INTEGRATING MULTIPLE IRRIGATION TECHNOLOGIES FOR OVERALL IMPROVEMENT IN IRRIGATION MANAGEMENT[1]

T.A. Howell*, S.A. O'Shaughnessy, and S.R. Evett
Lab. Director, Research Agric. Engr., and Research Soil Sci.
USDA-ARS
Bushland, Texas
*Contact Author — Voice: 806-356-5746 Fax: 806-356-5750
Email: terry.howell@ars.usda.gov

INTRODUCTION

There are many tools, techniques, and/or schemes to assist producers in irrigation water management and specifically in irrigation scheduling. This paper will highlight several of those but emphasize that several methods should be used simultaneously as an improved or advanced procedure to avoid biases and to improve reliability.

Water management decisions are basically strategic and tactical ones. Strategic decisions are decisions made after reviewing a season's data (e.g. reviewing field yield maps, accounting reviews of field/farm productivity and costs to determine profits or losses) or pre-season ones like changing or modifying irrigation system methods or technology; irrigation well additions, treatment, or power selection; selecting field crop hybrids/varieties; selecting field water management techniques; and field agronomic decisions on tillage, fertility, planting, etc. Tactical decisions for water management include the day to day ones on field to farm irrigation scheduling as well as scheduling irrigation system maintenance or emergency repairs (e.g. pipeline leaks or ruptures, irrigation well failures, power outages, etc.). Not every decision option may be necessary for either strategic or tactical options for specific operations. Figure 1 illustrates a diagrammatic flow chart for these decisions. An area of engineering or statistics is known as Decision Theory (DT). DT has several interesting concepts on the application to probabilistic or stochastic processes such as agriculture and

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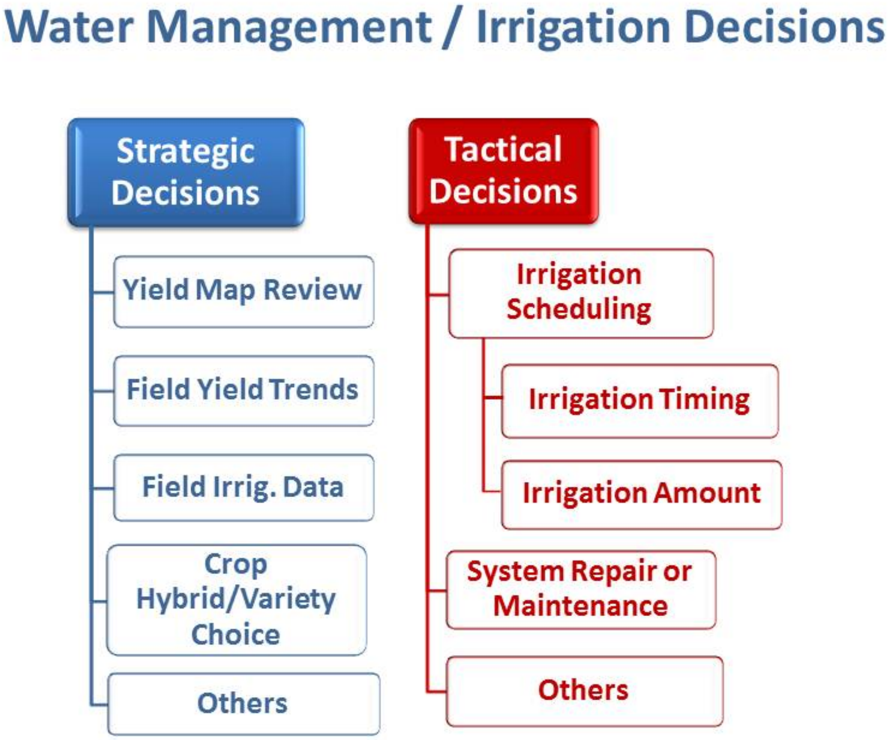

Figure 1. Water management / Irrigation decision diagram for illustration.

irrigation engineering. In some cases, not to be made light of, DT is a form of Game Theory (GT). GT is common in gambling not unlike agriculture where the card turn or dice roll (analogous to next day's events in agriculture) could dramatically impact profit or losses as well as affecting subsequent decisions. These decisions are all based on subjectivity based judgments, advice information or data, previous experiences, etc.

This paper will present a brief overview of these water management decisions both strategically and tactically and how multiple systems of measurements might impact the decisions. Our goal is not to suggest any information source or irrigation scheduling tool as superior but to illustrate each add valuable information to aid the decision maker. The decision maker must weigh the cost for the information, its reliability, and its suitability for his/her production system. Although other production decisions besides water management are important too, this brief paper will confine to water management.

