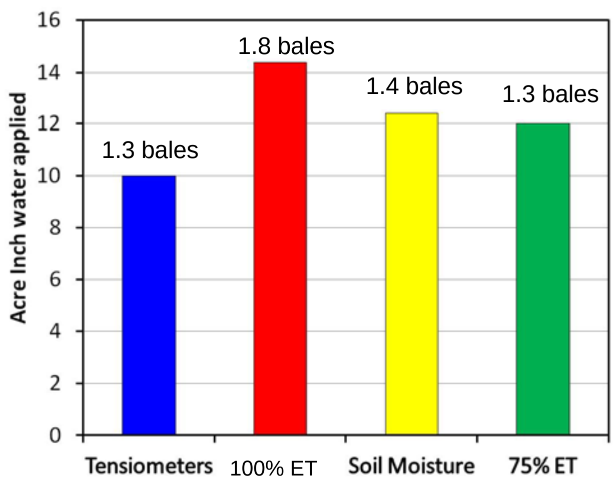
Demonstration project at Chillicothe Research Station



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We are indebted to the Texas Water Development Board for making this project possible, and especially to the many producers that provide the guidance, direction, and encouragement for our activities.

Appendix C

AgriLIFE RESEARCH

Cotton irrigation requirements

Nithya Rajan
Agronomist
Texas A&M AgriLife Research, Vernon, TX

1

AgriLIFE RESEARCH

Cotton water relations

- Environment changes every year.
- Cultivars change every year.
- Insect or weed pressure can change everything.
- Predictions are really reflections of past experiences and current circumstances

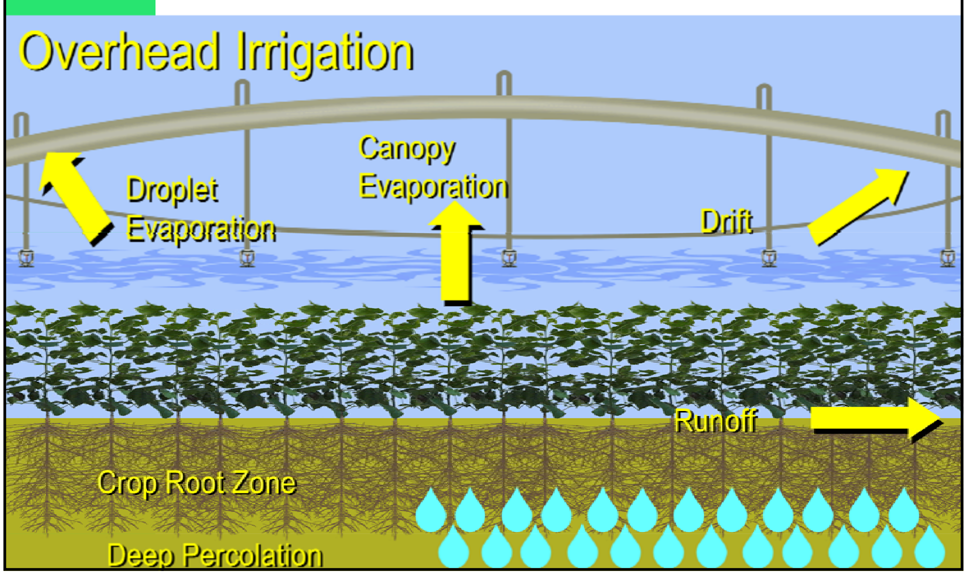
2

Why not play it safe and over-water?

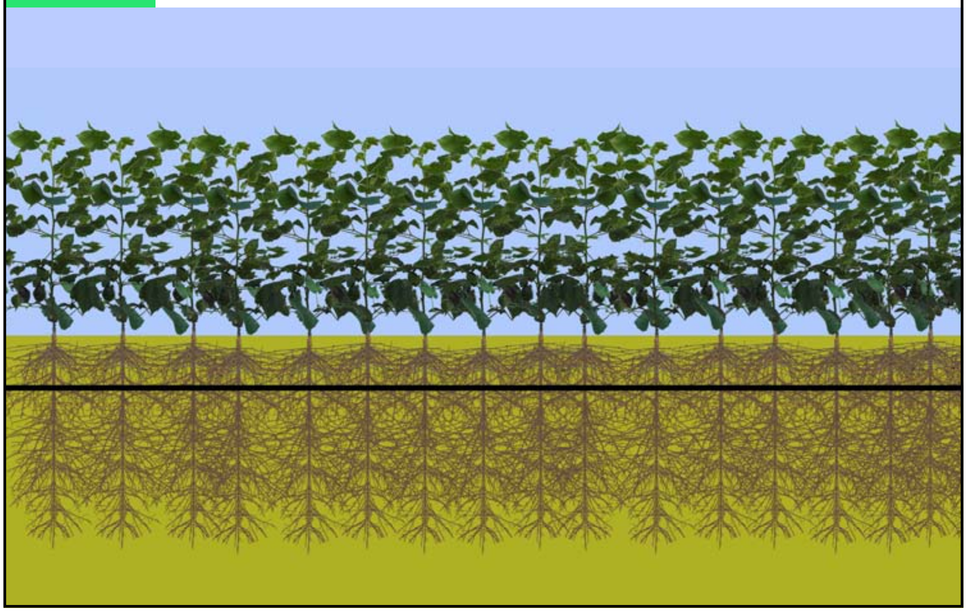
- Expensive
- Nitrogen leaching
- Roots become oxygen-starved

3

Irrigation efficiency

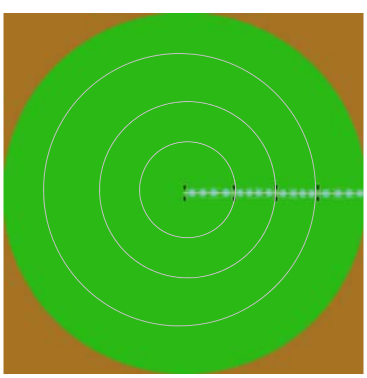


Drip - Irrigation efficiency



Pivot Irrigation

- Works well for circular fields



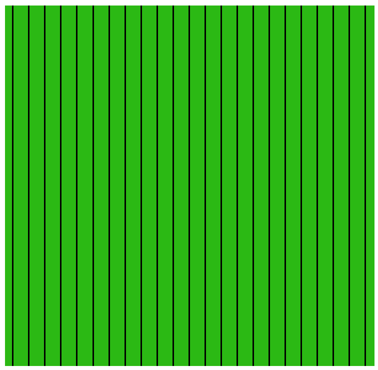
1,000 m

21% NOT WATERED

1,000 m

Drip Irrigation

Increased Efficiency



1,000 m

100% WATERED

1,000 m

Irrigation Recommendations

The two important questions involved in making irrigation recommendations are —

- WHEN?
- HOW MUCH?

