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Texas Corn Producer's Board

By the Principal Investigator

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For the Project

"On-farm evaluation of irrigation management options for corn in the Texas High Plains"

Report Period

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Summary: The year 2011 has been classified as a mega-drought year in the Texas High Plains region, and climatologists have stated it to be the "worst one-year drought since 1895." In addition to scant rainfall, maximum air temperatures were above 100^{o} F for most of the growing season. In the current project, four irrigation scheduling methods were evaluated using data from corn fields in the Hale and Floyd counties of Texas. These fields are part of the Texas Alliance for Water Conservation Demonstration Project led by Texas Tech University. At the beginning of the project, four center-pivot fields and one drip-irrigated field were selected in Hale and Floyd counties. Two of the center-pivot irrigated fields were abandoned later in the season due to extreme drought conditions. Irrigation of the study fields was monitored in real-time using the NetIrrigate telecommunications system. Two of the remaining center pivot fields were harvested for grain, while the drip-irrigated field was cut for silage. Analysis of four different irrigation scheduling methods (PET, remote sensing, SmartField, and Aquaspy) 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 PET-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. The remote sensing method uses real-time satellite images for

estimating the crop coefficient, and thus can adjust irrigation recommendations to the actual crop growth conditions in specific fields. The standard PET method and the remote sensing-based method both use the same kind of weather data currently available from established weather monitoring networks in the region. The remote sensing-based method additionally needs remote sensing observations, but these can readily be obtained at no cost from existing satellite systems. 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 soil moisture-based Aquaspy 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 moisture conditions in a given field. 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 PET and remote sensing-based methods are the simplest to implement, and would result in little cost to the producer. Of these two methods, the remote sensing method should be better at representing the actual water demand of individual fields, and thus may be less likely to result in over-irrigation. The SmartField and Aquaspy methods also appear to be suitable for practical use in irrigation scheduling, although each would involve a greater investment by the producer. The SmartField sensors might have some problems dealing with extremely high air temperatures.

Study Sites:

At the beginning of the project, four center-pivot fields and one drip-irrigated field were selected from the Texas Alliance for Water Conservation (TAWC) Demonstration Project in Hale and Floyd counties. Two of the center-pivot irrigated fields were abandoned later in the season due to extreme drought conditions (Sites 4 and 5). The details and locations of the project fields are shown in Table 1 and Figure 1. The fields are equipped with flow meters, GPS, and telecommunication systems (Netirrigate, LLC) so that the amount of applied water, time of application, and the location of the pivots can be monitored in real-time.

Figure 1: Locations of producer fields selected for monitoring in Hale and Floyd counties.

Site Number	Type of irrigation	Total area	Planting Date	Location	Remarks
1	Center-pivot (half)	65 acres	5 May	Hale County	Grain
2	Center pivot (full)	60 acres	24 May	Floyd County	Grain
3	Drip	30 acres	2 June	Floyd County	Silage
4	Center pivot	60 acres	n/a	Floyd County	Abandoned
5	Center pivot	130 acres	n/a	Floyd County	Abandoned

Table 1: Details of producer fields monitored in the TCPB study, "On-farm evaluation of irrigation management options for corn in the Texas High Plains"

Methods used:

Figure 2. SmartField Sensor.

SmartField sensors: These sensors were installed at various locations within the fields. They measure crop canopy temperature using an infrared thermometer and relay the information to a base station (Fig. 2). 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 from a demonstration project site is shown in Fig. 3. The critical temperature and time threshold were set at 82^{o}F and 360 minutes, respectively, which are the recommended values for corn. 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 has a rain gauge which records the rainfall at the demonstration site.

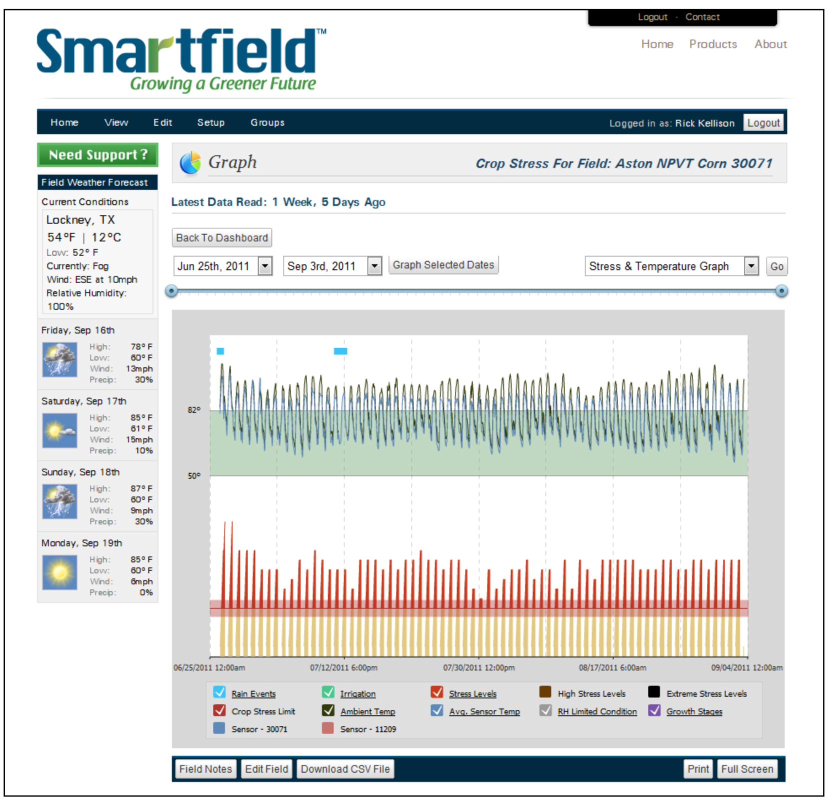


Figure 3. A screen shot of the real-time SmartField crop canopy temperature data from a demonstration site accessed from the website http://www.cropinsight.com/.

Aqua-spy: These capacitance-type soil moisture probes are commercially available and are used to monitor soil moisture conditions at multiple depths in the soil. The sensors were installed in all center-pivot irrigated fields in the study. The data from these soil moisture problems can be accessed on the website http://aserv.aquaspy.com/ using a username and password. A screen shot of this website with examples of real-time information from one of the demonstration project site is shown in Figure 4. As shown in the graph in this figure, data from these sensors track the change over time in soil moisture in the soil profile. By monitoring this change, the field operator can determine when to turn on the irrigation system and how much water should be applied to maintain the soil moisture at a desired level.

