# Advanced Technologies for Irrigated Cropping Systems

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**Abstract** Available supplies of water for irrigation and other uses are becoming more limited around the world, and this trend is accelerating. Emerging computerized precision irrigation technologies will enable growers to apply water and agrochemicals more precisely and site-specifically to match the status and needs of soil and plants as determined by the analysis of data from a variety of sensor networks, wireless communications systems and decision support systems. Speed control and zone control options for site-specific variable rate irritation (SS-VRI) system are currently available, with speed control the most common. Site-specific variable rate sprinkler irrigation systems are wonderful research tools that can provide maximum amounts of information from relatively small areas. A self-propelled SS-VRI sprinkler system has been developed for agricultural research applications and 5 of these systems are now in use. This fully functional research machine has been used from 2005 to 2012 and has been very reliable. These SS-VRI systems offer many benefits for research and they have tremendous potential for a greater use in sprinkler irrigation systems worldwide for both in research and general practice to conserve water, fertilizer and energy.

**Keywords** Precision agriculture · Decision support · Automation · Irrigation controls · Water conservation

## 1 Introduction

Production agriculture is facing a series of major challenges in providing sufficient food, fiber, and fuel to support a growing global population while our water

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resources, environmental health, and available arable land decline and climate changes. In agricultural ecosystems, physical and biological processes such as cycling of carbon, water, and nutrients are linked with social and economic processes. To achieve sustainability, it is essential that we understand how these processes interact, and their impacts on the environment through space and time. Innovative approaches will be needed to address these issues and maintain a safe and abundant food supply as the agronomic, economic and social problems facing production agriculture gain in complexity.

Irrigation can be fundamentally characterized as a temporal adaptation to seasonal and annual variation in rainfall (Turral et al. 2010). Irrigation has shaped the economies of many semi-arid and arid areas around the world over many centuries. It has stabilized rural communities, increased income and provided many new opportunities for economic growth. These practices have enabled human habitation, at times quite dense populations, where it otherwise could not exist (Postel 1999). In short, irrigated crop production underpins large sections of current society and lifestyles throughout the world.

Irrigated agricultural activities support diverse components of the world's food chain and provide much of the fruit, vegetables and cereals consumed by humans plus the grain fed to animals that are used eventually as human food. It also provides much of the feed to sustain animals used for work in many parts of the world, and these lands provide considerable sources of food and foraging areas for migratory and local birds as well as other wildlife.

Irrigated land constitutes approximately 18 % of the world's total cultivated farmland, but currently produces more than 40 % of its food and fiber. However, irrigation of lands accounts for over 70 % of fresh water consumed in the world, and is also a major user of energy for farming operations and pumping. Nevertheless, output from irrigated agriculture will have to increase dramatically in the next few decades to help meet the projected world food requirements and to maintain food security and irrigation will necessarily continue to be a major part of world's future agricultural production.

The importance of water and its uneven geographical distribution has made its acquisition and use a matter of great contention between various users and nations. Population growth, rising standards of living and competing uses are forcing major changes in how fresh water is allocated. Agricultural water resources are also coming under increasing pressure from environmental and other social issues, including declining water tables in many areas, industrial and municipal pollution and escalating energy costs. In addition, there is also a persistent loss of arable land to soil salination, soil erosion and urbanization, which collectively emphasize the need to maximize total irrigated food productivity wherever possible. Thus, current water use patterns and practices may not be sustainable in many regions of the world.

Reduced availability of water and energy for irrigated agriculture will require much greater levels of crop and water management than currently in use; but this will be difficult, if not impossible, without advanced irrigation methods. Higher levels of irrigation management and systems that enable greater efficiency of water use can potentially reduce operating costs as well as conserve energy, nutrients and water use. The potential to conserve water depends on the capabilities of the irrigation system and the commitment of the operator to implement timely water-saving practices and technologies (Schütze and Schmitz 2009).

## 2 Advanced Irrigation Systems

There are basically three types of irrigation systems: surface (which flows by gravity), and pressurized micro and sprinkler systems. Surface (also called gravity) irrigation introduces water at the highest elevation point in a field and the water flows over the soil surface by gravity. Pressurized irrigation systems that include several types of microirrigation and sprinkler systems where water is conveyed by pressurized pipes or tubing to a point in the field where it is applied by various devices. In addition, pressurized systems commonly function as site-specific application methods for fertilizers and other agrochemicals (chemigation), which require appropriate management to avoid environmental contamination. Technology levels in all three types of systems vary widely, and they all have advantages and disadvantages (Hoffman et al. 2007).

