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ADVANCED IRRIGATION ENGINEERING: PRECISION AND PRECISE

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ABSTRACT

Irrigation advances in precision irrigation (PI) or site specific irrigation (SSI) have been considerable in research; however commercialization lags. A primary necessity for is variability in soil texture that affects soil water holding capacity and crop yield. Basically, SSI/PI uses variable rate application technologies, mainly with center-pivots or lateral-move or linear irrigation machines, to irrigate prescription-specific management zones within a field by varying the application to match crop needs or soil water holding constraints. SSI/PI can avoid irrigating management zones with poor internal drainage; zones with poor crop growth or development (from fertility or salinity or other soil factors or even crop diseases); or zones with known problems (rock outcrops, physical obstructions, etc.). One limitation for SSI/PI is defining the objective function for the production goals/constraints. Examples of objective functions include optimizing overall field productivity, minimizing water use, or reducing environmental on-site or off-site impacts. The variable rate applications are achieved by a range of engineering options from variable nozzle flow rates, pulsing nozzle flows, or multiple nozzles on separate submains to vary application rates. Newer center pivot and linear machines are controlled by on-board microprocessor systems that are easily integrated with supervisory control and data acquisition (SCADA) controllers to integrate communication and variable rate application controls for specific sets of nozzles or individual nozzles for determined management zones. Communication for center pivot or linear controllers is typically done using radio telemetry, wireless internet links, or cellular telephones.

Precision irrigation is of limited utility without precise irrigation scheduling (temporally and spatially). Irrigation scheduling has advanced considerably in the past 20-30 years with improved technology to measure soil or plant water status and, especially, within the past 10-15 years to utilize remote sensing tools. Plant or soil sensors are most often utilized to initiate or complete an irrigation event based on specific criteria. Automated weather stations are now widely used to provide basic site information on the irrigation requirement using either crop development models or simpler reference evapotranspiration (ET) data to be used with crop coefficients (Kc). Remote sensing is increasingly being utilized to measure crop water status (usually through crop surface temperature) or crop development or ground cover based on spectral reflectance from specific electromagnetic wave bands, but future satellites (i.e., Landsat 8) may not contain a thermal radiation band critical for crop stress and ET. Usually, the red band (0.63-0.69 micro-m or band 3 on Landsat TM or EM+) and the near infrared band (0.76-0.90 micro-m or band 4 on Landsat TM or EM+) are used to determine the Normalized Difference Vegetation Index (NDVI). Satellite and aircraft remote sensing platforms have not proven useful for irrigation scheduling due to issues of too coarse spatial and temporal resolutions and too long turn-around times for getting data processed and useful information to the field. Inexpensive infrared thermometers (IRTs) are being used as crop thermal temperature detectors ranging from hand-held to fixed units in the field to newer wireless IRTs using mesh networks to communicate with controllers. Near-surface remote

sensing with sensors mounted on moving irrigation systems may provide critical spatial integration from point weather networks and useful feedback on crop ET and irrigation controls in advanced automated systems, particularly for SSI/PI.

INTRODUCTION

Many irrigation engineering advances in the past 20-30 years or longer have been focused on improving irrigation system performance (both efficiency and uniformity) and scientific irrigation scheduling using modeled soil water balance to predict irrigation dates or direct monitoring of soil or crop water status. Generally, these techniques or protocols are designed for an even irrigation application volume to a specific field area. These field areas are variable based on the farm scale and the particular situations. Most irrigation systems apply water with a predictable non-uniformity based on the irrigation method and usually the applied water depth (volume per unit area). Many other factors related to soils (nutrients, texture, and salinity) and biotic stress factors – disease or pests – or even environmental variables like rainfall or precipitation, air temperature and relative humidity, reference and/or actual crop evapotranspiration (ET) have a spatial non-uniformity, in many cases, that results in uneven crop yields even when irrigation is applied efficiently and uniformly and even when scheduled properly. This paper reviews advances in precision irrigation and precise irrigation scheduling. The principle goals of these technologies are to: 1) improve crop yield and quality; 2) reduce percolation or runoff with the adverse environmental impacts from irrigated agriculture (nitrate leaching, sediment transport, and nutrient and agrochemical transport); and 3) mitigate larger scale impacts on regional sustainability and groundwater mining or surface water degradation. These goals must result in greater producer net profit or meeting regulatory goals or irrigation district rules.