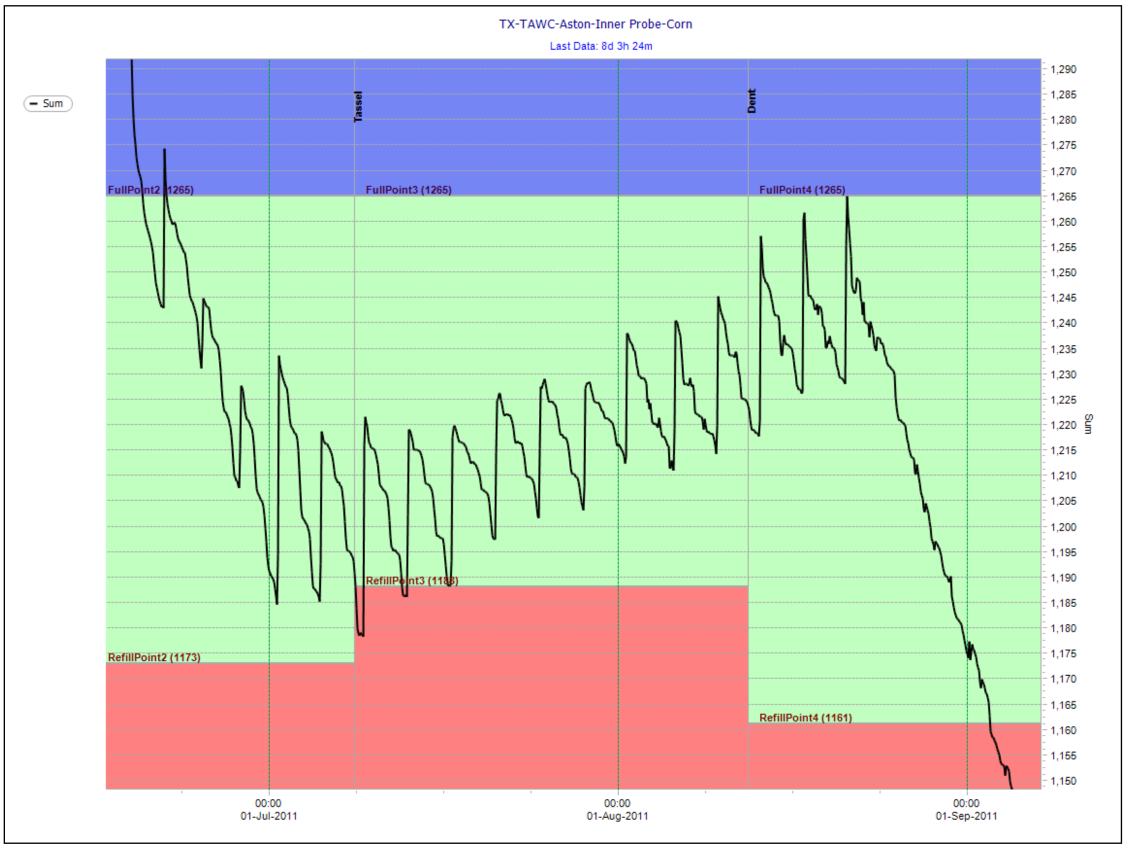


Figure 4. A screen shot of the real-time Aqua-spy soil moisture data from one of the demonstration sites accessed from the website http://aserv.aquaspy.com/.

Potential Evapotranspiration (PET) method: This method is based on the crop water demand calculated from weather data. Reference evapotranspiration (ET_0) data used in this method were accessed from the West Texas Mesonet website for the observing station near the study fields. Values of a crop coefficient (K_c), which is multiplied times ET_0 to give an estimate of the daily crop water demand (ET_c), were adapted for use in this project from the Texas High Plains Evapotransipration Network operated by Texas AgriLife. By keeping track of ET_c, the field operator can estimate how much water should be added by irrigation to replace the water lost by the crop through evapotranspiration.

Remote sensing-based method: In this method, the actual growth of the plant is monitored using real-time satellite image data. Using a method previously developed by the participants in this study, data are extracted for study fields from images obtained from the Landsat-5 and Landsat-7 satellites and are used to calculate crop ground cover (GC). The GC is then used as a crop coefficient (the "spectral crop coefficient" K_{sp}) in a manner analogous to the PET method previously described. To estimate values of K_{sp} between satellite observation dates (roughly every 8 days), a crop growth simulation model is used that produces values of K_{sp} for each day of the growing season. Using this information and weather data from the West Texas Mesonet, water demands were calculated for the study fields. A potential advantage of this approach over the standard PET method is that the crop water demand estimated based on satellite data will be specific to each individual field.

Results

2011 - Extreme drought year in West Texas:

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 for precipitation up to September recorded at the West Texas Mesonet observing station near Plainview was 15 inches. The corresponding recorded precipitation for 2011 at this weather station was only 1.7 inches. Precipitation data from 2011 are summarized in Fig. 5. The 2001-2010 average pre-season precipitation (January through March) was 3 inches. In 2011, the amount of pre-season precipitation received was only 1.5 inches.

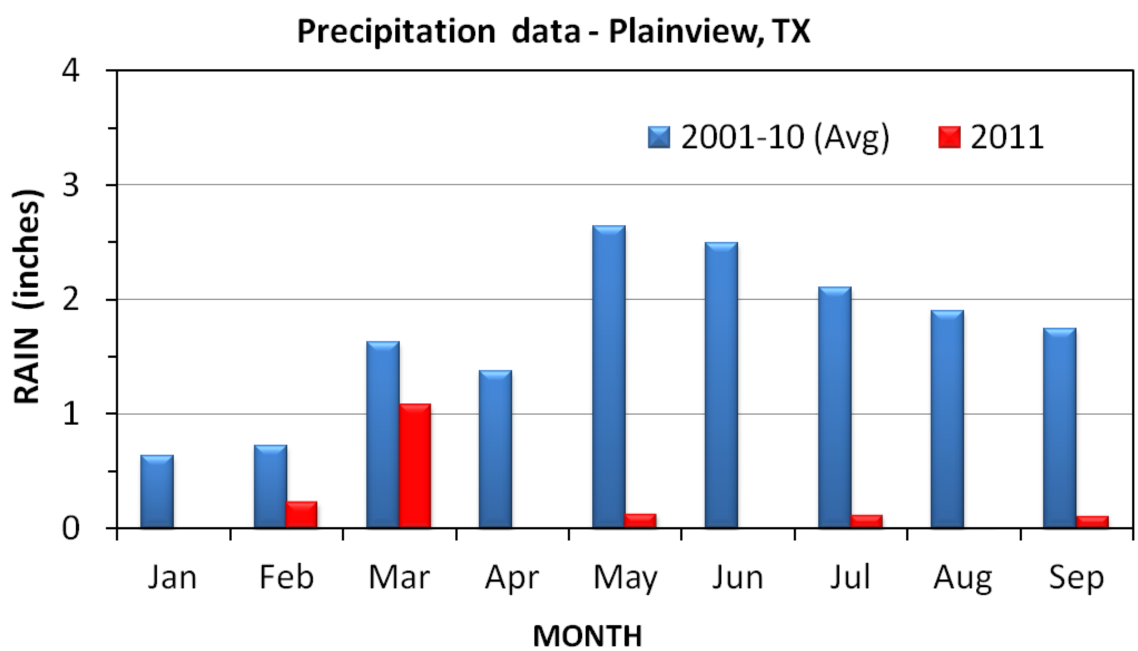


Figure 5: Precipitation data from the West Texas Mesonet weather observing station near Plainview, TX.