IRRIGATION *STRATEGERY*

Strategory is a good Texan term that we'll export to the US Central Plains region for making strategic decisions. In the current context, strategory will be defined as a planning process to prepare for the best possible success given the producer's circumstances (land, capital, labor, etc.) and importantly, Risk Aversion (RA). Some producers opt for one of the most Risk Adverse options to simply not farm, lease/rent the farm, or even to regain the capital investment or gain by selling the farm. This type of decision may be based on any number of rational and defensible factors. Essentially, this removes the producer from the game (if a game concept is applied to crop production in this case). Other producers have varying levels of RA that vary from highly conservative (adverse to much risk; seek rather 'safer' strategies) to risk loving or risk seeking (willing to accept greater risks of larger losses with the small possibility of a large profit). Typically, this is a continuum of situations as opposed to just one position. Producers, in general, are by nature somewhat risk seeking, although irrigated producers have the irrigation protection (i.e., their ace-in-the-hole, to speak) afforded from droughts that rainfed or dryland producers will not have. Some state or water district regulations may control on-farm irrigation area, irrigation volume (in a set time period), or even irrigation season depth volume per season per unit of irrigated land and, therefore, affect even an irrigated producers' RA. To illustrate two examples of this RA, we'll define an irrigated producer that is more conservative as a "water concentrator" to use a greater irrigation capacity (available flow rate per unit irrigated area). We'll define an irrigated producer willing to accept greater risk as a "water spreader" irrigating more area per unit available capacity expecting seasonal precipitation to match or exceed normal (median or probability equal to 50%) hoping (or gambling on) a greater opportunity for the return per unit irrigation water. The water concentrator may produce more consistent long-term mean profits while the water spreader may capture the greater opportunity for returns in years with greater than normal seasonal rainfall.

Options for Water Spreading

The most common form of water spreading is 'stretching' or using a small irrigation capacity to irrigate more area. This can be effective if based on accurate knowledge (soil water profile status, degree of tolerance of the hybrid/variety selected for soil water defects or more commonly named crop water stress, reliable long-range seasonal weather forecast, etc.). Most of this knowledge is provided from secondary sources or advisors (consultants, seed dealers, variety trials, various weather forecast sources). When the information provided is accurate then the chances of making a reliable (high probability of being correct) choice to 'stretch' the irrigation capacity and utilize the favorable opportunity could improve the overall profitability of the producer. This is often referred to as opportunity cropping to take advantage of better situations.

Most commonly water 'stretching' involves some form of deficit irrigation where the producer knowingly produces more area than can be profitably irrigated in normal or below normal rainfall seasons. Crop sequencing can provide some aid in this case (e.g. irrigating a previously fallowed area where precipitation has been captured and stored in the soil). Other strategic decisions might include conservation tillage (e.g. no till or ridge till or even furrow diking). The strategic decision to switch to conservation tillage will require a capital investment in different equipment and trial and effort to study and learn the equipment operation. These systems might retain previous crop residues to enhance winter/spring precipitation capture through better infiltration and reduced surface evaporation or precipitation detention and runoff reduction in the case of furrow diking.

Essentially, effective deficit irrigation involves a planned soil water depletion scheme. Usually, these require precise knowledge of planting soil profile water status, crop development stages when the crop hybrid/variety is least damaged by soil water deficits, and the exact gross and effective irrigation system capacity as well as solid information for the field on crop extractable soil water. Most of this information is gained from secondary sources (crop consultants, extension specialists, etc.) or built first-hand through experience.

Irrigation Technology

Certainly, irrigation application efficiency and reliability are important strategic irrigation decisions. Most of the irrigation in the Central Plains of the US began as some form of surface irrigation (border, furrow, etc.), but has migrated to predominately center pivot sprinkler irrigation since the late 1960s or 1970s. Center pivots now irrigate over 90% or more of the irrigated area in the Central Plains. Subsurface drip irrigation (SDI) has gained popularity, but remains a much lower percentage. These systems offer many advantages over surface irrigation:

Greater application efficiency and uniformity
Less labor
Ease of automation or control
Reduced dependence on soil to be the hydraulic distribution network
Ability to utilize smaller application depths

The strategic decision to modify irrigation technology involves an economic investment as well as time and effort to learn the newer technology. These might be individual step-wise developments over a multi-year time frame to reduce the capital investment per year. The availability of less expensive capital (lower interest rates, cost sharing programs, etc.) has made these attractive means to maintain irrigated area as irrigation capacity declines or to enhance profits through greater yields from the better irrigation uniformity and multiple system utility (chemigation, fertigation, etc.).