PRECISION IRRIGATION

Precision irrigation is often discussed but seldom wholly quantified (Camp et al., 2006). In general, we use the term in the larger precision agriculture (PA) concept (Kitchen et al., 1996; Stafford, 1996; Pierce and Nowak, 1999). In this review we characterize precision irrigation (PI) as some version of site-specific irrigation management (SSI) (Sadler et al., 2005). SSI/PI can have various utility uses: 1) address soil texture differences; 2) address soil or crop development differences; or 3) avoid field areas (rock outcrops, physical obstructions, etc.). SSI/PI uses various engineering solutions to apply water at controlled, variable rates to specific management zones. If the irrigation has multiple purposes (fertigation, chemigation, etc.), these additional management zone layers require further definition. This SSI/PI has been characterized as prescription irrigation. Rawlins (1996) defined precision farming as having the ability to apply inputs precisely when and where they are needed. He further characterized prescription farming as utilizing real-time information regarding the processes that might be limiting production on a spatial scale in the field. He also suggested that variable seeding rates or variable fertility in PA had been successful for nutrients that don't readily leach or transport (phosphorous, potassium, lime, etc.), but he emphasized the need for real-time spatial management for water and nitrogen and biotic crop stress vectors (pest, disease, etc.). However, the "when needed" part of Rawlins' definition has rarely been applied to irrigation management, even in research. Hoffman and Martin (1993) utilized the term prescription irrigation, and they suggested that the design of PI should permit variable irrigation to individual parcels throughout the season. SSI/PI needs to be applied at a spatial agronomic scale appropriately matched to the ability to sense soil or crop data and the engineering constraints of particular application technology. They believed that prescription irrigation should be equally applicable to all irrigation methods even if the irrigation technology cannot apply irrigation in a variable rate. This seems rather academic in that prescription requires an ability to match applications with desired management zone requirements.

Prescription irrigation, or as we prefer SSI/PI, requires the sensing of the crop irrigation need and the ability to apply irrigations at rates applicable to the desired management zone. Implicit for SSI/PI is the ability to define field management zone layers for the SSI/PI control (soil textural maps, soil fertility maps, soil salinity maps, etc.) and real-time management zone parameters (biotic stresses or water deficits). These will be discussed later in the precise irrigation section.

SSI/PI efforts have largely been focused on pressurized systems, although certain SSI/PI designs might be applied to surface irrigation. Typically, SSI/PI is focused on sprinkler irrigation machines (center pivot or lateral move) or solid-set sprinkler systems. Raine et al. (2007) estimated typical spatial scales for commonly used irrigation systems that varied from 0.1 m^2 to 10,000 m^2. SSI/PI is difficult to economically apply to microirrigation technology (drip emitters, micro-spray, drip tape, etc.). Most current applications use global positioning systems (GPS) and/or geographic information systems (GIS) to develop management zones within the field scale. SSI/PI applications for mechanical sprinkler machines require either individual nozzle/head controls or manifold control of a number of nozzles/heads. The management zone for SSI/PI on these systems will depend on the spatial scale coverage of the manifold and the distance coverage for the system (distance for a lateral-move system or radial path swath for a center pivot). These SSI/PI application zones can vary from ~50 m^2 for a lateral move to ~200 m^2 or more for a center pivot (larger zones are on the outer end). Sadler et al. (2005) reported a possible water savings and profits from near zero to 50% with averages in the range of 20-80%. They were principally addressing only soil texture effects for SSI/PI. A few SSI/PI efforts have involved drip irrigation and derived crop water stress (leaf water potential) and irrigation need from thermal imaging (Cohen et al., 2005; Sela et al., 2007).

Many engineering reports on center-pivot and lateral-move sprinkler systems described the spatial variable applications of water and nitrogen. Evans et al. (2006) provides a complete review of SSI/PI irrigation systems in Montana. Other examples are found in Camp and Sadler (1998); Camp et al. (1998); Evans et al. (1996); Duke et al. (1997); Heermann et al. (1997); King et al. (1996); King et al. (1998); and Sadler et al. (1997). The state of engineering, although somewhat diverse, demonstrates the options available. Most research efforts have focused on providing more relevant information to the irrigation manager, which is counterproductive since managers have limited time to process this information. It is more important to develop automated decision support systems (DSS) that process these data into real-time, automatic control of the irrigation system. Computer control is becoming more common with supervisory control and data acquisition (SCADA) systems or programmable logic controllers (PLC) systems. Most SCADA or PLC systems can be controlled remotely using radio links, wireless technologies, or even cellular phones. Spatial nitrogen sensing is also possible (Kim et al., 2007) to integrate fertility with SSI/PI. Figure 1 shows a SSI/PI system valve arrangement on a lateral-move sprinkler system.