This lack of rainfall was coupled with record high temperatures and, earlier in the growing season, high winds. The maximum air temperatures were above average in 2011. Figure 6 presents the 2011monthly maximum air temperature data compared to the average monthly maximum air temperature from 2006-2010. During most of the crop growing season, the maximum air temperatures were above 90°F. In the peak crop growth months of July and August, maximum air temperatures were above 100°F, a 10°F increase compared to the average air temperature of 90°F recorded for other years.

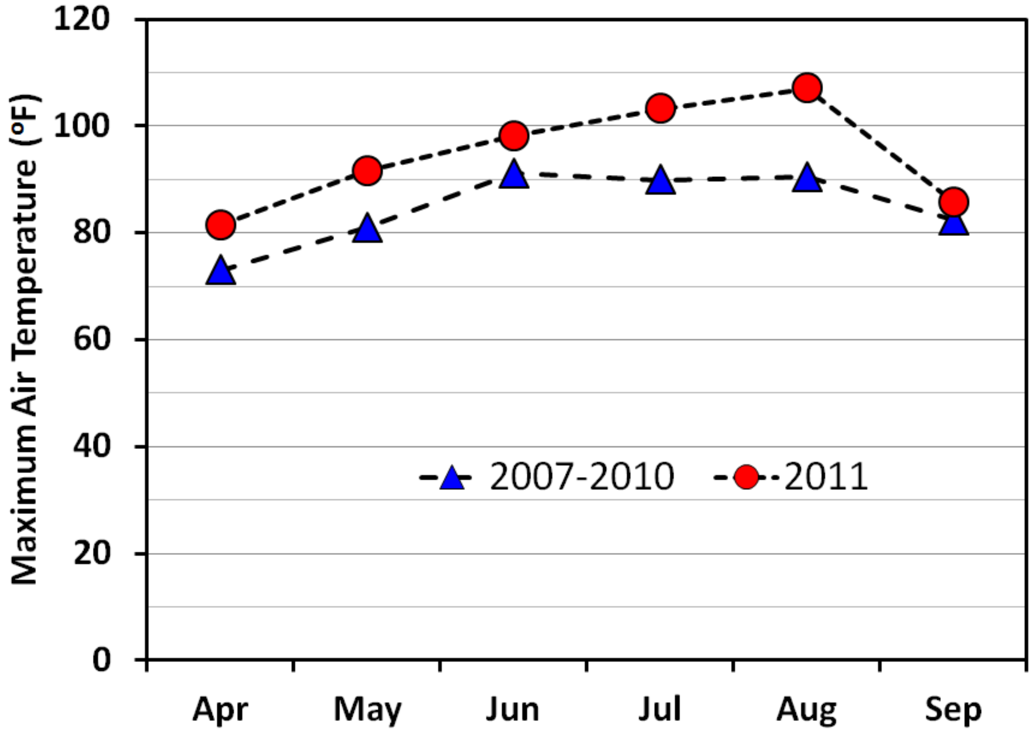


Figure 6: Maximum air temperature data from the West Texas Mesonet weather observing station near Plainview, TX.

The scant rainfall and high temperatures led to a combination of extreme water stress and heat stress for most of the growing season for corn plants in the study region. As a result, many corn fields were abandoned during the growing season when insufficient water was available to fully irrigate the crop. This includes two TAWC fields that were originally to be monitored in the project (sites 4 and 5).

Irrigation Data

Amounts and timing of actual irrigation water applications to the project sites are presented in Fig. 7. The highest water use was recorded for Site 2, the center-pivot irrigated field in Hale County. A total of 38 inches was applied to this field, which includes pre-plant irrigation. A total of 33 inches was applied to the center-pivot irrigated field in Floyd County. The least amount of water (22 inches) was applied to the drip field, which was harvested for silage.