Agronomics

One of the best strategic tools is simply good farm or field economic records. These should be a routine year end strategic decision opportunity to observe trends as well as possible trial practices that may or may not have performed as planned. One of the more valuable tools from Precision Agriculture is yield maps generated at harvest (for most crops) easily from combine equipment or accessories. These can show possible abiotic (water or soil issues) or biotic stresses (crop disease, insect damages, etc.). The former might be a lower yielding streak around a center pivot where incorrect nozzles were installed, nozzles were plugged or broken or distinct sections of a field that may have a soil textural difference that was inadequately fertilized or where nutrients leached from the root zone. The latter biotic damages are more likely to be sections or parts of a field. These are clues that need investigating and don't always easily lead to direct corrective strategic decisions without other corroborating measurements or observations.

Field crop yield records may also indicate a field that performed differently than anticipated for that crop hybrid/variety selection based on either seed company variety or university variety trials. The private or public sector variety trials may have been conducted under differing soils, fertility, irrigation, or climatic regimes than experienced in the year of record or without confounding biotic influences. Using these combined information sources, the producer can decide whether the crop hybrid/variety should be used in the future on a field or farm.

Water Management and Irrigation Scheduling

The post-season or post-year review should include of all available water management data on a field by field basis. These data might include any of the following (although seldom will all example items listed below be appropriate or feasible for a specific operation or field):

Preplant soil nutrient tests and fertilizer application records
Field rainfall and irrigation application records
Irrigation system performance records (any pressure gauge observation or water flow/volume records)
Soil water measurement records
Visual observation notes by calendar date
Crop advisor reports (whether insects, fertilizer, or irrigation)
Aerial photographs or satellite images

These records and data are invaluable in constructing a post-harvest review on a field or farm basis of the water management. The data allows determination of what changes in water management procedures or agronomic practices might maximize future profits or economic returns to land, labor and capital for the water investment. A useful index of the field water productivity is the crop yield per unit of water given as

$$WP_i = \frac{CY_i}{\left(R_i + I_i + SWD_i\right)} \tag{1}$$

where WP is water productivity (lb/ac per inch or bu/ac per inch or kg/ha per mm or as kg/m^3) for field *i*, CY is crop yield (lb/ac or bu/ac or kg/ha), R is rainfall (effective growing season rainfall if possibly estimated in inches or mm), I is ‘net’ irrigation application (in inches or mm) [Net irrigation = Gross irrigation x Irrigation application efficiency], and SWD is soil water deficit or seasonal water use from the crop root zone (in inches or mm). The field WP index calculated in this manner is much less precise than might be measured in controlled experiments, but can still provide producers with useful information.

However, this index provides an invaluable tool for inter-field or farm comparisons for specific crops. County extension, NRCS conservationists, or crop consultants should have available local information on WP values for major crops in specific regions.

TACTICAL WATER MANAGEMENT

Day to day tactical irrigation decisions depend on the irrigation supply system and/or the irrigation capacity (IC; flow rate per unit irrigated area). In the Central Plains of the US, almost all irrigation is supplied by wells and considered as an ‘on demand’ basis supply system regulated by state laws and/or water districts rules or regulations. So in these cases, the producer is essentially in control of decisions subject to only the constraints imposed by regulations or the IC. If the well power source is electrical, then the electrical supply company may have peak load controls that might override producer decisions.

Irrigation Scheduling

Irrigation scheduling generally determines the next time for irrigation and the amount of water to apply. For center pivots this might be the decisions of when to start the irrigation event and the selection of a center pivot rotation speed (sets the irrigation amount for a given IC). For SDI systems this might be the date to begin a SDI set and the length of time to run the irrigation set. Irrigation scheduling for these systems in common use in the Central Plains is different from surface irrigation methods because the application amount per irrigation is smaller and the applications are typically applied more frequently. Martin et al. (1990), Heermann et al. (1990), and Hill (1991) provide a thorough discussion of irrigation scheduling principles.

Irrigation scheduling integrates elements of the system hydraulic design and maintenance together with aspects of the soil and the crop characteristics with the atmospheric evaporative demand. It involves providing managers with the irrigation needs of the crop that must be organized together with the cultural aspects of growing and harvesting the crop. Irrigation scheduling for center pivots or SDI systems can be integrated into the system controls through automation.

Irrigation scheduling is typically accomplished by 1) measuring or estimating crop water needs, 2) measuring a soil water status property, or 3) measuring a plant water status property. The latter two are more often used to determine the need for irrigation and are easily integrated into an automated control system (Phene et al., 1990). The second can also be used to determine how much water to apply. The former, traditionally, has been used through an evapotranspiration-water balance model soil water balance model and is adaptable to both indicating the need as well as the amount of water that should be applied (Jensen et al., 1990; and Allen et al., 1998). Other factors influencing scheduling of irrigation systems may include soil salinity, impact of water deficits on crop quality, or the impact of rain on salt leaching into the root zone. These last factors are not typically an issue for crops in the Central Plains and are beyond the scope of this paper.