Irrigation Scheduling

Crop water requirements are different at different growth stages

Figure 1. Growth stages of the cotton plant

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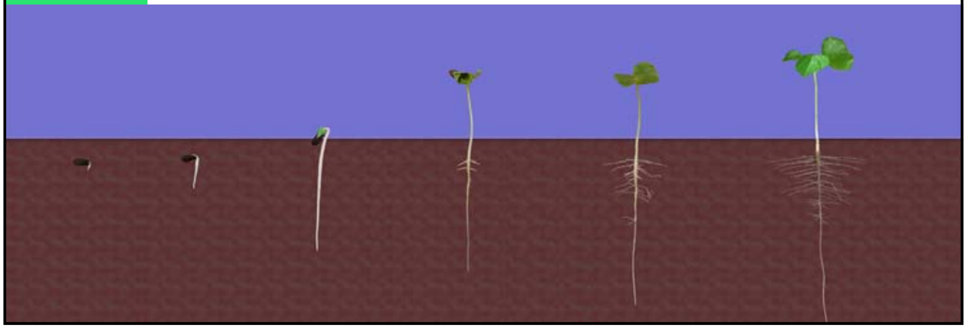
Germination

- Moisture critical for emergence & stand establishment
- Water use is small

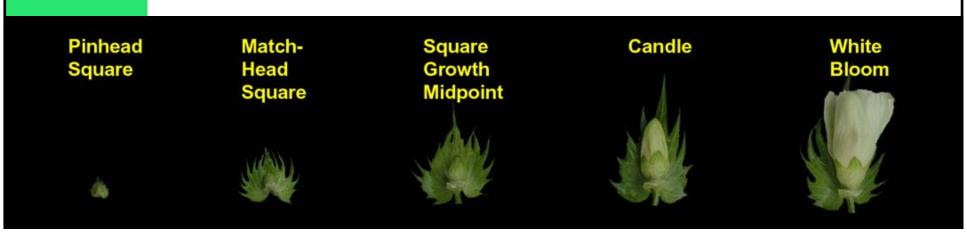


Early growth

- Root growth dominates total plant growth
- Photosynthesis increases
- Leaves begin to transpire more water

Squaring and Flowering

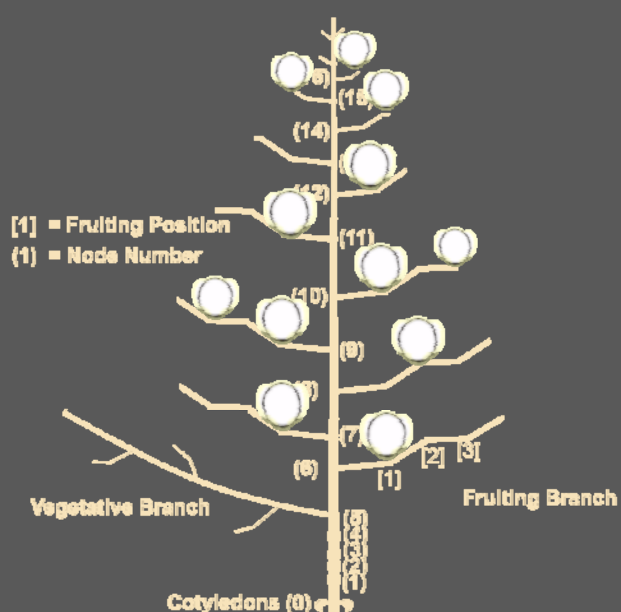
- Maximum level of photosynthesis
- Maximum level of water use
- Roots reach peak capacity as plant begins to shift priorities from roots to boll development



Cutout and Boll Filling

Drought affects

- **Boll retention**
- **Within-boll yield components**
- **Quality**



17-1	17-2	17-3
16-1	16-2	16-3
15-1	15-2	15-3
14-1	14-2	14-3
13-1	13-2	13-3
12-1	12-2	12-3
11-1	11-2	11-3
10-1	10-2	10-3
9-1	9-2	9-3
8-1	8-2	8-3
7-1	7-2	7-3
6-1	6-2	6-3
5-1	5-2	5-3

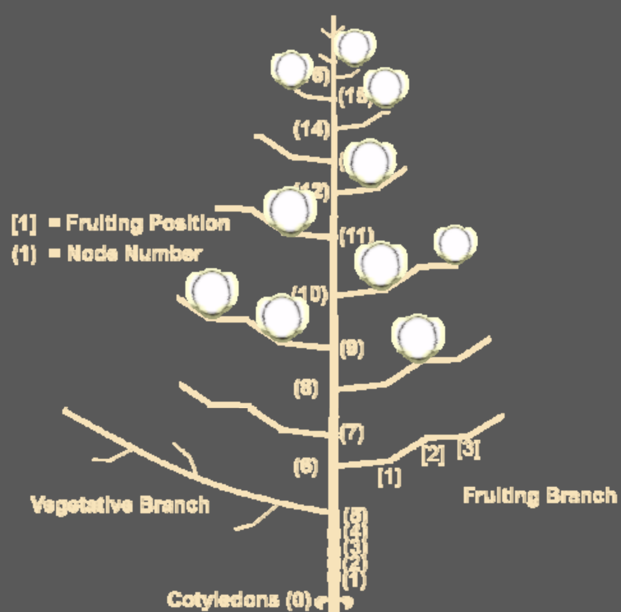
14

Early Fruiting

17-1	17-2	17-3
16-1	16-2	16-3
15-1	15-2	15-3
14-1	14-2	14-3
13-1	13-2	13-3
12-1	12-2	12-3
11-1	11-2	11-3
10-1	10-2	10-3
9-1	9-2	9-3
8-1	8-2	8-3
7-1	7-2	7-3
6-1	6-2	6-3
5-1	5-2	5-3

15

Late Fruiting



17-1	17-2	17-3
16-1	16-2	16-3
15-1	15-2	15-3
14-1	14-2	14-3
13-1	13-2	13-3
12-1	12-2	12-3
11-1	11-2	11-3
10-1	10-2	10-3
9-1	9-2	9-3
8-1	8-2	8-3
7-1	7-2	7-3
6-1	6-2	6-3
5-1	5-2	5-3

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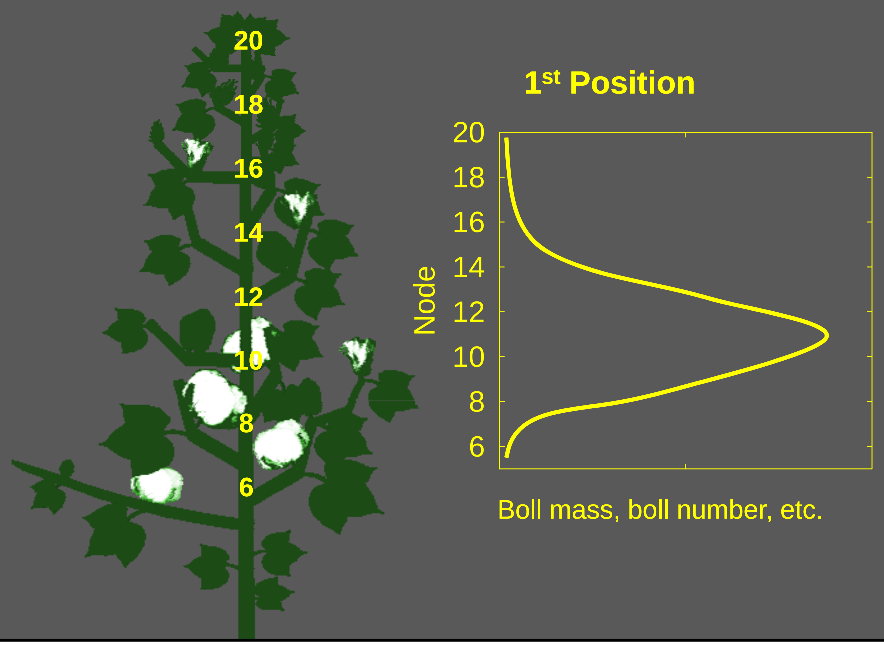
Late Fruiting



Irrigation Timing

- Crop water use varies by growth stage.
- Sensitivity to drought stress varies as well.

Cotton Irrigation Schedule Suggested For High Yields

	In./Week	In./Day
Wk. beginning at 1st bloom	1	0.15
2nd wk. after 1st bloom	1.5	0.22
3rd wk. after 1st bloom	2	0.3
4th wk. after 1st bloom	2	0.3
5th wk. after 1st bloom	1.5	0.22
6th wk. after 1st bloom	1.5	0.22
7th wk. after 1st bloom	1	0.15

Weekly quantities should be increased to compensate for run-off.