PRECISE IRRIGATION SCHEDULING

PI or SSI descriptions usually include irrigation scheduling information. Often soil water or crop water status sensors are included. However, precise irrigation scheduling (PIS) is at least as important as the correct spatial water placement, if not more important. Inherently, PIS needs to include aspects that affect the spatial aspects of crop water use for the field scale.

Recent reviews by Kim and Reid (2007) on crop chlorophyll remote sensing for estimating nitrogen deficiencies and by Evett et al. (2009) on crop water stress determination using remote sensing from both spectral and thermal indices indicate the potential of these technologies for PIS. Although remote sensing based on satellite or aircraft platforms has

shown promise for irrigation scheduling since the 1970s, the technology has not been utilized mainly due to these factors:

a) turn around times of data processing for useful recommendations at the field level have been too long
b) pixel sizes are too coarse to apply to individual fields, and
c) data collection intervals are too infrequent for useful irrigation control.

Figure 1. PI system from the USDA-ARS, Northern Plains Agricultural Research Laboratory, Sidney, MT in 2005 illustrating the valve arrangement, control wires and pneumatic tubing on the Sidney system for both the spray heads and low-energy, precision application (LEPA) application methods. Source: R.G. Evans, USDA-ARS, Sidney, MT.

Aircraft imagery and satellite imagery allow the determination of spatial variability in crop visible and thermal spectrums useful for irrigation scheduling, but often with temporal and spatial resolutions that are inadequate for day-to-day irrigation management (Jackson, 1984; Moran, 1994; Moran et al., 1994). Current research is investigating the sharpening of coarse resolution thermal images with higher resolution images in the near infrared and visible spectrums that might provide improvements for the spatial resolution problem (Kustas et al., 2004). In conjunction with these efforts, progress has been made on the combination of these procedures to return daily images by combining daily satellite data with the less frequent (weekly or biweekly) imagery from other satellites with greater resolution (Anderson et al., 2007). Most crop water deficiency remote sensing useful for irrigation management requires thermal infrared radiance data, but these data are currently unavailable at an acceptable temporal or spatial resolution and may even be totally unavailable in new satellite platforms under development. The challenges of using remote thermal remote sensing are being addressed by several approaches using sensors that are mounted on moving irrigation systems (Evans and Sadler, 2008: Evett et al., 2006; Sadler et al., 2007) or on masts set in fields (Evett et al., 2000), and with some using aircraft platforms, including unmanned aerial vehicles (UAVs).

Several approaches have been used for irrigation management using remote sensing including:

a) Scheduling irrigation to replace evapotranspiration (ET) estimated from a reference ET (ETo), calculated from local weather data, which is multiplied by a crop coefficient (K_c) estimated with a crop coefficient function, Kc(NDVI), where NDVI is the normalized difference vegetative index (NDVI) or a similar index adjusted for reflectance from soil. The NDVI is based on canopy irradiance in the red and near infrared bands, which can be remotely sensed.
b) Scheduling irrigation with a fixed amount of water whenever a threshold criterion (trigger point) is generated by a crop water stress index (CWSI), which is estimated using remotely sensed crop canopy temperature (Ts) and local weather data.

c) Scheduling irrigation with a fixed amount whenever a threshold criterion is determined by the time-temperature threshold index (TTTI) reaching a crop and region-specific value. The TTTI is calculated using Ts.
d) Scheduling irrigation to replace ET estimated with the field surface energy balance (FSEB), which uses remotely sensed surface temperature, Ts, determined from thermal infrared data, and data on canopy cover and surface emissivity deduced from the near infrared (NIR) and visible bands.
e) Sensing of crop characteristics in order to guide timing, placement and amount of fertilizer and water through irrigation (or fertigation) systems of various orders of precision. The characteristics, including crop cover fraction, nitrogen status of leaves, disease and pest damage, all of which vary spatially and temporally, are inferred from various remotely sensed vegetative indices (VI).

Of the five approaches listed above, only the CWSI and the TTTI have been commercialized and used by irrigators, the latter recently under the name BIOTIC[1] (Upchurch et al., 1996) and the former since the 1980s. Practical use of both measurement procedures has been quite limited.

Multispectral vegetation indices (VIs), such as the NDVI, are derived as ratios of signal strength in particular radiance bands. Multispectral VIs have been widely researched as means to quantify various biophysical aspects of vegetation canopies, such as leaf area index (Moran et al., 1995) and crop cover (Heilman et al., 1982). Remote sensing of VIs provides a means to synoptically and instantaneously determine crop conditions.