Irrigation System Capacity

Irrigation system capacity, IC, is a critical design and operational parameter. System capacity is typically defined as the ratio of the system flow rate (Q in gpm or m^3/s) to the land area (A in ac or ha). Common units for IC are gpm/ac or m/s). It is typically more convenient to express the IC ratio in units of inches/d or mm/d. Table 1 gives some common conversions for IC units.

Table 1. Irrigation system capacity conversions.

Base	English Units		Metric Units	
gpm/ac	1.0 gpm/ac	0.053 in./d	1.558×10^{-4} m^3 s^{-1} ha^{-1}	1.34 mm/d

The IC and the irrigation application depth determine the least amount of time necessary to complete irrigation or the irrigation frequency. IC is one of the main tactical irrigation scheduling constraint variables. IC importantly can estimate the irrigation system excess (rare) or deficiency in meeting the crop irrigation demand for a defined interval. As an example, if we assume a 500 gpm well irrigates a ¼ section center pivot (~125 ac or 51 ha), then for a mean ET of 0.35 in./d (8.9 mm/d), the ‘net’ irrigation plus ‘effective’ rainfall would need to exceed 1.38 in. or 35 mm to avoid depleting profile soil water reserves Additionally, for this IC center pivot to apply 1.25 in. (32 mm) of irrigation, it would take approximately 6 days for a complete revolution.

The soil water balance is commonly used in irrigation water management decisions and expressed as

$$SW_j = SW_{j-1} + R_j + I_j - ET_j - DP_j \tag{2}$$

where SW is profile soil water in the crop root zone for day '*j*,' R and I are defined previously, and ET is evapotranspiration and DP is percolation from the root zone with all terms in depth units (inches or mm). DP can be estimated several ways (Wilcox, 1959; Gardner, 1960; Stone et al., 2011). I and R each include application water losses and runoff, respectively. The soil water balance is widely used to estimate crop evapotranspiration (ET) as

$$ET_{(j-1)\text{ to }j} = \frac{\Delta SW_{(j-1)\text{ to j}} + P_j + I_j - DP_j}{j - (j-1)} \tag{3}$$

where ET_j is the crop water use (in./d or mm/d). If $ET_j > IC$, then the system is deficit irrigating and the soil water (SW) profile is declining; however, if $ET_j < IC$ then the system can match or maintain or increase the soil water in the profile. The degree of management flexibility in water management is largely dependent upon the difference between IC and the 'peak' crop ET rate called ET_{max}. For new systems being installed the design can correctly consider IC and the risk. For older system, the IC is a constraint that must be considered with the producer's risk.

Irrigation Flow/Volume Measurements

For any irrigation water management technique to be useful, accurate measurements of irrigation water applications are required. Since most Central Plains producers are using individual irrigation wells or well networks, flow metering should be considered essential. Many State and water districts now require annual reporting of water use data making metering both required and essential. Water application amount can be estimated without a water meter (although a water meter is preferred) based on indirect energy use (natural gas amount, electrical meter observations, or diesel fuel use); however, these indirect measurement methods require calibration to account for inefficiencies in energy conversion to water from engine or motor efficiency, drive efficiency, and pump efficiency. Flow metering, especially volume, is essential to estimate reliably the I value in the soil water balance (Eqn. 3) besides providing feedback verification on well flow rates and volumes. Flow metering now being required by State and water district regulations are being widely accepted despite earlier concerns about them being used for that purpose. In most Texas High Plains water districts, well metering and annual reporting is a requirement now (some have a 2013 report date for 2012 water usage). Water metering and system performance (pressure gauge observations) are required in water management decisions to both comply with regulations and to verify irrigation applications.

Visual Irrigation Management Observations

Visual crop and/or soil observations have long been used to guide irrigation targeting or timing based upon vegetation characteristics (leaf color changes, leaf rolling, leaf wilting, upper petiole flexibility, etc.). These are expanded aerially by photography whether black & white (B&W), color, or false color infrared (IR) imagery.

Similarly to crop observations, physical soil sampling and visual and 'feel' techniques are widely employed for their simplicity, ease, and minimum time requirement. However, all visual crop observations as well as soil water sampling require extensive training and experience for best results to indicate irrigation need. The single difficulty with crop visual indicators is that observations are likely to occur after yield impacting soil deficits have occurred. They can provide useful feedback information for water management decisions, particularly soil water measurements by the 'feel and appearance' method, if the observer is experienced and familiar with a specific field, farm, or region. A problem with the soil 'feel and appearance' method is the inability to quantify SW aswell as the need to sample many areas in a field to obtain reliable information. However, the SW 'feel' method can provide some feedback information to aid irrigation scheduling on both the profile soil water status to target or trigger irrigation as well as the root zone SWD to estimate approximate irrigation amounts to refill the soil profile. The "feel and appearance" method remains widely used by crop consultants and can be reliable with experience and knowledge of the field, farm, or region.