The design of a water application system will determine the maximum potential performance level, whereas management dictates the actual benefits realized and the magnitude of any positive or negative ecological impacts. Thus, the amount of water that can be conserved by advanced irrigation systems and practices depends on the ability of a particular type of irrigation system to implement various improved management strategies. Management skills are gained through education and technical assistance, but they are maintained by the irrigator’s commitment and economic incentives.

## 3 Microirrigation Methods

Microirrigation includes drip and microsprinklers. It is a flexible set of technologies that can potentially be used on almost every crop, soil type and climatic zone if justified economically. It is characterized by the applications of water in small amounts using frequent irrigations (i.e. daily). It is also sometimes referred to as localized irrigation and can provide numerous crop production and water conservation benefits that address many of the water quality and supply challenges facing modern irrigated agriculture. Microirrigation acreage is increasing steadily worldwide and is fully expected to continue its rapid growth in the foreseeable future (Lamm et al. 2007). Novel applications for microirrigation systems, such as the reuse of municipal wastewater in turf areas, are providing new opportunities for growth.

These systems can be laid on the soil surface or buried, and can be permanent or temporary installations. They can be used on gardens as well as in fields from 0.5 to more than 50 ha. Because of the relatively high capital cost of these advanced systems and the need for high levels of management, modern microirrigation technologies are typically permanent installations on small blocks of land (e.g. <10 ha) of intensively-managed, high-value specialty crops (e.g. vegetables, grapes, nuts, fruits and berries). Microirrigation could also become more common in perennial forage crops (i.e. alfalfa) and annual row crops such as maize using widely-spaced, buried drip lines in areas with limited water supplies or high water costs.

Greenhouse culture is largely irrigated by microirrigation methods. Year around greenhouse production of fresh vegetables, cut flowers and other high-value crops is rapidly expanding with some of the largest increases occurring around the Mediterranean Basin. All the major factors affecting plant growth can be controlled and managed precisely in these conditions, including the environment, water, nutrients, pests and diseases. Thus, these growing systems provide the ultimate opportunities for the application of many PA concepts.

Microirrigation systems are well suited for automated adaptive control with real-time sensor feedback and decision making capabilities. However, site-specific water management often occurs by default as a function of the scales of underlying environmental variability. Microirrigation systems are generally designed and installed in small blocks to match the needs of particular crop varieties or variations in soil texture and topography across a farm. Thus, additional site-specific irrigation within blocks may not be warranted, although it is technically possible.

A low-cost microirrigation method called pitcher or clay pot irrigation (Siyal et al. 2009) is used on some small fields (e.g. <0.5 ha) in several areas in northern Africa and Middle East. This labor intensive method uses unglazed, porous clay pots which are buried in the ground up to their neck to irrigate individual plants (i.e. fruit and nut trees) that are typically spaced 1 m or more apart. There may be more than one pitcher per plant, which are filled manually with water on at least a daily basis. Water seeps out through the unglazed walls of the pitcher to irrigate the crop.

The above discussion suggests that purposely designed pressurized microirrigation and sprinkler methods are the most suitable for advanced forms of site-specific irrigation. Of these, most of the following discussion will be directed towards self-propelled, continuous move sprinkler irrigation systems, which cover much larger areas than microirrigation methods and their use is rapidly expanding (Sadler et al. 2005; Evans and King 2012).

## 4 Self-Propelled Sprinkler Irrigation Systems

Self-propelled sprinkler irrigation systems such as centre pivots and linear (also called lateral) move systems have allowed large scale agricultural development of marginal lands that were unsuitable for surface irrigation including areas with light sandy soil and a large variation in topography within the same field. These adaptable systems have experienced tremendous growth around the world over the past 50 years due to their: (1) potential for efficient and uniform water application; (2) high degree of automation requiring less labor than most other irrigation methods; (3) coverage of large areas; and (4) ability to apply water and labeled agrichemicals (chemigation) economically and safely over a wide range of soil, crop and topographic conditions. Similar to microirrigation, these systems apply limited amounts of water during each irrigation event and require frequent applications. A single machine can irrigate fields ranging from about 5 ha to over 200 ha.