18

Irrigation Timing

- Which crop stage is most sensitive to stress?
- Experiment conducted at TTU with 4 cultivars subjected to the following irrigation treatments:
  - No irrigation from first square to first flower
  - No irrigation from first flower to 3 weeks after first flower
  - No irrigation from 3 to 6 weeks after first flower
  - No irrigation from 3 to 9 weeks after first flower

First Square to First Flower

- Severe stunting
- Fewer bolls
- 20-25% yield decrease

First Flower to FF + 3 Weeks

- Nearly full crop height
- Massive shedding
- Yields reduced 60-70%

Peak Bloom (3 weeks)

- Yields decreased 20-30%
- Decreased boll numbers at the top of the plant
- Less sensitive to stress than early bloom

Peak Bloom (6 weeks)

- Yields decreased 30-35%
- Decreased boll numbers at the top of the plant
- Less sensitive to stress than early bloom

Full Irrigation

Drought Episodes

Cultivar	Squaring	Early Flower	Peak Bloom (3 weeks)	Peak Bloom (6 weeks)	Full Irrigation
DP0912B2RF	1153	566	1123	1033	1552
DP0935B2RF	1253	545	1031	1076	1516
FM9170B2F	1184	476	1021	976	1440
FM9180B2F	1080	478	1115	1035	1345

Total lint yield per acre for different drought stress timings

Drought Episodes

Cultivar	Squaring	Early Flower	Peak Bloom (3 weeks)	Peak Bloom (6 weeks)	Full Irrigation
DP0912B2RF	74%	36%	72%	67%	100%
DP0935B2RF	83%	36%	68%	71%	100%
FM9170B2F	82%	33%	71%	68%	100%
FM9180B2F	80%	36%	83%	77%	100%

Percent of total irrigated yield for different drought stress timings

Timing - Termination

- We often get questions about the timing of irrigation termination
  - Cultivar-specific
  - In most cases, the extra irrigation does not pay for itself
    - Requires eyes on the field to make the determination

	Contribution of Uppermost 2 node cohort to yield	
cultivar	dryland	Irrigated
DP0935B2RF	2.1%	4.5%
DP0949B2RF	3.8%	3.4%
DP161B2RF	0.9%	1.4%
DP164B2RF	0.8%	2.9%
DP174RF	0.9%	2.1%
DP555BG/RR	4.0%	8.6%
PHY375WRF	1.9%	0.6%
PHY480WR	0.8%	0.7%
PHY565WRF	2.9%	2.3%
ST5288B2F	0.6%	2.2%
ST5327B2RF	3.0%	0.6%
ST5458B2RF	2.7%	0.9%

Irrigation Rate

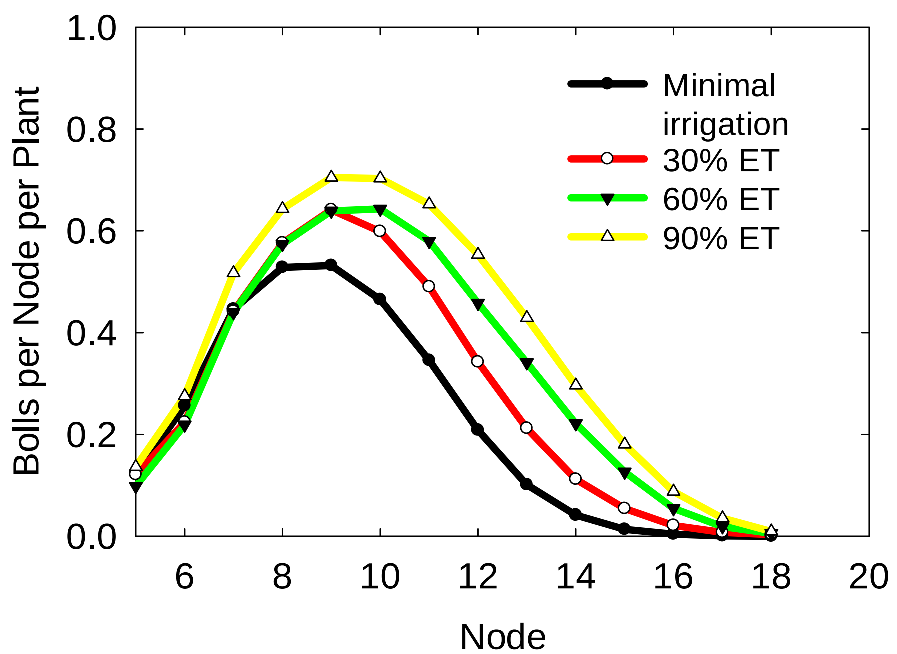
- Caveats:
  - Temperature and irrigation source

Cotton Irrigation Schedule Suggested For High Yields

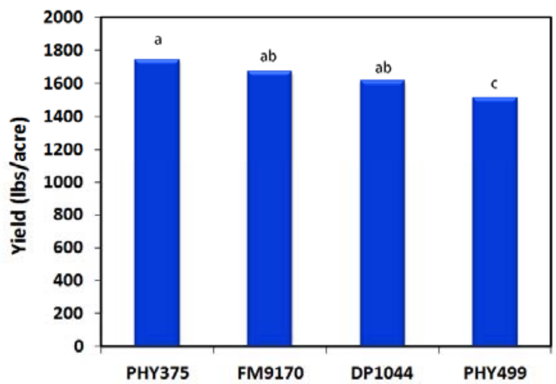
	In./Week	In./Day
Wk. beginning at 1st bloom	1	0.15
2nd wk. after 1st bloom	1.5	0.22
3rd wk. after 1st bloom	2	0.3
4th wk. after 1st bloom	2	0.3
5th wk. after 1st bloom	1.5	0.22
6th wk. after 1st bloom	1.5	0.22
7th wk. after 1st bloom	1	0.15

Weekly quantities should be increased to compensate for run-off.

2011 UGA Production Guide



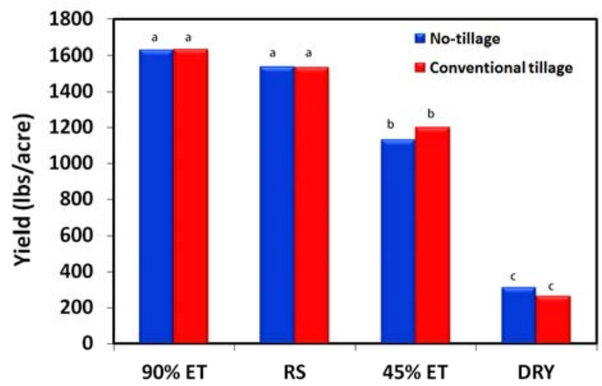
Results - Chillicothe



PHY375 - 3.5 bales/acre
FM9170 - 3.3 bales/acre
DP1044 - 3.2 bales/acre
PHY499 - 3.0 bales/acre

- Yields of all four varieties were similar except under the 90%ET irrigation treatment.
- Under 90%ET irrigation, PHY375 performed well.

Results - Chillicothe



Irrigation + Rain (8”)

90% ET – 25”
RS – 26”
45% ET – 17”
Dryland – 11”

All plots received an initial irrigation of 3”.