Soil Water Balance or Crop Growth Models

Soil water balance methods have long been advocated in various systems from simple checkbook methods to advanced computer models. All are based on some form of Eqn. [3] or [4]. The simpler ET methods rely on crop coefficients as

$$ET_j = \left(K_c K_s\right)_j \left(ET_{os}\right)_j \tag{4}$$

or

$$ET_j = \left(K_s K_{cb} + K_e\right)_j \left(ET_{os}\right)_j \tag{5}$$

where K_c is the crop coefficient for day j, K_s is a soil water deficit coefficient (0 to 1), ET_{os} is the reference ET for a short, smooth crop coefficient (i.e., mowed, irrigated grass) for a well irrigated crop but with a 'dry' soil surface, and K_e is a soil water evaporation coefficient to adjust the ET for a 'wet' soil from rain or irrigation (Allen et al., 1998). Eqn. [4] is known as the single coefficient approach, and Eqn. [6] is known as the dual coefficient approach. Eqn. [4] is used in the KanSched irrigation scheduling model (Clark et al., 2004) as well as in the Texas High Plains ET Network (Howell et al., 1998). Some form of Eqns. [4] or [5] is incorporated in most crop growth simulation models, too. In most crop growth models, the crop coefficient values are not directly used but similar relationships based on crop development or leaf area index simulated by the model are used.

Soil Water Measurements

Many methods exist to measure soil water (Evett, 2007) but few are designed for automated or continuous soil profile measurements desirable for irrigation scheduling. Many methods can make point or multiple vertical measurements, but only a few extend deep enough to measure the entire crop root zone depth (5-6 ft; 1.5-1.8 m). Although no instrument is perfect (Evett, 2008), several can be used reliably for irrigation management. Only a few offer a complete crop root zone measurement, but even a few point measurements, if accurate, can aid irrigation scheduling.

These measurements can verify irrigation or rain penetration into the crop root zone as well as excess soil water (leading to DP and nutrient leaching from the root zone and/or root oxygen deprivation or depleting soil water leading to crop water deficits impacting yield).

Soil water measurements can be categorized as either direct (sampling) or indirect (some soil property being measured) (Evett, 2007). Direct measurements include either gravimetric (mass based) or volumetric based or measurements. Seldom is volumetric soil sampling used commercially for irrigation scheduling.

Measurement of the soil water potential (energy) is useful because it represents the energy gradient against which crop roots must work to extract soil water and soluble nutrients. The volumetric water content and the soil water potential are interrelated through the soil hydraulic properties, and the function is called a soil characteristic curve or function. Figure 2 shows example soil characteristic curves for several soil textures from Evett (2007). Curves illustrated in Figure 2 typically exhibit hysteresis characteristics where the curves are really a ‘family’ of curves, called scanning curves, depending on if the soil is wetting or drying. More commonly, the soil characteristic curve is plotted with the soil water potential as the independent variable (X-axis).

The examples illustrated in Figure 2 show that the Loamy Sand soil has much less ‘available’ soil water (θ_{fc} - θ_{pw}) than the Silt Loam or Clay soil. Of these three example soil textures, the Silt Loam soil has much greater ‘available’ soil water based on the 1/3 bar definition for 'field capacity' and 15 bar definition for 'permanent wilting point.'

Soil water instrumentation is described in more detail in Evett (2007, 2008), Chávez et al. (2011), and Chávez and Evett (2012). Chávez and Evett (2012) compared four commercial soil water sensor instruments in field experiments in Colorado and Texas and recommended on site calibrations for each, which are typically beyond the capabilities of most producers or even consultants. However, as long as the sensor measurements are consistent, 'absolute' calibrations may not be required for most irrigation water management decisions.