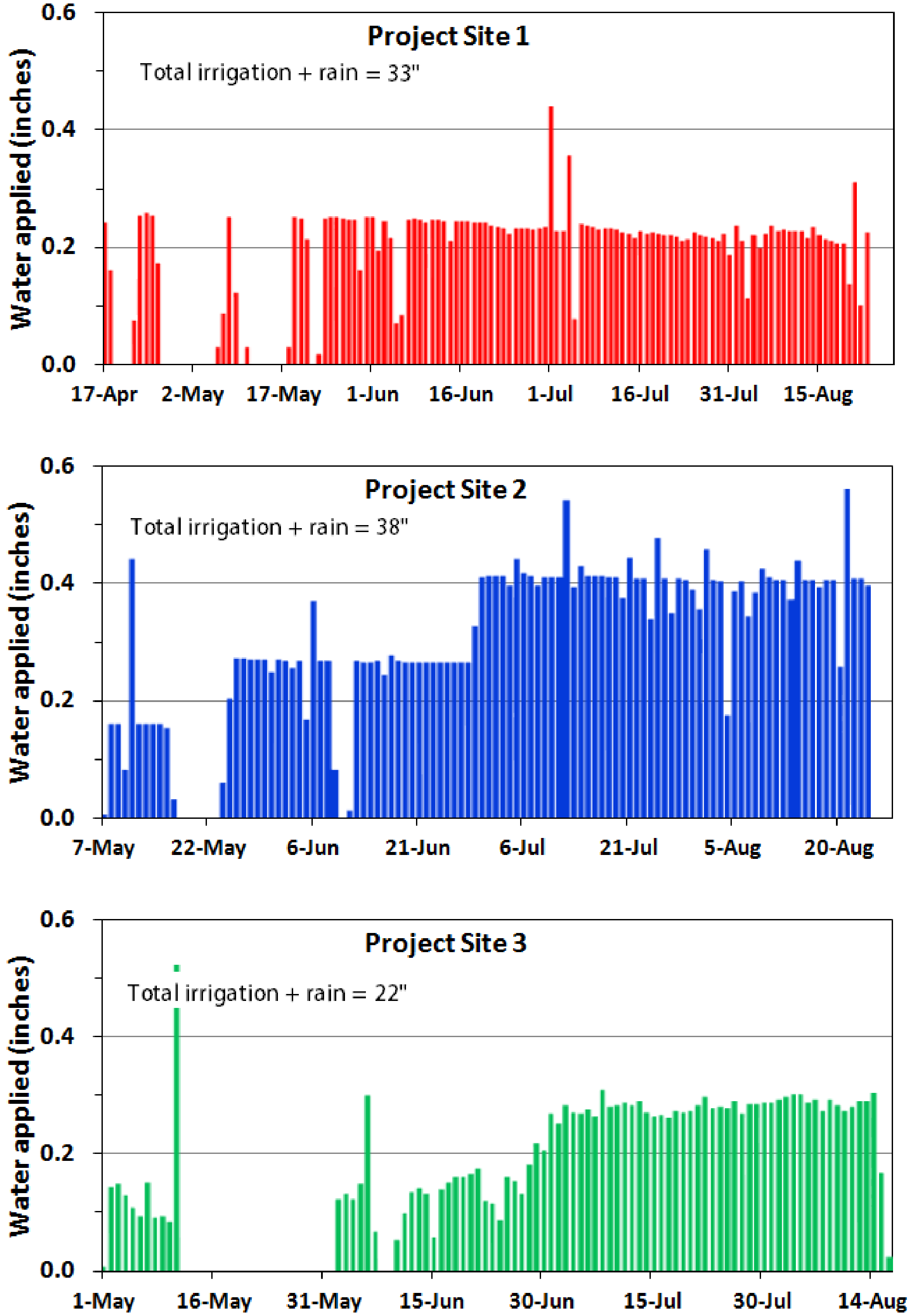


Figure 7: Daily irrigation data for project sites 1, 2 and 3.

Evaluation of irrigation scheduling methods

The irrigation scheduling methods were evaluated based on the amount of irrigation water recommended by each method and the comparison of these amounts with actual irrigation applied.

Potential Evapotranspiration (PET) method: ET_c rates for site 1 exceeded 0.40 in/day (10mm/day) for 45 days during the growing season. These high evaporative demands were recorded on days spanning from mid-June through mid-August. Except for few days early in the growing season, about 0.25 in/day of irrigation water was applied on most days during the growing season. The applied irrigation was well below the ETc rates for this site, as seen in Fig. 8. For site 2, the average irrigation applied from mid-June until mid-August was 0.4 in/day. During this time, irrigation water applied was similar to the crop water demand (ETc) calculated based on the PET method (Fig. 9).

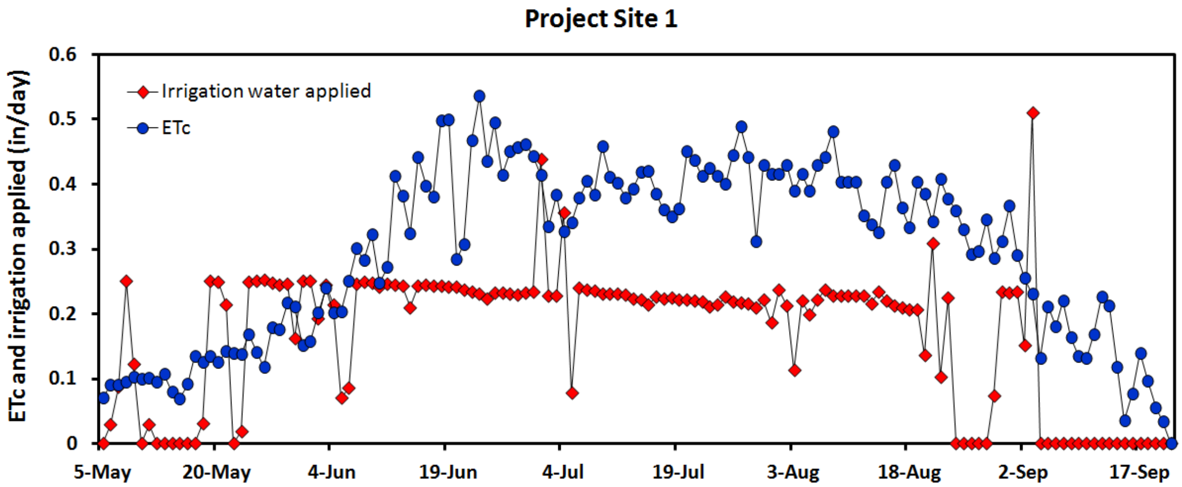


Figure 8: Evapotranspiration demand (ET_c) and irrigation applied for site 1 in the project.

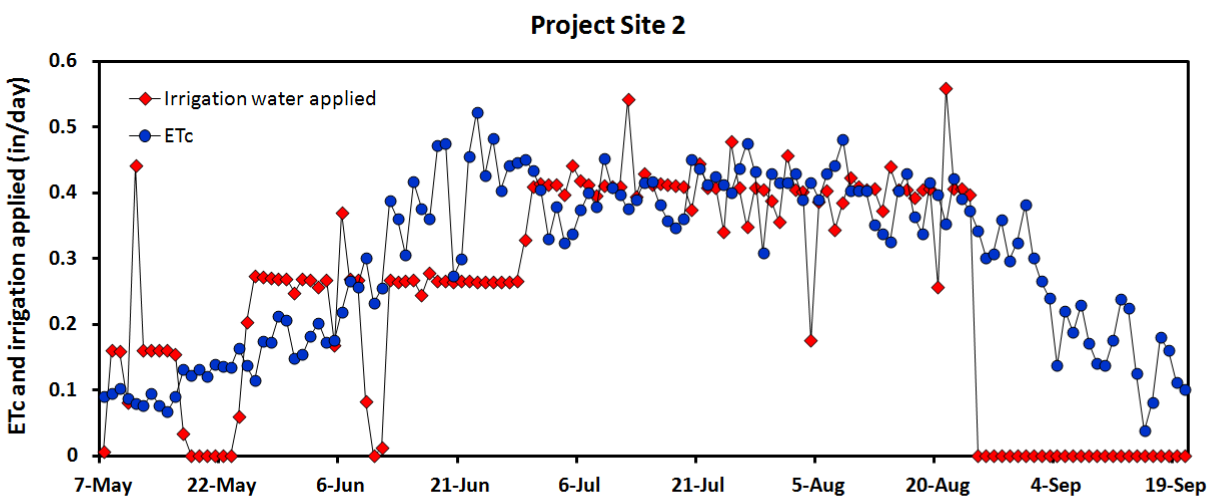


Figure 9: Evapotranspiration demand (ETc) and irrigation applied for site 2 in the project.

Site 3, the only drip-irrigated field in the study, was harvested for silage in mid-August. As seen in Fig. 10, the producer applied varying amounts of irrigation throughout the growing season, increasing from 0.1 in/day at the beginning of the season to 0.4 in/day before harvest in August.

