4 Precision Irrigation

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4.1 Introduction

Specialty crop production and processing systems are heavily dependent on the availability and quality of water resources in the United States. More than 90% of the major specialty crops in the United States are irrigated, with most receiving annual water application amounts greater than .25 ha-m (2 A-ft), with higher amounts in arid areas like AZ and CA and in crops like cranberries in MA (Table 4.1). Large quantities of water are used in fruit processing and management of processing waste water is also a major water quality concern. Not only are the majority of specialty crops irrigated, but the water resources used for irrigation are subject to significant competing uses and threatened by a range of water quality concerns (Gleick, 2003; Kassam et al., 2007; Sadler et al., 2007). There are perhaps no better examples of the stress on water resources particularly relevant to irrigated agriculture than the Colorado River and the Ogallala Aquifer (NRC, 2008) and recent outbreaks of contaminated vegetables from pathogens in the irrigation water (Associated Press, 2008). The science of irrigation is well understood and irrigation technologies today are mature and very robust (Hoffman et al., 2007 and Lascano and Sojka, 2007). However, concerns over water availability and water quality increasingly require more efficient use of water resources in irrigated agriculture. Evans and Sadler (2008) suggest that "the competition for existing freshwater supplies will require a paradigmatic shift from maximizing productivity per unit of land area to maximizing productivity per unit of water consumed".

Table 4.1: Irrigated acres and water application amounts for selected specialty crops in the United States (USDA, 2004).

Crop	*Irrigated*	*Non-irrigated*	*Irrigated*	*Water Use acre ft*	
	Acres		*%*	*National State*	*Average Maximum*
Potatoes	1,032,604	26,275	97.5	1.8	3.3 (AZ)
Vegetables	2,081,358	137,765	93.8	2.1	4.4 (WY)
Tomatoes	427,812	2,167	99.5	2.6	2.8 (CA)
Lettuce and romaine	276,705	340	99.9	2.7	3.6 (AZ)
Orchards,vineyards, nuts	4,104,946	119,778	97.2	2.2	5.2 (AZ)
Berries	229,542	21,705	91.4	2.1	6.7 (MA)

The seriousness of the concern over water availability is evident in the recent passage (July 30, 2008) by the U.S. House of Representatives The Water Use Efficiency and Conservation Research Act (H.R. 3957) that would establish a water-use efficiency and conservation research and development program within the EPA's Office of Research and Development. Precision irrigation is considered an important technology for improving water use efficiencies in both continuous move and fixed irrigation systems (Evans and Sadler, 2008).

4.2 Overview of precision irrigation

We begin our discussion with a summary of the major points reported in two major reviews of precision irrigation recently published by Camp et al. (2006) and Sadler et al. (2007). Precision irrigation is not a new term in irrigation, as being precise about the uniform application of water has long been a goal of irrigation science. The new dimension of precision irrigation is accounting for the spatial dimension of water management, i.e., applying water based on the site-specific needs of a given location in the field. While these authors describe precision irrigation as conceptually simple, they report that it has been primarily a research issue emerging in the early 1990's, with the majority of development done in continuous move irrigation systems because they are particularly amenable to site-specific approaches because of their current level of automation. There are limited examples of commercialization, with the implementation efforts in Georgia noteworthy (Milton et al., 2006). Precision irrigation in fixed irrigation systems, used particularly on small farms or in high value crop production systems (e.g., tree fruit) has been limited. The research focus has been primarily on the control aspects of precision irrigation, with more efforts including real-time monitoring of soil and crop conditions to trigger site-specific irrigation. They recognize the most serious limitation to the execution of precision irrigation is lack of site-specific production functions that optimize water use at a given site at a given time resulting from an insufficient knowledge base to make management decisions. Commonly, whole field recommendations are applied on a more spatially precise scale. They emphasize that precision irrigation systems must incorporate agrochemical (fertilizer and pesticide) applications to be cost effective and therefore profitable. Position and alignment technologies are required to use spatially indexed data to set application rates for various sites within a field. The cost of global positioning systems (GPS) with required accuracy has been the greatest challenge in positioning, although very recent cost reductions and miniaturization of GPS technology may alleviate this problem. Errors in water and agrochemical application rates are associated with transition zones where irrigation rates change which are related in part to nozzle configurations, for example, how many nozzles are grouped into zones along an irrigation span. In the future, these reviews suggest that growing demand for irrigation water, competition for water resources, depletion of existing water resources, and water quality concerns will likely be the drivers for the development and implementation of precision irrigation.