These large machines basically consist of a pipeline (lateral) mounted on motorized structures (towers) with large rubber tires. The section between the two towers is called a span, which can vary from about 30 to 70 m in length. Sprinkling devices are mounted on or below the pipe. Maximum application depths of water applied are controlled by varying the speed of machine travel. Field-scale water applications by these systems can be quite uniform.

A center pivot machine basically rotates around a ‘pivot’ at one end, usually in the centre of the field. These continuously moving systems can irrigate areas ranging from part circle segments to whole circles. Various optional accessories are also available to irrigate portions of field corners. Self-propelled linear move sprinkler systems look and perform almost identically to centre pivot systems except that they move in straight lines to irrigate square- or rectangular-shaped fields. Linear move systems require a global positioning system (GPS) or other methods for physical guidance, and they require considerably greater management and manual oversight than centre pivot systems.

Center pivot and linear move sprinkler systems are designed and generally operated so as to replace the average water used by the crop over the past few days as uniformly as possible across the field. Irrigations are frequent and apply relatively low amounts of water so that soil water is ideally maintained at relatively constant levels. Application rates and base uniformity are primarily established by the sprinkler nozzle package, but the depth of water applied per irrigation with self-propelled center pivots and linear move sprinkler systems is generally controlled by the travel speed of the machine.

Traditionally, irrigation system design and management has strived for maximum uniformity of water applications over the entire irrigated field. However, agricultural fields are never physically or biologically uniform and substantial agronomic and environmental differences can occur. The effects of different spatial and temporal sources of variation on management can be additive, and the stochastic variation of several interrelated factors across a field can affect crop growth, yields and crop quality. Often, the underlying causes of crop performance variation are often not well understood, and they can vary substantially from field to field and year to year. Some sources of variation such as pest problems may have both temporal and spatial considerations.

The high frequency of the irrigations under these machines potentially reduces the magnitude of variability in soil water content in the field. However, stochastic spatial and temporal variability of a number of other interrelated factors (e.g., variations in soil properties, topography, runoff, within field runoff (also called runon), pests, tillage, fertilization, uneven incident precipitation and hail, pesticide carryover effects, and herbicide drift from adjacent fields) across a field can still affect crop growth during the growing season and from one season to the next. These factors can influence management decisions over time, which may also introduce additional in-field variability to crop production. Consequently, the center pivot industry is beginning to market irrigation systems that can adjust for at least some of this spatial and temporal variability, which is typically referred to as site-specific variable rate irrigation (SS-VRI). Manufacturers are just starting to offer site-specific controls for linear move sprinkler systems. Kranz et al. (2012) has summarized characteristics of some of the various currently available commercial site-specific control systems and panels.

SS-VRI can be defined as the ability to vary water application depths spatially across a field to address specific soil, crop and/or other conditions. It is included in the spectrum of precision agriculture technologies because advanced SS-VRI methods can potentially impose treatments in ways that optimize plant responses for each unit of water applied in different areas of the same field. It can also include site-specific applications of water-soluble agrochemicals including fertilizers.

Irrigation management can amplify the negative effects of different sources of variation with a field or it can help to minimize these effects depending on the grower’s objectives. Site-specific irrigation management strategies can be justified to account for variation under non-uniform growing conditions. Reducing areas of excess water applications within a field will decrease the potential for runoff, limit the movement of nutrients and agrochemicals below the plant root zone and create conditions for improving crop yield and quality.

Spatial and temporal variation can influence irrigation management decisions, and site-specific managers attempt to characterize the major sources of variation throughout the growing season. However, growers cannot practically manage for all of the many sources of variability. Therefore, they tend to group the most critical properties into relatively homogeneous management zones within a field as much as possible. Thus, different PA technologies may be managed simultaneously at different scales in the same field. For example, the smallest zone that a large scale farmer (e.g. >20 ha fields) prefers to manage for irrigation is probably in the order of about 5 ha even though other PA technologies (e.g. planting and spraying) will often be managed at much smaller scales (e.g. 0.1 ha).

These factors can also accelerate localized leaching of soil nutrients and other agrichemicals past the root zone. Field variability can result in excessive energy use for pumping, affect irrigation system design initially, and, later, management decisions. Furthermore, some management decisions may introduce additional sources of within-field variability.

Self-propelled center pivot and linear move sprinkler irrigation systems are particularly amenable to site-specific approaches because of their current levels of automation and large area coverage with a single lateral pipe. The definition of sprinklers in these applications includes the use of LEPA, bubblers, sprayers, spinners and other related spray techniques to apply water. These devices are usually on drop tubes in or just above the crop canopy. Impact type sprinklers are generally not included because the methods used to vary applied depths of water (e.g., pulse modulation) on commercial systems are not compatible in practice.