An approach that may improve the spatial representation of crop ET estimation is to incorporate remote sensing observations into irrigation scheduling protocols. Bausch and Neale (1987) proposed the utilization of multispectral VIs to estimate corn crop coefficients. Recent research has shown that observations of multispectral VIs can provide real-time surrogates of crop coefficients (K_c) for a variety of crops (Bausch, 1995; Neale et al., 2003; Hunsaker et al., 2005). Remote sensing that infers that the spatial distribution of K_c across the landscape can improve the ability of standard weather-based ET based irrigation scheduling methods to more accurately estimate the spatial crop water use within an irrigated-field (Hunsaker et al., 2007) or at the farm-scale level (Johnson and Scholasch, 2005). Although the VI-based K_c approach has strong practical appeal, this approach is hindered by its reliance on empirical relationships between VIs and K_c and the problems previously discussed on imagery availability and the transferability of K_c calibrations from one region to the next, and by timeliness and cost effectiveness of the necessary imagery (Gowda et al., 2008).

Sensors, especially infrared thermometers (IRTs) or multi-band spectral sensors, mounted on irrigation systems such as center-pivot or lateral-move systems offer an alternative to satellite or airborne platforms. In regions where center-pivot or lateral-move irrigation systems are popular, they appear to be a logical sensor platform for irrigation management since they pass over the field at regular intervals. These sensors can reduce turn-around time for imagery because they do not require extensive processing such as atmospheric or geometric correction. Phene et al. (1985) provided an early example of the deployment of IRTs aboard a mechanical-move irrigation system. However, thermal radiometric sensors are responsive to soil emittance in addition to reflection from vegetative canopy. Less than full canopy cover may cause false positive irrigation threshold triggers in the early growing season and thermal measurements from mixed pixels of sunlit soil and vegetation can provide unduly high temperature readings. Discrimination between thermal radiance from soil and vegetation in low cover or leaf area index situations is a problem still under active investigation, and the solution will probably require an imaginative combination of multi-spectral data, sensor view

[1] The mention of trade names of commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

angles and understanding of canopy and soil characteristics. Figure 2 illustrates a scaled canopy temperature procedure (Peters and Evett, 2004) to activate an irrigation event based on one-time-of-day measurements with IRTs.

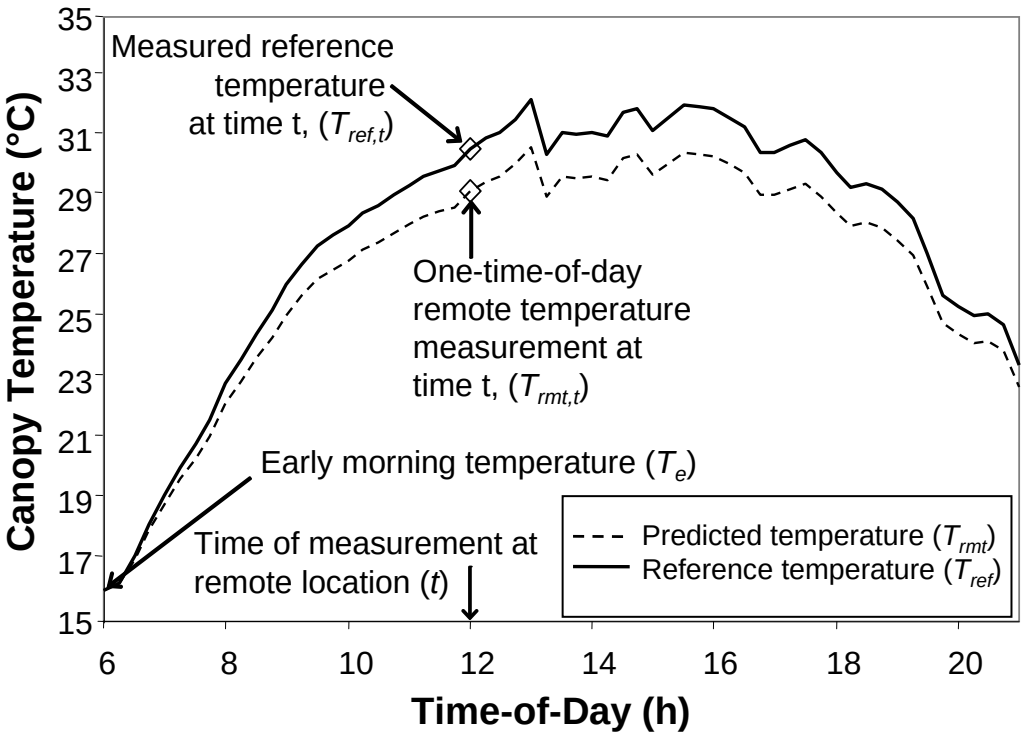

Figure 2. Example diagram of the scaled canopy temperature from one-time-of-day measurements by IRTs. Source: Adopted from Peters and Evett (2004).