Fiber Quality: Micronaire

- Micronaire is closely tied to irrigation level in most cases
  - Related to fiber maturity (Montalvo and Holden, 2005)
  - Related to fineness (Montalvo and Holden, 2005)
- Micronaire can vary from one part of the plant to another (Bauer 2009)

Fiber Quality: Strength

- Strength appears to be controlled more by genetics than growing environment (May, 1999)
- We will sometimes see differences in strength between irrigation treatments for a cultivar, but they seem to occur only under severe stress

Fiber Quality: Length and Uniformity

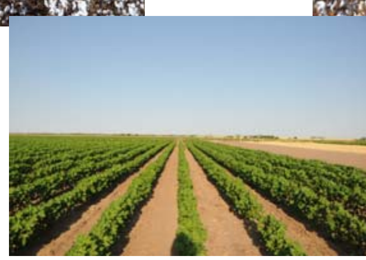
- Length
  - Affected under severe deficit (if you lose 40% of your yield or more, length will often be lower, too)
  - Complex physiological interactions (Bradow and Davidonis, 2000)
- Uniformity follows length pattern in many cases
  - More affected by temperature than length is

The Bottom Line

- Timing
- Rate
- Cultivar effects

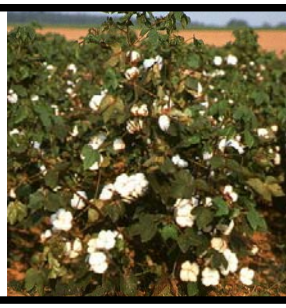
Acknowledgements

- Cotton Inc. and TWDB
- Glen Ritchie, TTU



Appendix D

On-Farm Evaluation of Irrigation Management Options for Cotton In the Texas Rolling Plains.



Nithya Rajan, Srinivasulu Ale, Paul DeLaune, Mimi Roy and Sriroop Chaudhuri
Texas A&M AgriLife Research, Vernon, TX

AgriLIFE RESEARCH

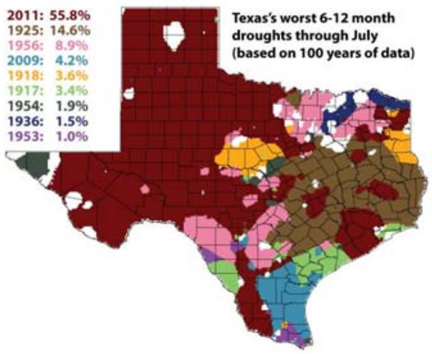
Objective

- Evaluate irrigation scheduling methods for cotton
- Location: Chillicothe Research Station (Texas A&M AgriLife Research)

AgriLIFE RESEARCH

Drought in Texas

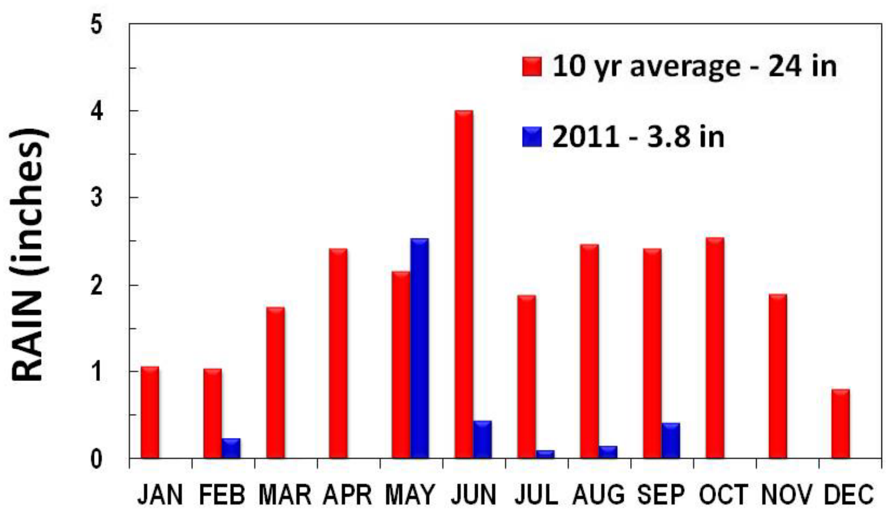
- Worst one-year drought since 1895.
- Rating: 'Exceptional drought'



SOURCE: Brent McRoberts and John Nielsen-Gammon, Texas A&M University

AgriLIFE RESEARCH

Precipitation



AgriLIFE RESEARCH

Methods

- Cotton planted on 23 May 2011
- Soil type: Abilene clay loam
- Plots – 16 rows x 150 ft
- Drip irrigation
- RCBD, 3 blocks
- Fertilizer: 100 lbs of N
  2 applications: pre-plant and side dressing (28-0-0)

AgriLIFE RESEARCH

Irrigation Schedule

- Pre-plant irrigation : 5.5”
- Irrigation applied daily or every other day
- 4 methods
  - Canopy temperature
  - Crop evapotranspiration
  - Soil moisture depletion
  - Soil tension

AgriLIFE RESEARCH

SmartField

- Crop canopy temperature-based.
- 'Irrigate signal'

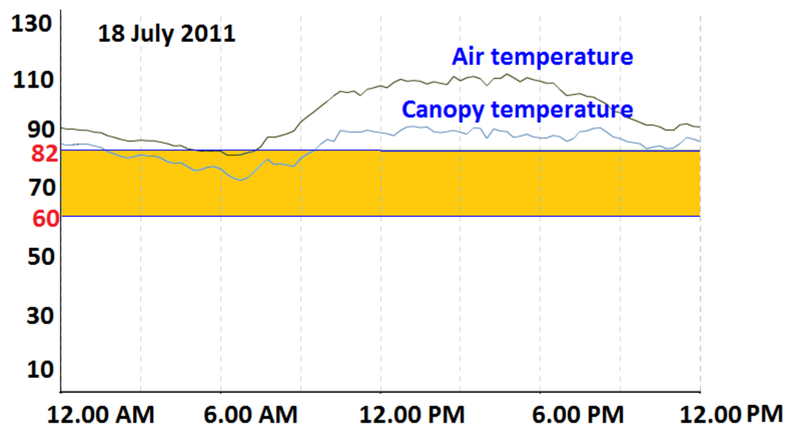
AgriLIFE RESEARCH
Texas A&M System

SmartField

- Access the data online
- cropinsight.com

AgriLIFE RESEARCH
Texas A&M System

SmartField



Tensiometers (Irrometers)

Soil Moisture

- CS 616 TDR probes (2 ft)
- Calibrated based on soil type

AgriLIFE RESEARCH
Texas A&M System

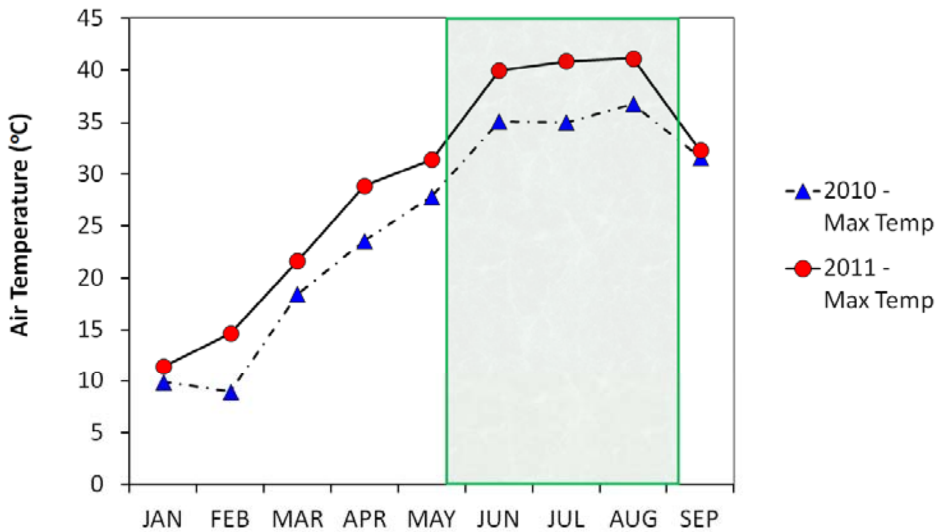
Crop Evapotranspiration

AgriLIFE RESEARCH
Texas A&M System

Measurements

- Plant measurements
  - Plant height, main stem nodes, leaf area index (LAI), biomass, fractional ground cover, and NDVI (Crop Scan)
- Biweekly