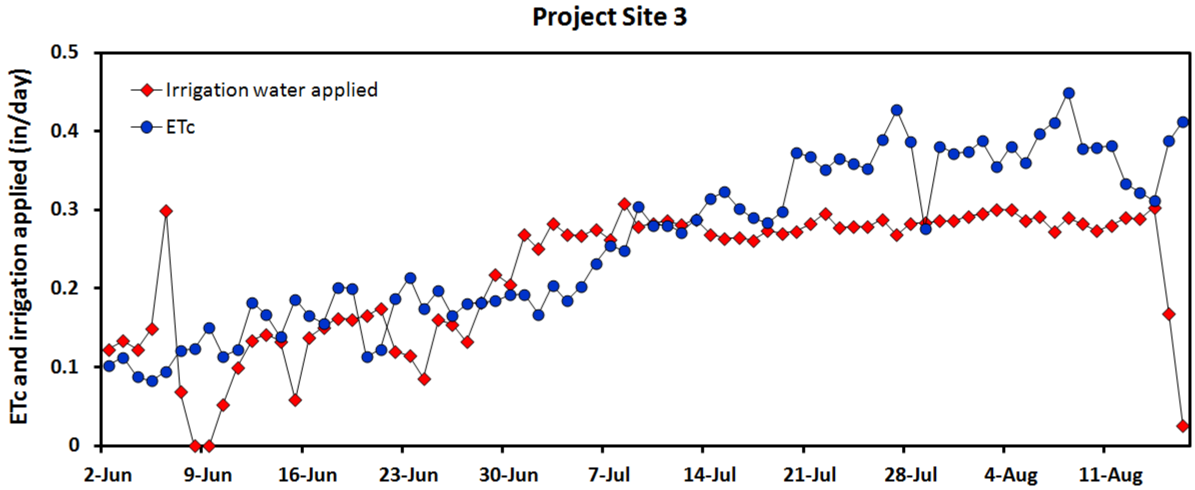
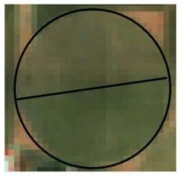
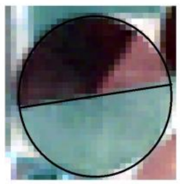
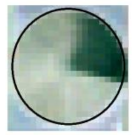
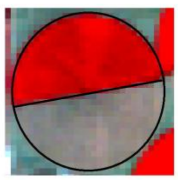
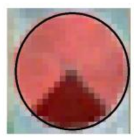
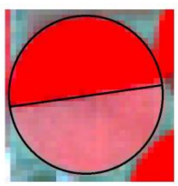
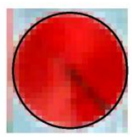
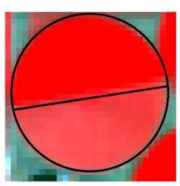
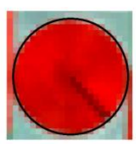
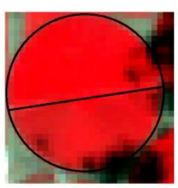
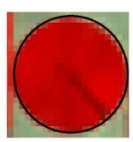


Figure 10: Evapotranspiration demand (ETc) and irrigation applied for site 3 in the project.

Remote sensing-based method: Landsat-5 Thematic Mapper (TM) imagery containing the study site was acquired on 7 dates during the 2011 growing season. Each image, located according to the Landsat World Reference System (WRS-2) along Path 30 at Row 36, was obtained from the U.S. Geological Survey (USGS) EarthExplorer website (http://edcsns17.cr.usgs.gov/EarthExplorer/). Pixel size in the imagery is 30 m. Figure 11 presents false-color composite Landsat images of the project sites at various times during the growing season. In a false-color composite image, vegetation appears in different shades of red depending on the amount of vegetation, with bright red indicating the most dense vegetation. During May, the sites appear largely grayish-green in color, which indicates that there was bare soil or only small amounts of vegetation in the field. As the growing season progressed, the amount of vegetation increased and the sites progressed to a bright red color.

The advantage of remote sensing is that the spatial variation in crop growth can be directly observed and analyzed using special image analysis software. The spatial variability in crop growth can be primarily attributed to difference in soil characteristics, and the condition of the vegetation (incidence of pests or diseases). In the current project, data extracted from the Landsat imagery were used to estimate vegetation cover and leaf area index for all project sites using the procedure described by Maas and Rajan (2008). These data are presented in Fig. 12. The figure shows that site1, due to its early planting date compared to the other two sites, reached 50% vegetation cover by early June. Site 3, the drip irrigated field, attained 50% vegetation cover by mid-August, when it was harvested for silage.

Figure 11: Landsat images of the project sites displayed as false-color composite images. As the plants grow, the fields progress to a brighter red color.

Date	Site 1	Site 2	Site 3	Remarks
11 May 2011				Site 1: Top half of the pivot is planted to corn. Bottom half is planted to cotton.
27 May 2011				Darker areas are wet soils
12 June 2011				
28 June 2011				
14 July 2011				
30 July 2011				Site 1 affected by cloud shadows
15 August 2011				Site 1 affected by clouds