The underlying notion is that improved irrigation water use efficiency in agriculture can be achieved by better targeting of water both spatially and temporally to more precisely meet the site-specific water requirements of plants while concomitantly improving environmental quality of irrigated cropland. Camp et al. (2006) call this approach to irrigation precision irrigation, which they defined in terms of "site-specific water management, specifically the application of water to a given site in a volume and at a time needed for optimum crop production, profitability, or other management objectives at that specific site". We accept this as our operational definition for precision irrigation in the remainder of our discussion. While the majority of work on precision irrigation deals with continuous move irrigation systems, primarily center pivot and linear move systems, recent advances have also been made for

fixed irrigation systems, for example, for tree fruit (Coates and Delwiche, 2008). Precision irrigation in continuous move irrigation systems has evolved since the first system was reported in 1992 by Fraisse et al. (1992) and Duke et al. (1992). Our intent is not to repeat the recent literature reviews but rather to provide an overview of precision irrigation as it relates to irrigation water management in specialty crops. To that end, our discussion will focus on three critical aspects of precision irrigation: 1) control of irrigation amount and timing for a given site, 2) determination of the irrigation requirement for a given area for a given crop, and 3) assessing the value proposition.

4.3 Spatial variability

The underlying rationale for precision irrigation is the presence of spatial variability within an irrigated field that affects water availability (sufficiency or excess) to a crop, limits crop yield or quality thereby affecting crop water demand, or regulates water application due to erosion, runoff, leaching or other environmentally sensitive problems. Common sources of within field variability derive from variation in soil properties and topography, either naturally occurring or induced by human management (e.g., compaction, erosion, organic matter depletion) that in turn regulate soil water holding capacity, soil and terrain hydrologic properties, and nutrient supply. Nielsen and Biggar (1973) were one of the first to quantify the within field variability of field-measured soil water properties in an irrigated field. Clay content, C content, and tillage method were reported by Pires da Silva et al. (2001) to influence soil water storage patterns. Topographic factors, specifically elevation, slope and curvature, were found by Tomer and Anderson (1995) to explain 51–77% of spatial variability in soil water content in a sandy hill slope. New technologies for mapping soil properties, specifically soil electrical conductivity (Corwin and Lesch, 2005; Hedley et al., 2004), have revealed considerable within field variability that could guide site-specific irrigation (Brevik et al., 2006; Chiericati et al., 2007; Farahani, and Buchleiter, 2004; Hedley and Yule, 2009). Camp et al. (2006) suggest precision water management may be required in fields containing ground water recharge zones in order to meet regulatory statutes or to limit water application to areas with poor infiltration rates in order to achieve trafficability for farm equipment to optimize field operations. There can be considerable non-crop acreage within a field including drainage ditches, waterways and structures for which irrigation is not required. For 33 irrigated fields, Milton et al. (2006) reported the noncrop acreage covered by pivot irrigation system ranged from 0.08 to 15.8 ha in fields 4.45 to 133.3 ha, respectively, averaging 6.9 ha. Site-specific irrigation may only change the timing and not the amount of irrigation applied. King et al. (2004) reported gross receipts were approximately \$159 ha^{-1} greater under site-specific water management compared to conventional uniform irrigation management for potato primarily due to improvements in tuber quality rather than increased yields.