Air temperature

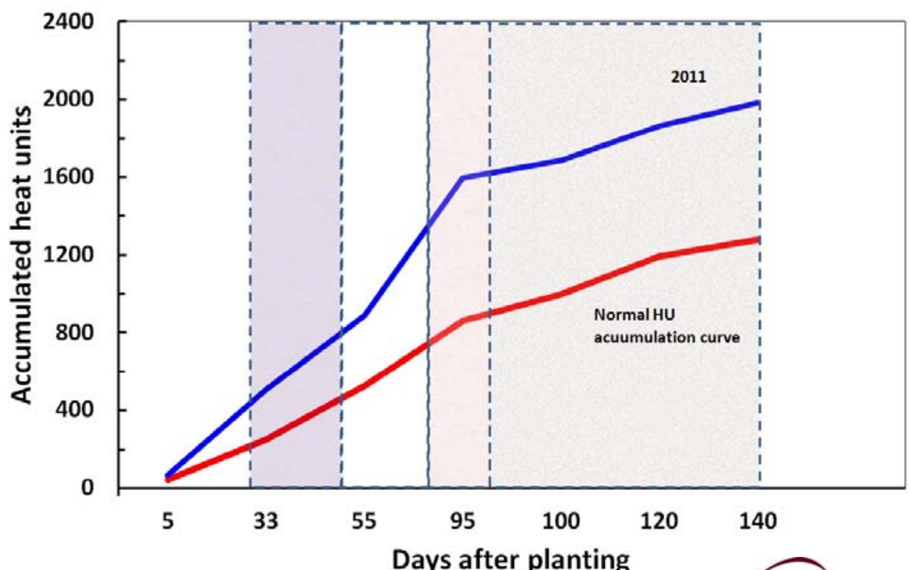


Cotton – Heat Units

Stage of development	Days after planting	Accumulated heat units
Germination-seedling	5-15	44-55
Square initiation	33-50	250-306
First flower	55-70	528-556
Peak flower	75-95	506-861
First open boll	100-120	1000-1056
50% open boll	120-140	1194-1250
80% maturity	140-170	1278-1361
100% maturity	150-180	1389-1444