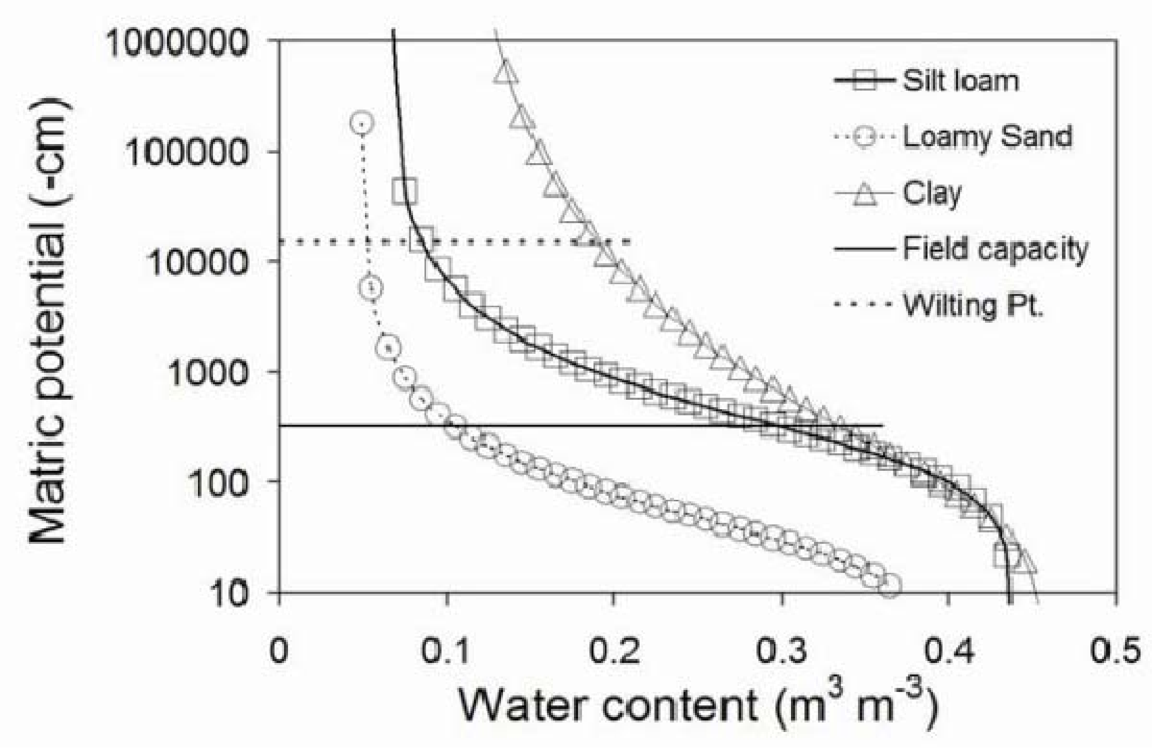

Figure 2. The soil water content vs. soil water matric potential relationship for three soil textures as predicted by the Rosetta pedotransfer model (Schaap et al., 2001). Horizontal lines are plotted for the field capacity, taken as −333 cm (~−33 kPa), and for the wilting point, taken as −15 000 cm. http://www.ars.usda.gov/Services/docs.htm?docid=8953. Source Fig. 2-2 from Evett (2007) p 30. Note: that the -333 cm equals 1/3rd bar (θ_{fc}; field capacity) and -15,000 cm equals 15 bar (θ_{pw}; permanent wilting point), and the Y-axis is plotted as a log scale.

Plant Water Measurements

Plant water status measurements used for irrigation scheduling or control usually are leaf water potential (energy), canopy or leaf temperature, or direct measurements of plant transpiration (e.g., stomatal conductance or sap flow) (Jones , 2004). Although the latter is highly desirable and possible, its field application and equipment costs are generally not practical for producers or consultants.

Leaf water potential (LWP) is one part of the driving force for water movement through a plant (Jarvis, 1976). In a non-stressed, well-transpiring plant, there is a difference in potential energy between water in the leaves and water in the root system. This difference is what causes water to move through the plant. The difference in potential can be assessed from leaf stem water potential measurements made using a pressure chamber instrument (e.g., PMS Instrument Company, Albany, Ore.). LWP measurements are commonly used in viticulture (Moller et al., 2007) to schedule irrigations and for characterizing water stress in cotton crops (Alchanatis et al., 2009). Although LWP measurements are an accepted method to characterize water stress, the method is tedious, inconvenient and not amenable to automation.

Another plant-based method for determining crop water status involves crop canopy (leaves) temperature measurements. A decrease in water uptake reduces transpiration and increases leaf temperature (Blonquist et al., 2009). Stressed plants typically exhibit greater differences in canopy to air temperature. These measurements are usually accomplished using non-contact infrared thermometers. Hand-held infrared thermometers have been used to time irrigations (Nielsen, 1990; Garrot et al., 1994; Gontia and Tiwari, 2008), however these measurements represent spot assessments of a limited number of plants, usually taken at one time per day (Hattendorf et al., 1988; Nielsen, 1990; Farahani et al., 1993) near solar noon and may provide inadequate information for decision making. However, continuous crop canopy temperature measurements