The key to success in precision irrigation is applying the correct amount of water at the right time to meet the water requirements of a crop and that requires accurate knowledge of the within field production functions for all locations within a field. As we discuss later, lack of knowledge of site-specific production functions is a major limitation for precision irrigation (Camp et al., 2006; Sadler et al., 2007).

4.4 Irrigation control

The design of any precision irrigation system for continuous move systems (center pivot or linear move) must include the ability to control the water application volume per unit area at any time or place

in the field. Note that the unit area may not be the same either within the field or from one irrigation event to another depending on how the irrigation requirement is determined. Unit area may vary when agrochemicals are site-specifically applied in a given irrigation event since these application maps may not correspond to the water application map. Volume control per unit area has been achieved by varying the application rate of the sprinkler(s) and/or controlling the ground speed of the continuous move system. While the ideal technology is a variable rate sprinkler with a range of water application rates, such as the variable orifice method conceived by King and Kincaid (1996), the most common approaches have been the pulsing of nozzles on and off over a fixed time cycle or the use of multiple-nozzle system each with a different application rate that provide a range of water application rates depending on which nozzles are operational at a given time (Camp et al., 1998). Refer to Camp et al. (2006) for a detailed discussion of various control systems for continuous move irrigation systems.

A recent example of a precision irrigation control system for continuous move irrigation systems is the remote, real-time irrigation monitoring and control system (RIMCS) developed by Chavez et al. (2010a),with recent modifications by Pierce and Elliott (2008). The system consists of individual nozzles connected to a 24 VAC solenoid/control valve wired to a nozzle node controller developed by Pierce and Elliott (2008). The nozzle controller accommodates other electronic devices so that sensors, such as flow, pressure, and GPS position can be monitored. A single wire carries power and communications from the nozzle controllers to a master controller located at the linear move cart (Figure 4.1). The master controller is a single board computer connected to a remote server via wireless radios. Water application rate is varied by pulsing nozzles on and off for a set number of seconds over a 1 minute cycle. The on/off times are determined by a water application map that is sent to the master controller via a wireless internet connection as depicted in Figure 4.2. Field tests of the RIMCS system on two different linear move irrigation systems installed in Washington State and in North Dakota showed accurate water application accuracies were achieved over a range water application rates (Chavez et al., 2010b).

For fixed irrigation systems (orchards, groves, vineyards, berry fields, and nurseries), nozzles or emitters are fixed so spatially variable control requires a network capable of controlling a large number of sensors and valves (Miranda et al., 2005). Two strategies have been used to spatially vary irrigation rates in fixed irrigation systems. One is individual nozzle or emitter control, the other is zone management.