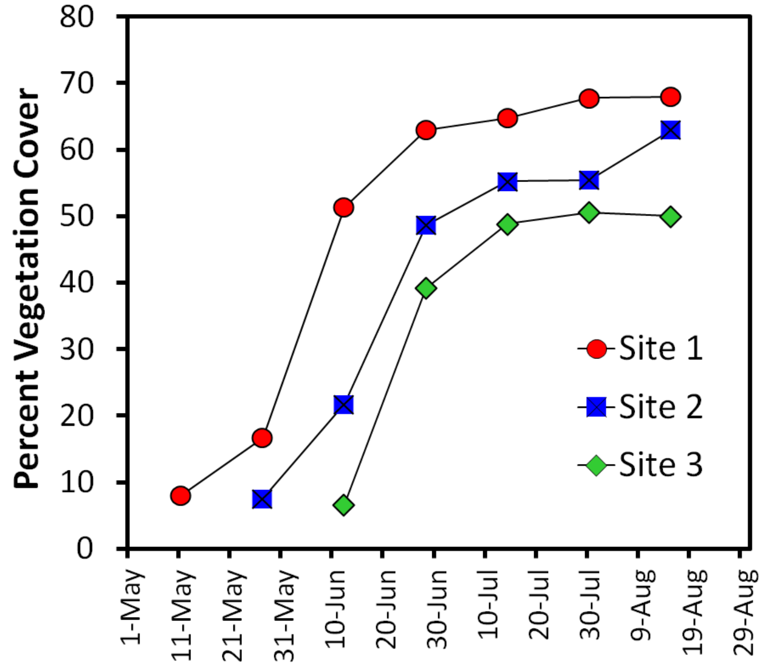
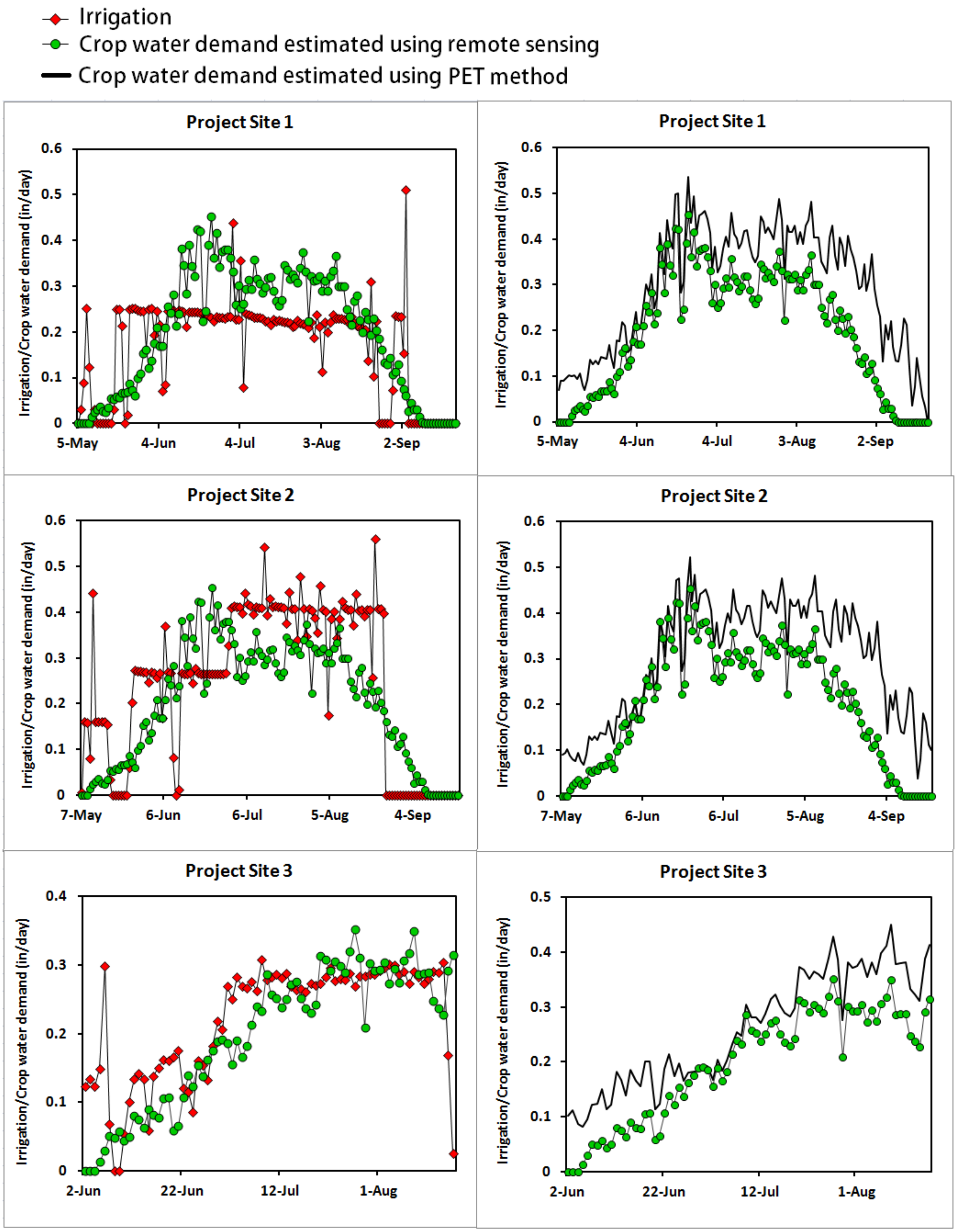


Figure 12: Percent vegetation cover estimated using Landsat-5 images. These data were used to construct the spectral crop coefficient (K_{sp}) curves for each field.

A spectral crop coefficient (K_{sp}) curve was constructed for each of the three project sites (sites 1-3) by estimating daily vegetation cover from infrequent satellite observations using a crop growth simulation model. Using this information and weather data from the West Texas Mesonet, crop water demand was calculated for each of the project sites. These results are presented in Fig. 13. The crop water demand calculated using the remote sensing method followed the same trend as the PET method, but the remote sensing-based estimates were lower compared to the PET-based methods, especially during the mid-season. This was primarily due to the capability of the remote sensing-based estimates to adjust the crop water demand based on the crop growth of individual fields. The PET approach assumes a standard, well-watered condition for all fields.

The crop water demand calculated using the remote sensing method for site 1 exceeded 0.30 in/day on most days during June, July, and early August. Although the evaporative demands were high, the producer applied only about 0.25 in/day of irrigation water on most days during the growing season. For site 2, the average irrigation applied from mid-June until mid-August was 0.4 in/day. During this time, irrigation the water applied was greater than the crop water demand calculated using the remote sensing method by about 0.05 to 0.1 in/day (Fig. 9). Site 3 was harvested for silage in mid-August. As seen in Fig. 13, the producer applied varying amounts of irrigation through the growing season, increasing from 0.1 in/day at the beginning of the season to 0.4 in/day before harvest in August. The producer-applied irrigation agreed with the crop water demand calculated using the remote sensing method on most days during the growing season.

Figure 13: Crop water demand calculated using the remote sensing method presented for all project sites, along with the corresponding crop water demand calculated using the PET method. The irrigation applied is also shown in each chart.



SmartField sensors: We tracked crop canopy temperature using SmartField sensors in two of the project sites. The critical temperature and time threshold were set at 82°F and 360 minutes, respectively, which are the recommended values for corn. When the crop is water-stressed (i.e., canopy temperature above 82°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 high temperature and drought in 2011 presented a unique situation involving the use of SmartField sensors for scheduling irrigation. Because of high air temperatures, irrigation up to 0.4 to 0.5 in/day was ineffective in bringing the canopy temperature below 82°F on all days during the growing season, and the crop remained stressed for several hours (i.e., canopy temperature above 82°F for six hours) during the day. An example of the data from SmartField sensors are presented in Fig. 14, which shows the 15-minute average crop canopy temperature data on 25 July 2011 for Sites 1 and 2. On this day, site 1 received an irrigation of 0.23 inches, and site 2 received an irrigation of 0.48 inches. Although site 2 received more than double the irrigation compared to site 1 (see Fig. 3), the crop canopy temperature stayed above the 82°F threshold for about 9 hours, of which the last 3 hours is considered as a crop stress period. 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.