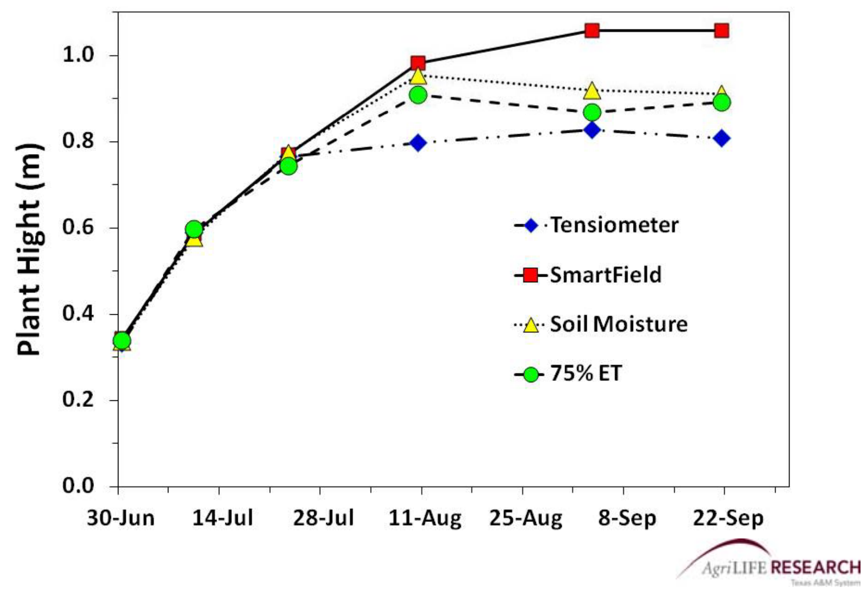
AgriLIFE RESEARCH

Heat Unit accumulation in 2011

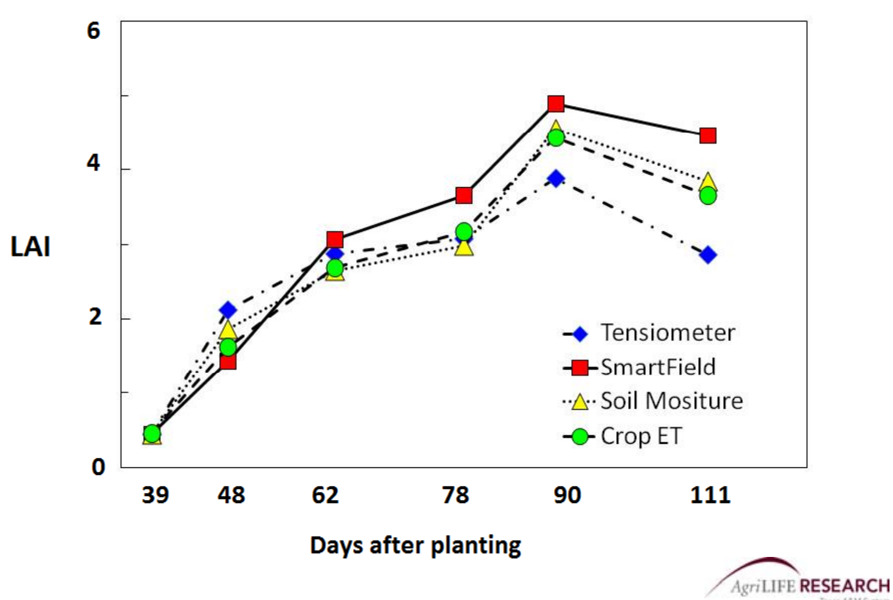


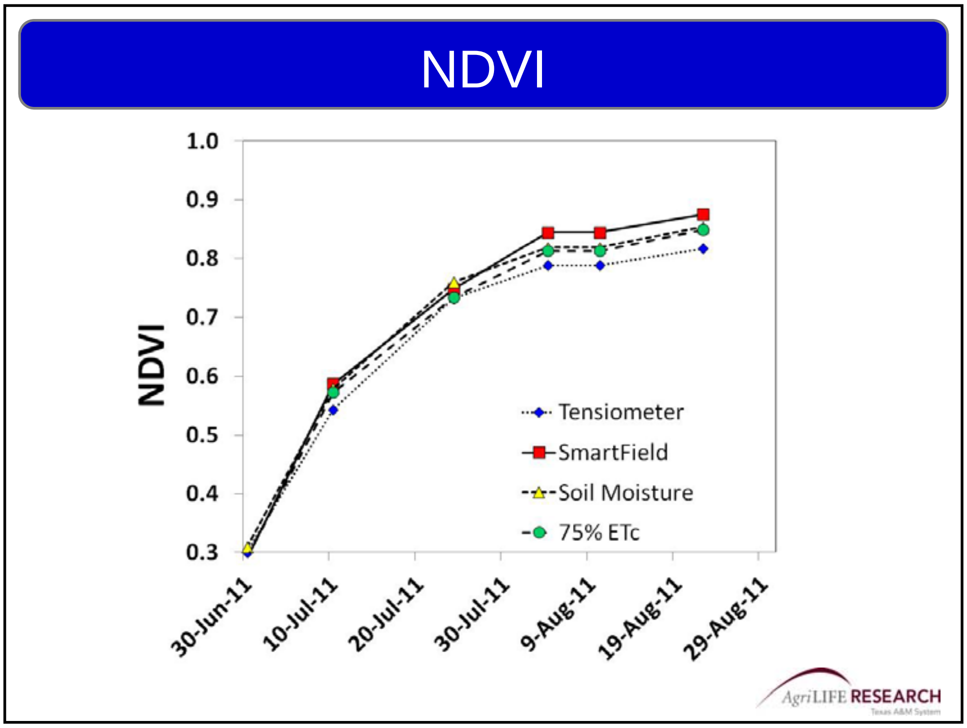
AgriLIFE RESEARCH

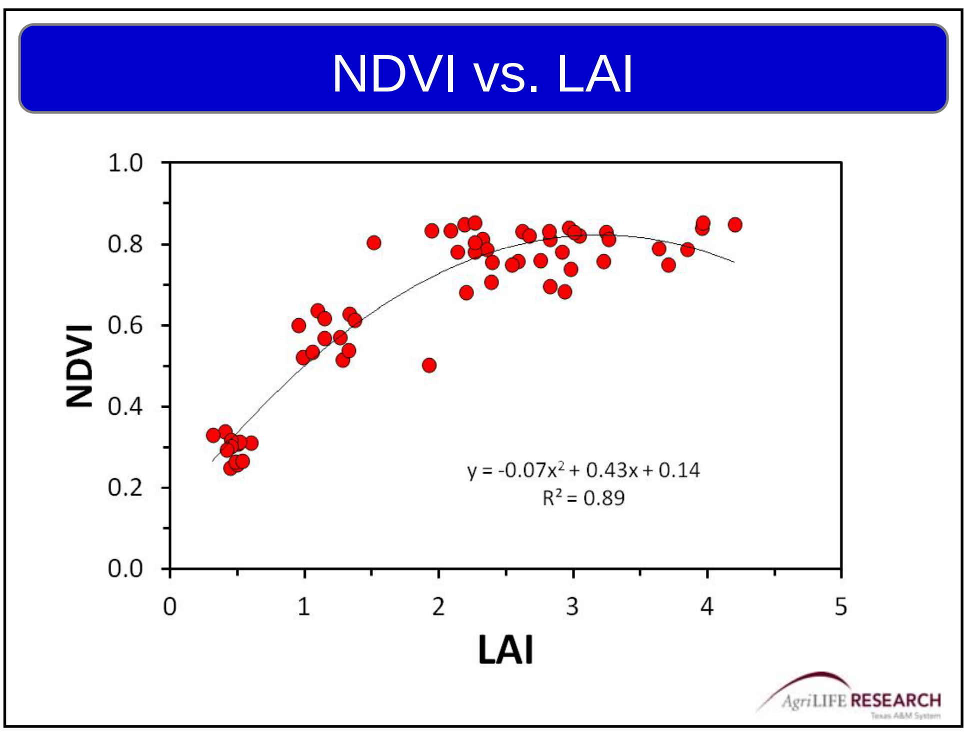
Plant height



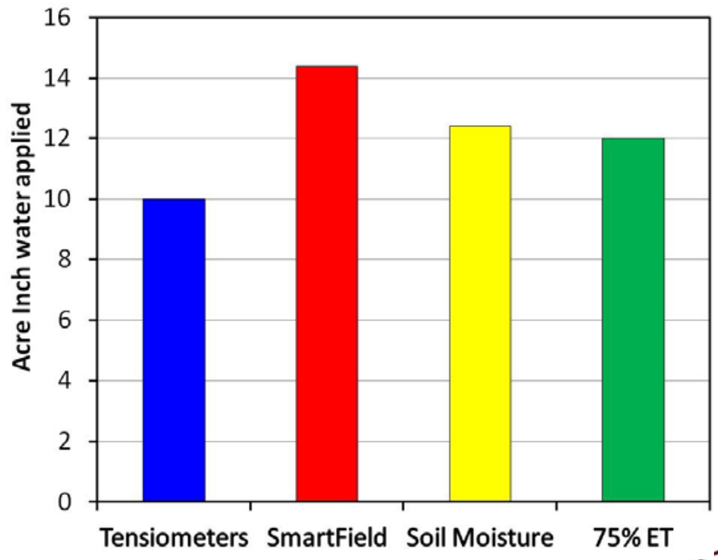
Leaf area index




NDVI
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
NDVI
Tensiometer
SmartField
Soil Moisture
75% ETc
30-Jun-11
10-Jul-11
20-Jul-11
30-Jul-11
9-Aug-11
19-Aug-11
29-Aug-11
AgriLIFE RESEARCH


NDVI vs. LAI
1.0
0.8
0.6
0.4
0.2
0.0
NDVI
y = -0.07x² + 0.43x + 0.14
R² = 0.89
0
1
2
3
4
5
LAI
AgriLIFE RESEARCH

Total Irrigation applied



Irrigation termination

How much longer continue irrigation, or whether or not continue irrigating the crop?

No soil moisture reserves

Post cutout

Conclusions

- Irrigation applied varied based on the scheduling method
  - SmartField
  - Soil Moisture ~ 75% ET
  - Tensiometer
- Crop canopy temperature-based irrigation scheduling is challenging in drought years with high temperature

Acknowledgement

- Texas Water Development Board

Appendix E

Start | View At a Glance | Author Index

67-2 On-Farm Evaluation of Irrigation Management Options for Cotton In the Texas Rolling Plains.

See more from this Division: ASA Section: Climatology & Modeling
See more from this Session: Soil-Plant-Water Relations: Modeling and Measurements

Monday, October 17, 2011: 1:20 PM
Henry Gonzalez Convention Center, Room 213A, Concourse Level

Nithya Rajan*, Texas AgriLife Research and Extension Center, Vernon, TX, Srinivasulu Ale, Texas AgriLife Research and Extension Center, Texas AgriLife Research, Vernon, TX and Paul DeLaune, Texas Agrilife Research-Vernon, Vernon, TX*

The growth and yield of cotton (Gossypium hirsutum L.) in the semiarid Texas Rolling Plains is driven by the amount of water available to the crop through rainfall and irrigation. Various methods have been developed for scheduling the irrigation of agricultural crops. A project is being conducted in the Texas Rolling Plains for demonstrating various irrigations scheduling methods to producers in this region. These include irrigation scheduling using tensiometers, soil moisture sensors, smartfield sensors, and crop evapotranspiration data. By matching the water application according to crop water requirements, it is possible to significantly improve on-farm irrigation efficiency. In this presentation, we are presenting the preliminary results from this study.
See more from this Division: ASA Section: Climatology & Modeling
See more from this Session: Soil-Plant-Water Relations: Modeling and Measurements

<< Previous Abstract | Next Abstract >>

AgriLife Research: Soil moisture-monitoring tools will pay off

View all articles by skledbetter →

August 29, 2011

VERNON – A wide variety of irrigation scheduling tools of various prices are available to producers, but most Rolling Plains crops are still being grown without the benefit of that knowledge, according to a Texas AgriLife Research scientist.

Dr. Nithya Rajan, AgriLife Research agronomist, is completing her first year of data comparing and demonstrating different tools to aid producers with irrigation efficiency. The two-year study is partially funded by the Texas Water Development Board. Project collaborators are Dr. Srinivasulu Ale, hydrologist, and Dr. Paul DeLaune, soil scientist, both with AgriLife Research in Vernon.

Dr. Nithya Rajan looks at the SmartField sensor that is a part of her study on irrigation scheduling tools. (Texas AgriLife Research photo)

"This has been a good year to test these, because there has been no rain," Rajan said. "Most of the farmers in this region don't use irrigation scheduling tools, so they might not apply the right amount of water. If they use some type of irrigation scheduling, they will be making a better decision and possibly saving some water."

While Rajan said irrigation scheduling tools are a key to efficient irrigation, there has not been a demonstration project in the past showing which tool might fit the needs of the producer best in the Rolling Plains.

The demonstration project, which began this summer on a cotton crop, is comparing four different irrigation scheduling tools as a guide on when and how much to irrigate.

The SmartField sensor being used in the study is based on crop-canopy temperature, Rajan said. When the crop canopy temperature gets above 80 degrees, the crop is assumed to be in stress and needs irrigation within about six hours.