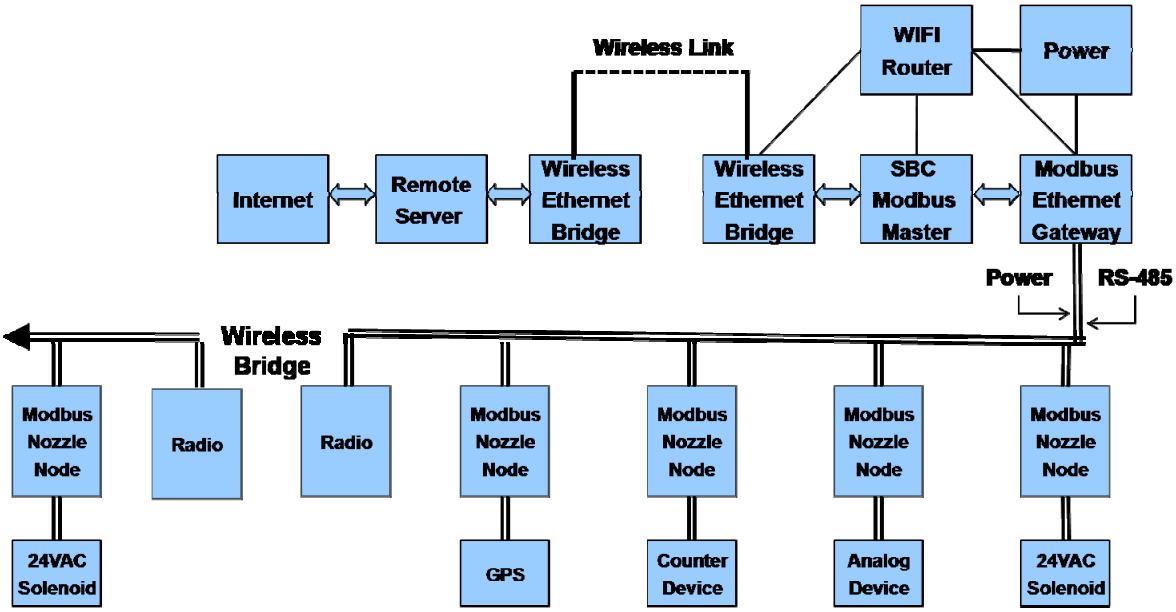

Figure 4.1: Conceptual diagram of a MODBUS RTU, multi-drop bus irrigation control system (Pierce and Elliott, 2008). The upper portion of the diagram illustrates the control system and wireless interface with a remote server. The lower portion illustrates that the bus accommodates the solenoids, analog and counter devices and a GPS device and can be extended via a wireless bridge. The SBC is the main controller and the nozzle node is the nozzle controller.

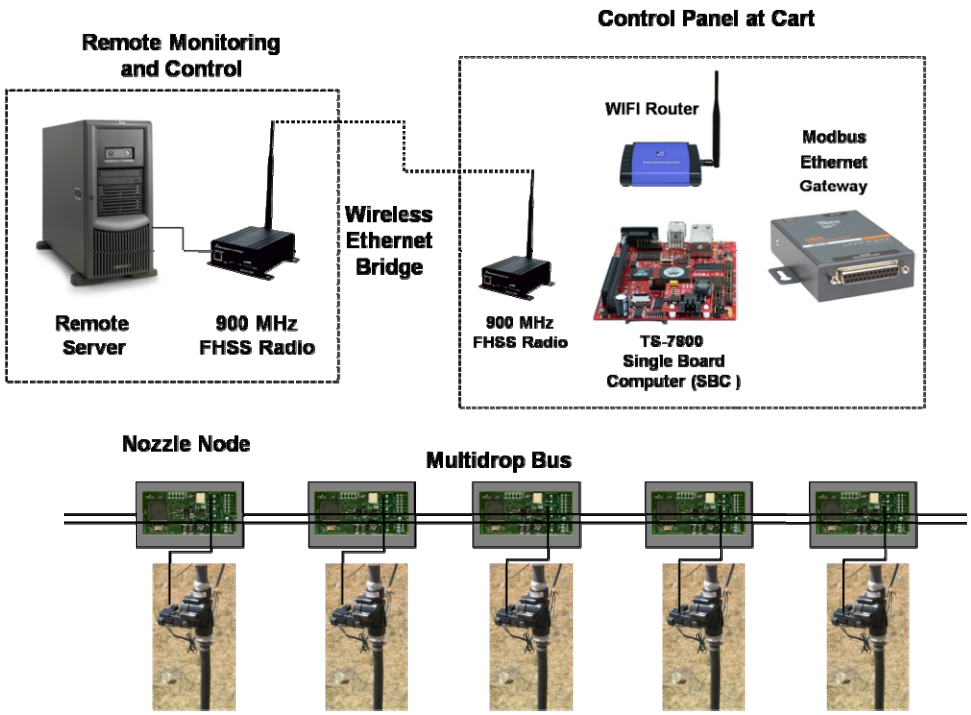

Figure 4.2: Illustration of the multi-drop/RTU bus for the linear move irrigation at Prosser, WA (Pierce and Elliott, 2008).