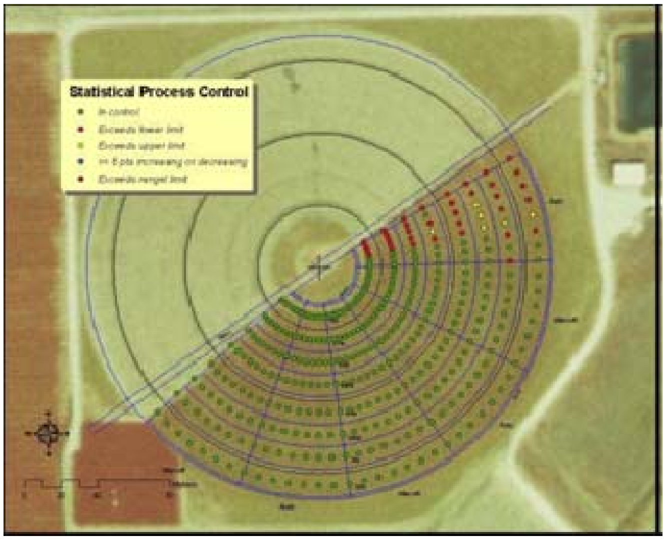

Figure 3. Field map for DOY 258, 2005 showing out-of-control points in a soybean field. Although the effects were not visible to the naked eye, the out-of-control points highlight the region where excess herbicide was sprayed (Peters and Evett, 2007).

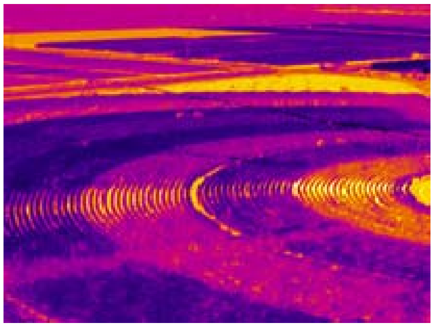

Figure 4. Whole-field image of a cotton field under a 3-span center pivot irrigation system showing the inner four concentric treatment plots (I100%, I33%, I67%, and I0%) and the corresponding values of CWSIe (0.51, 0.78, 0.64, and 1.08, respectively). Thermal image taken at Bushland, TX, on DOY 213 (Jul 31) in 2008 (O'Shaughnessy and Evett, 2009).

made during daylight hours using wired or wireless infrared thermometers mounted on moving mechanical irrigation systems, or on masts in subsurface drip irrigated fields are capable of assessing a larger field area on a frequent basis, automatically.

Irrigation scheduling that makes use of canopy temperature measurements typically involves a stress index and a predefined threshold value that is crop and region specific. If the threshold value is exceeded, irrigation is scheduled. Examples of such stress indices include the Time Temperature Threshold (Evett et al., 1996; Peters and Evett, 2008; O'Shaughnessy and Evett, 2010) and the integrated CWSI (O'Shaughnessy et al., 2012). Both of these plant-monitoring irrigation control systems have been successful in producing crop yields and crop water use efficiency responses that are similar to or better than those achieved with irrigations based on direct soil water measurements with the neutron probe. Continuous crop canopy measurements not only provide a measure for calculating an integrated stress index, they can also provide a spatial picture of performance or crop water status feedback to a farmer throughout the growing season when the data are mapped, either as raw temperature data or as out-of-control points (Fig. 3), a stress index (e.g., the CWSI as shown in Figures 4 and 5), relative leaf water potential or potential yield (Peters and Evett, 2007; O'Shaughnessy and Evett, 2009; O'Shaughnessy et al., 2011).

INTEGRATION OF WATER MANAGEMENT TECHNOLOGIES

Although there are numerous techniques and instruments that can aid irrigation water management decisions or even automate irrigation control, none are perfect and without error or bias. Irrigation scheduling can tolerate considerable error if it is random. However, bias errors that are common with many soil, crop, or water metering systems can lead to erroneous or non-optimum irrigation decisions. Relying on one measurement technology may miss diagnose either abiotic (water or soil effects) or biotic effects (crop, insect, or disease) on irrigation decisions.

It is rather simple to use one or more water management techniques as a check to avoid these problems. The checkbook or ET model approach is for near ideal crop conditions, but various forms of abiotic or biotic crop stress could be detected by crop thermal methods or even imagery, and/or soil water measurements. Soil sampling can be used to correct or reset an ET model or a crop growth development model that may be either missing the crop development or the crop water use. These biased measurements or models may offer inaccurate information for irrigation water management decisions. Biased information is particularly harmful in deficit irrigation water management where the IC constrains irrigation making it difficult to catch up the SWD and where the tolerance for acceptable crop yield or profit is small. The risk adverse producer would likely invest more capital in water management systems that are more reliable and accurate to obtain more nearly 'perfect' information to guide and assist in the water management decision. Improved dividends or profits should accrue for this water management capital investment, whether monetary capital or intellectual capital, over the longer operational horizon.