"But the problem in the area this year is with the heat," she said. "The air temperature is so high that even though the plants are transpiring and cooling down, the crop canopy might still be showing 80 degrees even though irrigation is being applied."

In this case, the producer may have to use some of their own judgment in applying irrigation, or use the SmartField sensors in combination with other tools, Rajan said.

Another tool for irrigation is tensiometers, she said. Tensiometers cost about $70 to $100 per unit and basically consist of a sensor placed into the ground. The sensor must be filled with water and an air-tight cap is placed on it. The tensiometer has a ceramic tip that contacts the soil and when the soil gets dry, it draws water out of the device, which shows up as increased soil tension.

"This tension in the sensor can be read on a meter which is part of the tensiometer," Rajan said. "When the meter reaches about 50 (centibar,) it is a common practice to irrigate and bring the pressure back to about 10-20."

Tensiometers are easy to use and easy to install, she said. Generally several are installed in a group in the field, and the producer must refill water in the sensor at least once a week.

Electronic soil-moisture sensors indicate the amount of water held in the soil, with the goal being toirrigate just enough to keep the soil moisture close to 75 percent of field capacity, Rajan said. The soil-moisture sensors require some simple calculations on the producer's part to determine when and how much to water. As the crop grows, the rooting depth changes and must be taken into account in the calculations.

The soil-moisture sensors with a digital readout cost around $700-$800, Rajan said.

The final method being considered – potential evapotranspiration – uses data from weather observing stations. Sources for these observations include the High Plains Potential Evapotranspiration Network, operated by AgriLife Research in the Panhandle, and the West Texas Mesonet, operated by Texas Tech University in the West Texas region. The West Texas Mesonet has stations located at Odell, Haskell, Knox City, Goodlett and Seymour in the Rolling Plains region.

This tool is based on using the potential rate of evapotranspiration and the growth stage of the crop to determine how much moisture should be applied to replace what is being lost by plant and soil evaporation, Rajan said.

The cotton crop in this study was planted on May 23 and a uniform irrigation was made for the first 45 days of growth to ensure a good crop stand was established, she said. After that, water was applied every other day in varying amounts, depending on what each tool indicated was needed. This ranged from a quarter of an inch to a half inch to an inch on most watering days in July and August as a result of the extreme heat this year.

The cotton is being grown under subsurface drip irrigation and is about a two months away from harvest, she said. At harvest, Rajan will have more complete data on the different tools and how much irrigation each called for, along with the different costs of operating the various systems.

Those results will be posted to the AgriLife Research website in Vernon, http://vernon.tamu.edu/ when they are finalized. To get to the results or find out more about Rajan's project, click on the Cropping Systems link under Center Programs and then on Cropping Systems Research.

"We will be able to determine which method was the most efficient, how much water we saved and what is the most cost-effective method," Rajan said. "That data will be finalized after the irrigation is turned off for the season."

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Appendix G

TWDB Contract # 1103581253 – Review of Draft Final Report

“Demonstrating tools for improving on-farm irrigation efficiency”

TWDB comments on the *Draft* Final Report, June 2013

General comments:

1. Please refer to “Exhibit D: Guidelines for Authors Submitting Contract Reports to the Texas Water Development Board” in the original contract document for information on formatting and editing the final report.

   Response: The formatting guidelines are followed.

2. Please include all TWDB comments as the last Appendix in the Final Report including text addressing each comment and/or where (page numbers) the changes may be found, if appropriate.

   Response: This is added as Appendix G.

Specific comments by page number:

3. title page: Please consider adding “, Ph.D.” behind Dr. Delaune’s name and check spelling (N*ii*thya).

   Response: This is corrected.

4. pages 1 and 2: There should be a period after “Table No**.**” or “Figure No**.**” or “Page No**.**”.

   Response: This is corrected.

5. page 4: Please remove the period from after “Point.” in PWP. Also, please consider adding the following abbreviations to the list: K_c, $K_{c\ ini}$, $K_{c\ mid}$, $K_{c\ end}$.

   Response: This is corrected.

6. *page 5: Please consider revisiting the “Executive Summary” section as it is currently the same text as the “Conclusion” section and lacks information on the major objectives/goals of the project. Also, evapotranspiration is misspelled.*

   Response: Executive Summary is added as suggested. Page Number: 1-3.

7. page 6: Please include an estimate of the typical range of water savings a producer can expect to realize as a result of adopting these irrigation scheduling technologies and the overall impact that could result if a large number of producers in the region also adopted the technologies.

   Response: This information is added in Executive Summary. Page Number: 2.

8. page 7: Please consider adjusting the headings to better match the content, such as "Background" instead of "*Description of the Research*" and "Introduction" instead of "*Scope of Work and Objectives*".

   Response: This is corrected.

9. page 7: Please enlarge Figure 1 and center it on the page rather than wrapping the text.

   Response: This is corrected. New page number is 4.

10. page 7 and elsewhere: Please use either English units or both English & Metric throughout and spell out the unit at least once, as in
    "…more than 6 million acres (2.4 million hectares) to around 4.4 million acres (1.8 million ha) (Stewart, 2003)."

    Response: All the suggested changes had been made. New page number is 4.

11. page 8: Please add a period to "(Sij et al., 2009)."

    Response: This is corrected. New page number is 5.

12. page 8: Please consider removing the numbering of {"The two important questions regarding irrigation scheduling are *When to turn on/off the irrigation?* and *How much to irrigate?"*} since this text is so near to the numbered project objectives.

    Response: This is corrected. New page number is 5.

13. page 9: Please remove the '/' in "through rainfall and/ irrigation". Please indent the numbered classes of irrigation techniques.

    Response: This is corrected. New page number is 5.

14. page 9+: As this report will be read by the public and will continue to serve as an outreach and education document, it might benefit from changing the order of a few sections. To that end, please consider adding a heading under "*Introduction*" for "*Soil and Water*" with the following moved text sections (beginning of first sentence through end of last sentence of the paragraph/section is listed):
    a. "The growth and yield of crops such as cotton in ... to maintain a healthy plant cover." pg. 9

b. “Most plants receive water from the soil … irrigation can be applied to refill the rooting zone.” pg. 19-21 including figure 8 and equation 2
c. “Figure 3a shows typical characteristic curves for … when half of the PAW has been depleted in most soils.” pg. 11-13 including figures 3a and 3b

Response: All the suggested changes had been made. New page numbers are 6-8.

15. page 9+: Please consider placing your “*Irrigation Scheduling Methods*” section under the “*Introduction*” heading mentioned above.
    a. Also, consider moving the following paragraph to within the “*Irrigation Scheduling Methods*” section but *not* within the “*Tensiometers*” sub-section: “Why is a value of one-half PAW …. avoid significant stress effects on plant growth.”
    b. Also, consider numbering the sub-headings for the four irrigation scheduling techniques demonstrated in the project, such as
        1. Tensiometers
        2. Crop Coefficients, etc.

Response: All the suggested changes had been made.

16. page 10: On figure 2, instead of including the entire reference citation in the caption, please consider using only the in-text citation style such as “Figure 2. Standard soil tensiometer. (Risinger and Carver, date)”.

Response: All the suggested changes had been made. New page number is 10. New figure number is 4.

17. page 10+: Please at least once spell out kiloPascals and give an explanation.

Response: This is added in page 7.

Also, please be sure that a negative sign appears directly in front of a number value rather than on the previous line, here and elsewhere in the text.

a. “…tension is that they can measure tension only down to a value of around <u>-0.85</u> atmosphere…”

instead of

b. “…tension is that they can measure tension only down to a value of around -
0.85 atmosphere…”

Response: All the suggested changes had been made (Page 7).