Zone management in fixed irrigation systems has been approached in a variety of ways. Torre-Neto et al. (2000) installed multiple lateral lines in citrus grove rows in order to vary water application rates according to tree size. Nemali and van Iersel (2006) developed an irrigation controller that irrigates substrates in potted plants to a set-point volumetric water content and maintains that water content close to that set-point for several weeks. The controller uses calibrated, dielectric moisture sensors, interfaced with a datalogger and solenoid valves, to measure the volumetric water content of the substrate every 20 min. Irrigation is triggered when the water content goes below the set point to maintain a constant water content in the container. Owen (personal communication, 2008) employed a similar system in Oregon to control irrigation in nurseries by potted plant type. Miranda et al. (2005) implemented a low cost, solar-powered feedback controller that uses sensed soil water potential (SWP) measurements to control the amount of water applied to specific irrigation management areas within a field delineated based on soil characteristics, crop water requirements, and/or economic factors. For each irrigation management unit, an irrigation controller is installed that monitors three SWP sensors, soil temperature, system pressure, and controls a solenoid valve for irrigation. The controller autonomously controls the soil water potential (SWP) between field capacity (FC) and management allowed deficit (MAD) by triggering an irrigation event when two sensors indicate that SWP falls below the MAD. Irrigation continues until two sensors indicate that the SWP exceeds the MAD. A large scale version of zone management is the valve control and meter reading system developed by Damas et al. (2001) for centralized remote control of large irrigated areas with a large number of individual control points. Commercial irrigation companies also offer systems that monitor and control multiple continuous move via the Internet. Pierce et al. (unpublished) developed a remote, real-time wireless control system to monitor and control fixed irrigation system in a research cherry orchard in Washington State. The system included a relay board and a data logger/900 MHz frequency hopping, spread spectrum radio configured in a point-to-multipoint network with a base located at a remote site connected directly to the internet. The orchard had two drip lines installed in each row and three zones of microsprinklers per row, each controlled by a solenoid (Figure 4.3). A flow meter and pressure sensor were installed in the water supply line. A microprosser on the datalogger/radio contained an irrigation control program that could be updated via the radio network, with communication set by the user to a set time interval for logging pressure and flow. Flow rates can be calculated from flow rate and nozzle output ratings over time.

Individual nozzle or emitter control systems designed to vary water and fertilizer rates to individual trees have been reported by Coates et al. (2006a, b). Their system used individually addressable microsprinkler nodes and a drip line controller that stored the irrigation schedule and issued commands to each node. Each microsprinkler node included a standard microsprinkler emitter, latching solenoid valve, and control circuit with a master computer connected to each drip line controller using a wireless modem. Large or small valves can be installed according to tree size to allow a unique schedule to match differing water and nutrient requirements to accommodate replants, disease, growth, or seasonal changes. Data from electrical conductivity, pressure, soil moisture, or flow sensors could be installed to allow closed-loop irrigation and fertigation control. More recent work used wireless mesh networks for remote control of the individual nozzle system as illustrated in Figure 4.4 (Coates and Delwiche, 2008).

4.5 Irrigation requirement

The factor most limiting precision irrigation is lack of production functions that guide the timing and amount of irrigation within a field (Sadler et al., 2007). While the system of Coates and Delwiche (2008) can remotely control irrigation for an individual tree, it cannot determine the crop water needs for every tree in a given orchard. The science and practice of irrigation scheduling are well known and apply to precision irrigation. What varies is the spatial scale at which irrigation scheduling is applied. If the production goal in irrigating specialty crops is to maximize both crop yield and quality, then irrigation should be guided by the water requirements of a crop. The value from precision irrigation is realized by matching irrigation rates to variable crop water need within a field.