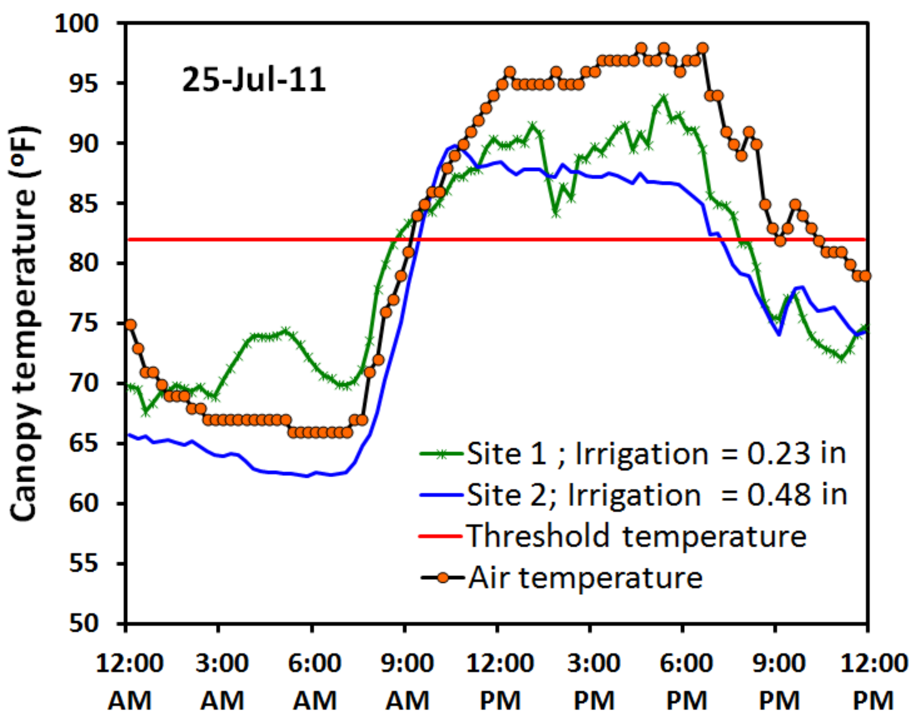


Figure 14: Crop canopy temperature data from the SmartFiield sensors for site 1 and 2.

Aqua-spy: One of the project sites in the TAWC demonstration project that was abandoned due to extreme drought conditions in 2011 was to be used for the direct evaluation of Aquaspy soil moisture sensors. Its abandonment made this comparison not possible in the current project. Project sites 1 and 2 were equipped with Aquapsy soil moisture sensors, but were not used for scheduling irrigation. The analysis of the data from the Aquaspy sensors in these fields (Fig. 15) revealed adequate soil moisture conditions in both fields on most days during the growing season. This was due to the daily irrigation for both sites, which kept the soil moisture conditions generally above the levels that would be associated with water stress (the red areas in the charts).

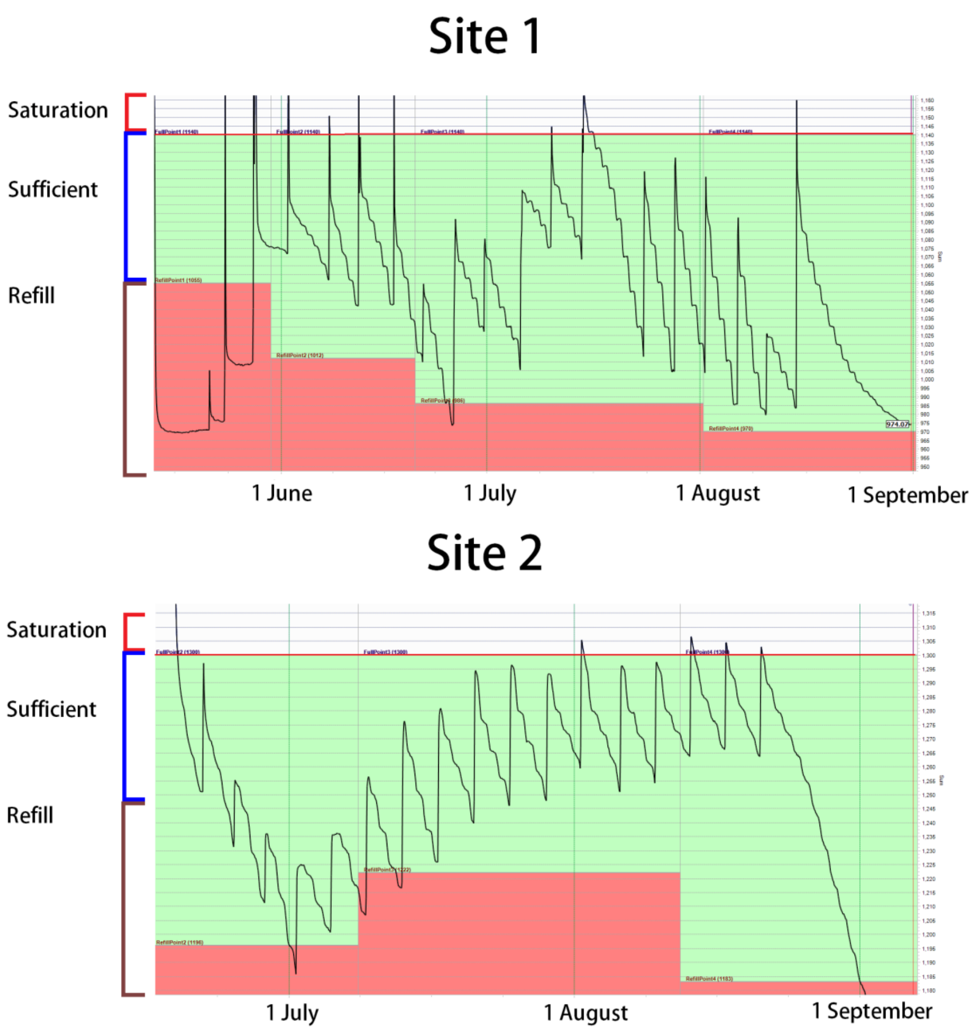


Figure 15: Aquaspy soil moisture data from site 1 and site 1.
Source: http://aserv.aquaspy.com/

Economic analysis

All costs and prices were held constant in the study, except the irrigation cost and cost of harvesting. The irrigation cost was allowed to vary with the amount of irrigation water applied and the irrigation method used. The harvesting and hauling cost was considered as a variable cost as it depends on the yield.

The Texas A&M Crop Budget for 2011 for the South Plains region (District 2, including both Floyd and Hale counties) was used to calculate the net returns for center-pivot irrigated corn for grain (Texas AgriLife Extension Services, 2011a) and center-pivot irrigated corn for silage (Texas AgriLife Extension Services, 2011b). Since the budget for drip irrigated corn for silage was not available, the budget for drip irrigated cotton for the South Planes region (Texas AgriLife Extension Services, 2011c) was used to supplement the data on irrigation cost and maintenance cost of drip irrigation systems.