Center-pivot and linear-move irrigation systems generally apply water quite uniformly; however, substantial variations in soil properties and water availability exist across most fields. In these cases, the SSI/PI ability to match spatially and temporally variable conditions can offer attractive opportunities for increased application efficiencies to reduce environmental impacts from leaching or runoff, more effective agrichemical use, and the potential to improve crop yields and quality. Additionally, these systems offer the ability to precisely manage deficit irrigation strategies. The development of in-field sensor-based control of SSI/PI applications of water and water soluble nutrients through the irrigation system offers an effective means to implement PA technologies. However, the seamless integration of sensors, irrigation control, data interface, software design, and communication at costs that are in balance with the profit advantages of site-specific applications is challenging requiring novel engineering solutions and eventually parameterization standards.

Wireless sensing systems seem to offer the necessary control and versatility required to implement PIS with SSI/PI. Peters and Evett (2008) illustrated the potential to integrate TTTI with a SSI/PI center-pivot irrigation system. Evett et al. (2006) demonstrated the control of microirrigation systems using the TTTI concept with IRTs. Miranda et al. (2003) used a closed-loop irrigation system and determined irrigation amount based on distributed soil water measurements. Shock et al. (1999) used radio transmission for soil moisture data from data loggers to a central computer logging site. Wall and King (2004) explored designs for smart soil moisture sensors and sprinkler valve controllers to implement plug-and-play technology and proposed architectures of distributed sensor networks for site-specific

irrigation automation (King et al., 2000). Kim et al. (2008, 2009) used distributed sensor networks and GPS with Bluetooth® wireless communications to control water applications with off-site computers. Software design for automated irrigation control has been studied by Abreu and Pereira (2002). They designed and simulated set sprinkler irrigation systems by using software that allowed the design of a simplified layout of the irrigation system.

The coordination of control with data from sensors is effectively managed using data networks and low-cost microcontrollers (Wall and King, 2004). A hard wired system from in-field sensing station to a base station takes extensive time and cost to install and maintain. It may not be feasible to hardwire the system for long distances, and it may not be acceptable to growers because it can interfere with normal farming operations and the maintenance costs may be unacceptable. A wireless data communication system can provide dynamic mobility and cost-free relocation. Radio frequency technology has been widely adopted in consumer wireless communication products and it provides numerous opportunities to use wireless signal communication in agricultural systems. Industrial wireless standards such as the ZigBee protocol are open standards that allow integration of sensors and equipment from different manufacturers into a SCADA system (O'Shaughnessy and Evett, 2007, 2008). Present challenges include meeting power requirements of remote sensors, radio interference, cost reduction, interfacing with existing irrigation control equipment, and development of rugged and inexpensive but accurate sensors (e.g., reflectance photodiodes and infrared thermometers).

OBJECTIVE FUNCTION

Critically important to SSI/PI with PIS is the definition of the objective function for the added technology and management. In the simplest case, the principle objective of the producer is usually to maximum net profit. Operations research theory has several potential variations that might be adopted depending on the risk the producer is willing to accept. These are to 'minimize' the maximum loss or to 'maximize' the minimum profit. Other objectives include 1) minimize labor costs; 2) maximize reliability; 3) maximize water use efficiency; 4) maximize 'irrigation' water use efficiency; 5) minimize off-site environmental impacts (water quality, etc.); or 6) minimize irrigation water use to avoid groundwater over exploitation or minimize any institutional regulation exceedence and/or sell or lease the remaining water. With SSI/PI the producer has added complex decisions regarding whether to increase productivity on he lower producing zones or to maximize production on the more productive zones. In the future, we expect environmental and institutional restrictions to have a greater dominance limiting profit in most cases but emphasizing the value of SSI/PI and PIS for sustainable productivity.

SUMMARY

Precision irrigation offers advanced technology to meet constraints imposed by spatially variable soil and crops. The use of site-specific application technology is feasible engineering wise; however, its acceptance depends strongly on a simple interface using technology with which the producer is already familiar (i.e., wireless communication, cellular telephones, internet, etc.). For precision irrigation to be effective, precise irrigation scheduling based on soil water status or crop water status seems to be a weak link currently, but research is improving the integration of crop water status and evapotranspiration feedback based on spectral and thermal remote sensing. Additionally, spectral sensing offers great potential with the spatial management of nutrients and biotic stresses from pests and diseases. The larger remaining obstacle appears to be in characterizing the objective function for this advanced technology and management to benefit the producers and the public.

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