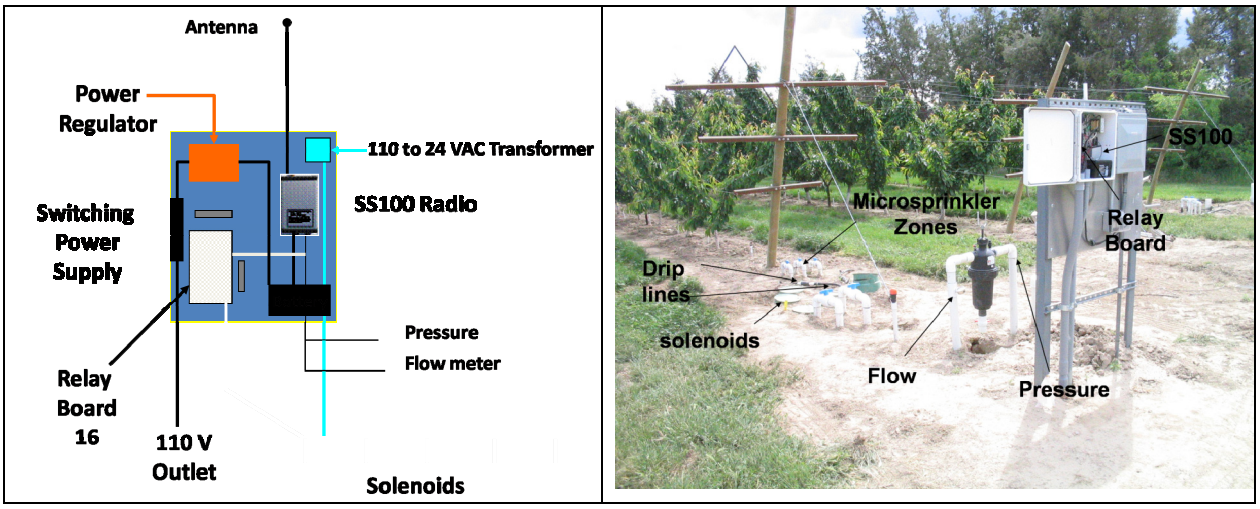

Figure 4.3: Remote real-time monitoring and control system for a combined drip and microsprinkler irrigation system in a research orchard in Washington State (Pierce et al. unpublished).

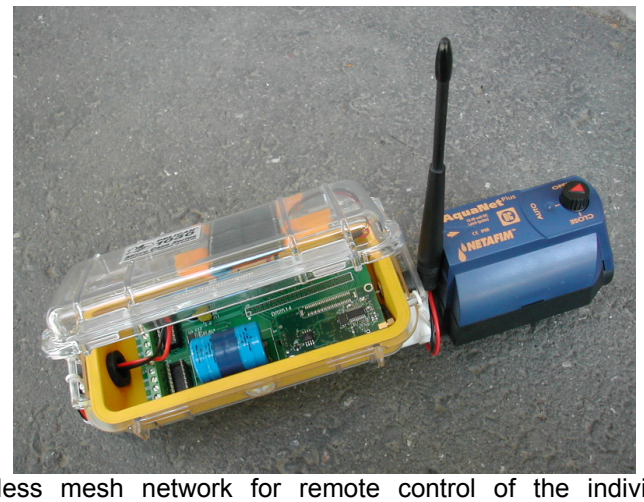

Figure 4.4: A wireless mesh network for remote control of the individual nozzle (personal communication Coates and Delwiche, 2010).

Variable water demand is created when factors that regulate water availability to plants vary in space and time and or when a field contains plants with different requirements due to stresses, age differences, genetic variation, and other factors. A pear orchard block, for example, can contain trees of different size or condition due to age, variety, or root stock, that have different water requirements. A frost damaged orchard may have a range of fruit load on the trees. A given field may have different soils with a range of water holding capacities and over time have different irrigation requirements depending on the weather. The conundrum for precision irrigation is the temporal variation in spatial variability. This may explain the lack of production functions cited by Sadler et al. (2007).