18. page 11 & 12: Please consider reducing the length of the caption on Figures 3a and 3b by moving caption text into the paragraph as appropriate. Also, consider using only the in-text citation style rather than the entire citation in the caption, as in

Figure 3a. Characteristic curves for a sand and a clay soil. (Levitt and Young, 2003)
Figure 3b. Characteristic curves with field capacity (FC) and permanent wilting point (PWP) shown. (Levitt and Young, 2003)

Response: All the suggested changes had been made (Pages 7 and 8).

19. page 15: Please consider using only the in-text citation style rather than the entire citation in the caption, such as (Allen et al., 1998).

    Response : This is corrected. New figure number is 5 and page number is 11.

20. page 16: Related to Figure 5- "These values were obtained from the Texas **High Plains** ET network website…" but the address listed is for the Texas ET network.
    a. If the data are from the Texas ET network site, please correct the text. Also, Guy Fipps is the author of that page; therefore you'd need to add his name and citation to your reference list and to the caption.
    b. If the data are from the Tx High Plains ET network, please change the website to reflect either (https://watermgmt.tamu.edu/weatherdata.jsp) or (http://txhighplainset.tamu.edu).

    Response: All the suggested changes had been made. New figure number is 6 and page number is 12.

21. page 16: "According to this crop coefficient curve, corn requires more water than cotton and grain sorghum." Please consider adding a sentence or two here that helps the reader understand better the relationship between K_c values in the graph and amounts of water required by each crop.

    Response: Additional sentences are added (page 12).

22. page 17: Please consider moving the paragraph at the top of page 17 to the beginning of the "*Crop Coefficients*" section.
    "The crop coefficient approach … vegetation, like agricultural fields.

    Response: This is corrected (Page 10).

23. page 17: Please center and set apart Figure 6 and also include a source for the photo.

    Response: This is corrected. New figure number is 7 and page number is 13.

24. page 20: Please be consistent in the formatting of equations, such as

    $$PAW = FC - PWP \qquad [2]$$

    instead of
    "PAW = FC – PWP [Eq. 2]"

    Response: This is corrected. New equation number is 1 and page number is 7.

25. page 21: Please move the "TASKS" section to the beginning of the report and amend the tasks to match what is written in Exhibit C of the original contract.

Response: This is corrected (Page 5).

26. page 22: Please consider changing the heading from "*Materials and Methods*" to "*Methods and Results*" with sub-headings of "*Field Demonstrations*", "*Outreach Activities*", and "*Water Savings*", in order to separate the different portions of the project.

    Response: This section was renamed as "Methods and Results" with sub-headings of "Field Demonstrations", "Outreach Activities", and "Water Savings".

27. page 22+: After describing the planting and other 'common to all techniques' methods for setting up the demo fields (text through "*…were irrigated uniformly from emergence to first square at a rate of 0.2 incher per day.*"), please consider numbering each 'technique' within the *methods and results* sections, such as

    1. Tensiometers

        Discussion of methods for installing & monitoring the tensiometers followed by discussion of results of this technique…etc.

    Response: All suggested changes had been made.

28. page 23: Please removed the word "were" from the second sentence in the first paragraph and also the first sentence in the second paragraph.
    a. "*All plots* ~~**were**~~ *received a total of…*"
    b. "*All blocks* ~~**were**~~ *received a pre-plant irrigation of…*"

    Response: This is corrected (Page 15).

29. page 23+: *Please use* 12 inches *or* 12 in *instead of* 12".

    Response: This is corrected throughout the document.

30. page 24: Please correct the spelling of "Campbell Sc*ie*ntific" and consider *not* splitting website addresses across two lines.

    Response: This is corrected (page 18).

31. page 25: Please add "*the*" to the last sentence of the first paragraph.

    "In addition, *the* base station…"

    Response: This is corrected (page 19).

32. Page 25; correct the last sentence to "where" instead of "were".

    "Irrigation was applied at 100% ET replacement level in demonstration plots *where*…"

    Response: This is corrected (Page 19).

33. page 26: Please consider moving the text about IWUE to the aforementioned section called "*Water Savings*". ("Irrigation Water Use Efficiency (IWUE) was…Water savings ($IRRIG_{sav}$) was calculated as: equation 6".)

    Response: This is corrected (Page 21).

34. page 27: Please explain in further detail how the *Producer Application* was known or estimated in calculating the irrigation water savings.

    Response: Additional sentences are added on page 21.

35. page 27: Please consider moving the "List of Products" toward the beginning of the report.

    Response: This is moved to the end of introduction of the report (Page 5).

36. page 28: Please consider renaming this section "*Discussion*" instead of "*Results*". Please remove the sub-heading "**Tasks 1 and 2**" from the text.

    Response: This is corrected.

37. page 29: Text should say "Figure 14 presents the 2011 monthly…" instead of "Figure *11* presents the 2011monthly…"

    Response: This is corrected. New figure number is 15 and page number is 23.

38. page 31: Figure 16- Please consider using only a line instead of a line connecting the symbols for 2011 and 2012 ET in the plot. Also, the x-axis labels indicate 2011 but the plot shows both years.

    Response: This is corrected. New figure number is figure 11 and page number is 17.

39. page 32 & 33: Please consider changing the footnotes below table 1 and table 2 to read "*Data shown are in inches."

    Response: This is corrected (Tables 1-4).

40. page 34: The title of Table 3 should reflect data for **2011**, not 2012.

    Response: This is corrected.

41. Page 34; please include the number of acres in each of the demonstration project sites so that TWDB can calculate an actual volume of irrigation water savings resulting from the project.

a. Consider including a discussion of the number of producers that may have adopted these irrigation scheduling technologies as a result of attending the field days and other events, did producers realize additional water savings, etc.

Response: Area information is added on Tables 5 and 6. We did not include a discussion of the number of producers that may have adopted irrigation scheduling strategies. Although we generated interest among farmers on water saving technologies, we have to conduct an elaborate survey to generate these numbers. We will try to add this as an objective in future water conservation projects.

42. page 35: Please consider increasing the indent to 0.5 inches and changing the formatting to single spaced for the block quote by Singh et at., 2007.

    Response: This is corrected (Page 25).

43. page 36: Please consider moving the "Outreach activities" text from here to the aforementioned "*Outreach Activities*" section and delete the text "**Task 3**".
    a. Also, please consider elaborating on the outreach activities that incorporated results from the project with details such as how many extension meetings were attended and approximately how many producers heard you deliver your presentations overall.
    b. Also, the abstract included in Appendix E is from the ASA meeting in *San Antonio*, but the text mentions *Cincinatti, OH*.
    c. Please consider elaborating on the functions of the website created for this project.

Response: Additional sentences are added (Page 20). The meeting was in San Antonio.

44. page 36: Please correct the project website address (**the "~" is missing in front of "~nrajan"**).

Response: This is corrected (Page 20).

45. page 37 & 38: Please move the article "Soil moisture monitoring tools will pay off" to the end of the report as Appendix F (and add to Table of Contents), and correct the article title in the text.

Response: This is corrected.

46. page 39: Please consider changing the final section heading from "*Conclusions and Recommendations*" to "*Conclusions*".

Response: Additional sentences are added

47. page 40: Please include an estimate of the expected water savings that can be realized from adopting these technologies.

Response: This is added in the conclusions section on page 26.

48. page 41: Please arrange in alphabetical order by last name of first author. Also, please add the following works appearing in the text to the “References” section as full citations.
    a. Risinger and Carver, date.
    b. Levitt and Young, 2003.
    c. Allen et al., 1998
    d. Any website from which you collected data.

    Response: All suggested changes had been made.

49. Appendix A: TWDB would like to reproduce this handout to provide at various farm shows and irrigation conferences. Please consider providing it as a separate document with high image quality pictures (if available) for printing and reproduction purposes. TWDB will give credit to AgriLife, Dr. Rajan, and the other project participants and research associate as listed.

    Response: This will be emailed to the Project Manager at TWDB.