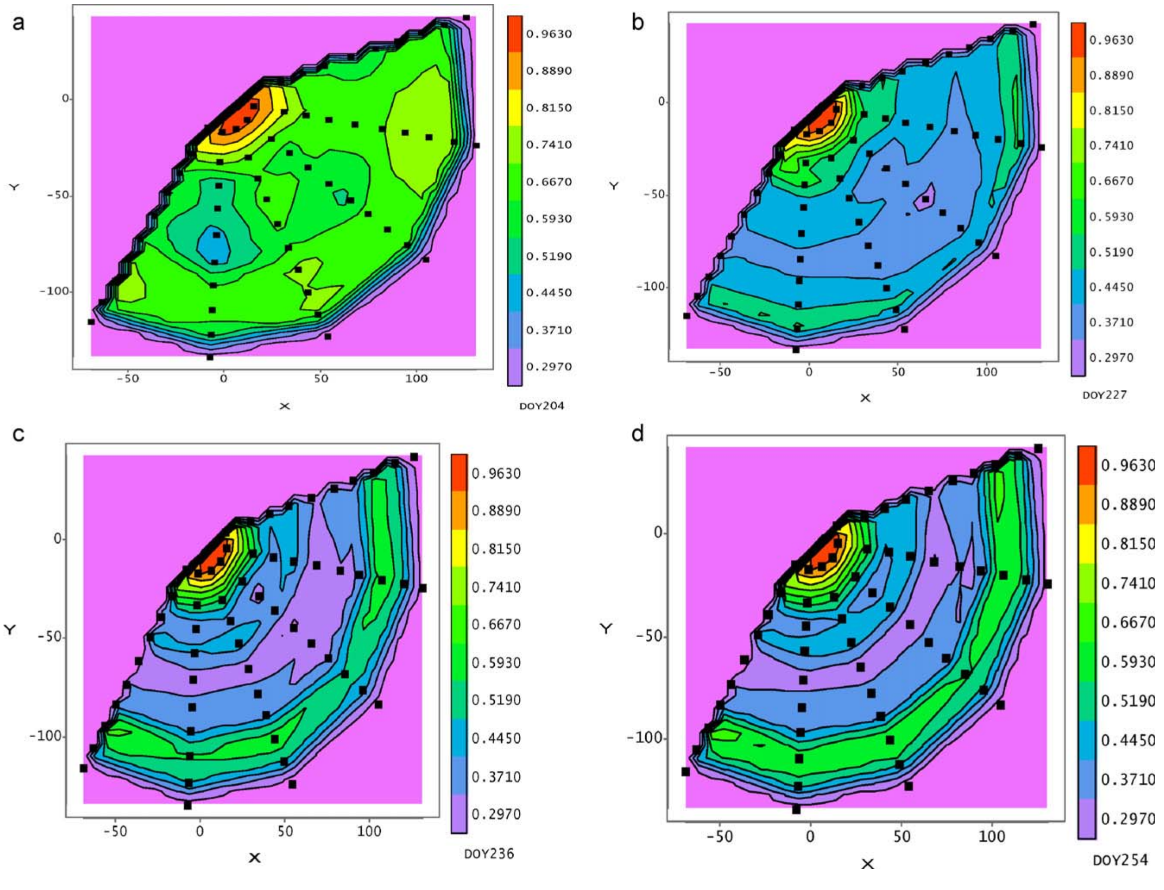

Figure 5. Spatial map of average empirical CWSIe for cotton over growing season 2007, averaged values from DOY 198 through listed date: (a) DOY 204, 6 days after start of irrigation treatments; (b) DOY 227, 29 days after start of irrigation treatments; (c) DOY 236, 38 days after start of irrigation treatments; and (d) DOY 254, 2 weeks after halting irrigation treatments (O'Shaughnessy et al., 2011).

For a producer to have knowledge and awareness of the potential effects of irrigation decisions with inaccurate or even erroneous data is reduced by having good data or information about the crop water requirements and the stochastic effects of the probabilistic variations in weather (whether temperature, rainfall, or reference ET). These 'good' or accurate data should permit better irrigation decisions. These better decisions are important in water conservation as well as producer profit. Soil or crop based measurements together with water metering offer insurance for making better water management decisions.

The irrigation decisions should always consider the 1) no later than date of irrigation and 2) the no sooner than date for a specific irrigation amount. Then the irrigation amount decision may avoid over filling the profile SWD with its non-uniformity and possible nutrient leaching and avoid critical SWD where the soil water deficits that may reduce crop yields and profits.

Although many of these water management measurement tools can be expensive, the cost needs to be weighed against the opportunity to make better water management decisions as well as the lost opportunity costs when incorrect water management decisions are made.

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