According to the crop budget, the total direct expenses other than the harvesting and irrigation-related costs was 353.36 $/acre for center-pivot irrigated corn for grain. The total fixed costs on the implements, tractors and irrigation system was 57.94 $/acre resulting in total specified expenses other than harvesting and irrigation of 411.30 $/acre. The harvesting and hauling expenses were 0.40$/ bushel. The total irrigation cost, that included the irrigation fuel cost, irrigation labor cost and maintenance cost, was 12.64 $/acre-inch. In light of these data, the returns above direct expenses and returns above total specified expenses were calculated using Equation (1) and (2), respectively.

$$NR(DE)_{GC(CP)} = \left[(p_G - 0.40) \times Y_{GC(CP)}\right] - [(I \times 12.64) + 353.36] \qquad (1)$$

$$NR(SE)_{GC(CP)} = \left[(p_G - 0.40) \times Y_{GC(CP)}\right] - [(I \times 12.64) + 411.30] \qquad (2)$$

where $NR(DE)_{GC(CP)}$ and $NR(SE)_{GC(CP)}$ are the net returns above total direct expenses and above total specified expenses , respectively, for center-pivot irrigated corn for grain in $/acre, p_G is the price of corn grain in $/bushel, $Y_{GC(CP)}$ is the corn yield in bushels/acre and I is the amount of irrigation water applied in acre-inch.

Similarly, for center-pivot irrigated corn for silage, the total direct expenses other than the harvesting and irrigation-related costs was 318.44 $/acre. The total fixed costs on the implements, tractors and irrigation system was 64.06 $/acre, adding up to a total specified expenses of 411.30 $/acre. The harvesting and hauling expenses were 7.00 $/ ton. The irrigation-related expenses per acre-inch were the same as those for center-pivot irrigated corn for grain (12.64 $/acre-inch). From these data, the returns above direct expenses and returns above total specified expenses were calculated using Equation (3) and (4), respectively.

$$NR(DE)_{SC(CP)} = \left[(p_S - 7.00) \times Y_{SC(CP)}\right] - [(I \times 12.64) + 318.44] \qquad (3)$$

$$NR(SE)_{SC(CP)} = \left[(p_S - 7.00) \times Y_{SC(CP)}\right] - [(I \times 12.64) + 382.50] \qquad (4)$$

where $NR(DE)_{SC(CP)}$ and $NR(SE)_{SC(CP)}$ are the net returns above total direct expenses and above total specified expenses, respectively, for center-pivot irrigated corn for silage in \$/acre, p_G is the price of corn silage in \$/ton, $Y_{SC(CP)}$ is the corn silage yield in tons/acre and I is the amount of irrigation water applied in acre-inch.

For drip-irrigated corn for silage, the total direct expenses other than the harvesting and irrigation-related costs were assumed to be the same as those for center-pivot irrigated corn for silage (318.44 \$/acre). The irrigation cost was calculated to be 12.89 \$/acre-inch. The fixed cost was 86.06 \$/acre and, hence, the total specified expenses was 402.50 \$/acre. The returns above direct expenses and returns above total specified expenses for drip-irrigated corn for silage were calculated using Equation (5) and (6), respectively.

$$NR(DE)_{SC(DRIP)} = \left[(p_S - 7.00) \times Y_{SC(DRIP)}\right] - [(I \times 12.64) + 318.44] \qquad (5)$$

$$NR(SE)_{SC(DRIP)} = \left[(p_S - 7.00) \times Y_{SC(DRIP)}\right] - [(I \times 12.64) + 382.50] \qquad (6)$$

where $NR(DE)_{SC(DRIP)}$ and $NR(SE)_{SC(DRIP)}$ are the net returns above total direct expenses and above total specified expenses , respectively, for drip-irrigated corn for silage in \$/acre, p_S is the price of corn silage in \$/ton, $Y_{SC(DRIP)}$ is the corn silage yield in tons/acre and I is the amount of irrigation water applied in acre-inch.

The price received for corn grain in Texas in November 2011 was 6.39 \$/bushel and the U.S. average price was 5.70 \$/bushel (USDA, NASS, 2011). The price of corn grain used in the crop budget was 5.50 \$/bushel (Texas AgriLife Extension Services, 2011b). The price of corn for silage was 50.00 \$/ton (Texas AgriLife Extension Services, 2011b)

Site	Type of irrigation	Total area	Irrigation (inches)	Yield (bushels/acre)	Returns above direct expenses (\$/Acre)
1	Center-pivot	65 acres	32	172	119.36
2	Center pivot	60 acres	37	191	153.06
3	Drip	30 acres	21	22 tons of silage	356.87

Table 1: Returns above direct expenses (\$/acre) estimated for producer fields monitored in the current project.

Summary and Conclusions

The year 2011 has been classified as a mega-drought year in the Texas High Plains region, and climatologists have stated it to be the “worst one-year drought since 1895.” In addition to scant rainfall, maximum air temperatures were above 100^{o} F for most of the growing season. In the current project, four irrigation scheduling methods were evaluated using data from corn fields in the Hale and Floyd counties of Texas. These fields are part of the Texas Alliance for Water Conservation Demonstration Project led by Texas Tech University. At the beginning of the project, four center-pivot fields and one drip-irrigated field were selected in Hale and Floyd counties. Two of the center-pivot irrigated fields were abandoned later in the season due to extreme drought conditions. Irrigation of the study fields was monitored in real-time using the NetIrrigate telecommunications system. Two of the remaining center pivot fields were harvested for grain, while the drip-irrigated field was cut for silage.

Analysis of four different irrigation scheduling methods (PET, remote sensing, SmartField, and Aquaspy) 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 PET-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. As indicated by the results presented in Table 3, the crop water demand estimated for fields in this study using the remote sensing method were considerably less than the corresponding values obtained using the PET method. The remote sensing method uses real-time satellite images for estimating the crop coefficient, and thus can adjust irrigation recommendations to the actual crop growth conditions in specific fields. The standard PET method and the remote sensing-based method both use the same kind of weather data currently available from established weather monitoring networks in the region. The remote sensing-based method additionally needs remote sensing observations, but these can readily be obtained at no cost from existing satellite systems.

Site	Type of irrigation	Actual Irrigation during the crop growing season: excludes pre-season irrigation (inches)	Estimated crop water demand	
			PET method	Remote sensing
1	Center-pivot	24	41.3	27.7
2	Center pivot	31.5	38.4	27.1
3	Drip	17.8	27.6	20.8

Table 3: Summary of seasonal irrigation and crop water demand estimated using the PET and remote sensing-based methods.

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 soil moisture-based Aquaspy 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 moisture conditions in a given field. Direct evaluation of the effectiveness of irrigation recommendations based on this method was not possible in the current project due to abandonment of the fields in the project (due to extreme drought conditions) that were to use irrigation scheduling based on this method. However, from the type of data collected by these sensors, it is likely that a producer could schedule irrigations using this method that could maintain the crop at levels of soil moisture above those corresponding to stress.

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 PET and remote sensing-based methods are the simplest to implement, and would result in little cost to the producer. Of these two methods, the remote sensing method should be better at representing the actual water demand of individual fields, and thus may be less likely to result in over-irrigation. The SmartField and Aquaspy methods also appear to be suitable for practical use in irrigation scheduling, although each would involve a greater investment by the producer. The SmartField sensors might have some problems dealing with extremely high air temperatures.

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