A potential solution to this conundrum is the development and use of effective tools that accurately estimate the crop water need site-specifically and in real-time. The next generation of precision irrigation technology will likely include real-time monitoring of plant and soil water conditions with wireless sensor networks feeding data to crop simulation models or other decision support systems that specify crop water needs by location within the field. A good example of emerging technology is the system developed by Oshaughnessy and Evett (2007, 2008) that varies irrigation rate based on leaf temperature. Their system uses wireless infrared thermometers mounted on center pivot irrigation arms as well as in the field to help determine whether to skip watering parts of a field because plants are suffering from disease rather than drought or because no plants have survived in that part of the field. Real-time or near real-time methods of assessing crop water needs may be the future of precision irrigation.

4.6 Remarks

A value proposition is what the customer gets for what the customer pays (Wikipedia contributors, 2008). It is clear from our discussion that the technology to remotely monitor and control irrigation is available, operationally effective, and increasingly affordable. However, the value proposition for precision irrigation, although seemingly intuitive, is not well defined. Warren Buffett is quoted as saying “Price is what you pay. Value is what you get" (http://hubpages.com/hub/Warren-Buffet-Quotes). Today, while the price of precision irrigation may be definable; the value, however, is not. Sadler et al. (2005) and Lu et al. (2005) conclude that so far, the research has proven that the equipment can be built to do precision irrigation, but economics are not favorable under current prices and costs. A large gap in knowledge about the production functions for a given site-crop-environment scenario is largely unknown and remains the biggest obstacle for precision irrigation (Sadler et al., 2007). Almas et al. (2003) conclude that feasibility of precision irrigation depends on field variability, crop value, economies of scale, and useful life of the equipment but suggest that prospects for precision irrigation were positive for Texas agriculture. Milton et al. (2006) reported costs for commercially available precision irrigation systems exceeded $21,000 and that cost-share is critical to the adoption of this technology. Intuitively precision irrigation is often perceived positively in terms of improved water use efficiency and increased yield when it in fact can have negative impacts on crop yields and the soil ecosystem. From their economic analysis, Feinermanz and Voet (2000) suggest that utilization of site-specific farming and adoption of improved irrigation and/or cultivation technologies do not guarantee water savings. Using a crop simulation model, DeJonge et al. (2007) concluded that precision irrigation showed slightly lower yields than scheduled uniform irrigation in a scenario where supplemental irrigation was valuable in only one of 28 years in Iowa corn production. Oliveira et al. (2004) reported that for tomato production in Tennessee, uniform management required 20% more applied water compared with site-specific management. Raine et al. (2007) estimated that 10% of the irrigated land

area within Australia could be adversely affected by root zone salinity resulting from the adoption of precision irrigation. They attribute this problem to a lack of understanding of all aspects of the whole system and significant knowledge gaps in many factors associated with precision irrigation decisions.

The reality is that precision irrigation is technologically feasible but remains primarily a topic for research. Conceptually, it makes sense to vary water application in ways that accommodate variable growing conditions across a field (Evans and Sadler, 2008). The key is accurate knowledge of the production function for site-specific water management. Perhaps real-time sensing of the soil-crop-atmosphere continuum across a field will adequately predict site-specific irrigation amounts and frequencies. Clearly, much more field experience with precision irrigation across a broad range of soils and crop production systems is needed before the full extent of its value proposition to farmers and to society can discerned.

The value proposition of precision irrigation remains largely undocumented. This may relate to the limited adoption of precision irrigation, although little data exists on the level or rate of adoption. However, the factors that favor precision irrigation remain, particularly the inability of agricultural producers to control inputs in ways that accommodate variable growing conditions across the field (Evans and Sadler, 2008). Because precision irrigation is a knowledge based management practice, the need is great to fulfill the knowledge gaps that currently limit its use in commercial agriculture, whether those gaps are lack of production functions (Sadler et al., 2007) or fundamental water flow in soils (DeJonge et al., 2007).

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Section 4. Precision irrigation

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