The ability to vary water application along the main lateral of a center-pivot system based on position in the field allows the field manager to address specific soil and/or slope conditions and avoid areas of over- or under irrigation, depending on preset management criteria. By aligning irrigation water application with variable water requirements in the field, total water use may be reduced, decreasing deep percolation and surface runoff. Reducing excess water applications will decrease the potential to move nutrients past the plant root zone (Sadler et al. 2000, 2005; King et al. 2009), and fungal disease pressure should also decrease. Site-specific application technologies can be used to treat small areas of a field with simple on/off sprinkler controls in single span-wide treatment areas or to treat the whole field by controlling all spans. Thus, site-specific irrigation can potentially provide water conservation benefits in cases of overirrigation, erroneous irrigation scheduling, in-season precipitation harvesting, or inefficiencies associated with particular crop production practices (e.g., potatoes). Some examples of water conservation strategies under full ET conditions (minimal water stress throughout season) where site-specific applications are potentially able to reduce total water applied include:

- A major cause of excessive water applications can occur when dry areas appear in a center-pivot irrigated field; irrigators tend to run the irrigation systems longer and more often to ensure adequate water across the whole field. These poor management practices result in much of the area being over-irrigated, and large amounts of water are wasted to compensate for suspected drought in relatively small areas. Site-specifically varying water applications can assist in addressing the management decisions that lead to localized, within-field drought and help conserve water, but they do not address the root causes.
- Water can also be conserved by applying less water to hillsides to reduce within-field runoff to low areas, to improve yields by eliminating water ponding in low areas, or to purposefully manage wet areas to reduce the extent of waterlogging problems.
- Water application amounts are generally high for the first span from the pivot point to the first tower even though application rates are low because it moves much more slowly than the outer towers. This area is typically either overwatered by as much as 20 %, because the available nozzle selections do not allow for the correct application of water, or too dry since the nozzles are very small and prone to plugging. The often-wetted foliage in this area also has higher incidences of fungal diseases. One option is to turn off every other sprinkler

along the first span for one or two rotations, and then turn on the sprinklers that are off and turn off the sprinklers that are on for one or two rotations. Another approach to eliminate both the overwatering and plugging problems within the first span area is to use relatively large nozzle sizes and site-specifically pulse the sprinklers on and off, applying the desired amount over time.

- Reduce or eliminate irrigation in wet areas in a field that develop from precipitation runoff, subsurface flow, high water table, springs, or unavoidable irrigation runoff.
- Manage soil water deficits on a spatial basis to maximize the opportunity to capture in-season precipitation in humid climates for subsequent use as crop evapotranspiration.
- The development of control and management technologies that can spatially and temporally direct the amount and frequency of appropriate agrochemical applications by site-specific self-propelled irrigation systems could also be very powerful tools that could increase productivity while reducing total water applications and minimizing adverse water quality impacts.

Evans and King (2012) conducted an analysis of several published simulation studies comparing conventional and SS-VRI management and reported water savings of 0–26 %. Ironically for well-watered crop production, water savings from site-specific irrigation may be greatest in humid climates by spatially optimizing use of non-uniform growing season precipitation. In arid and semi-arid climates, the greatest potential water savings could come from highly managed deficit irrigation strategies (managed drought stress).

## 5 Site-Specific Sprinkler Irrigation Technologies

Recent innovations in low-voltage sensor and wireless radio frequency (RF) data communications combined with advances in Internet technologies offer tremendous opportunities for development and application of real-time management systems for agriculture. These have enabled implementation of advanced state-of-the-art water conservation measures with self-propelled sprinkler systems such as SS-VRI for economically viable, broad scale crop production with full or limited water supplies.

SS-VRI technologies use many of the same management tools as other precision agriculture technologies, and make it possible to vary water and agrochemical (chemigation) applications to meet the specific needs of a crop in each unique zone within a field. However, site-specific sprinkler irrigation technologies and strategies are not a silver bullet for conserving water and energy; and they must also be integrated with other state-of-the-art farming technologies for maximum potential benefit (Sadler et al. 2005).

Basically, any water application device used on self-propelled sprinkler systems can be utilized for site-specific management of water and agrichemicals applied by the irrigation system. Water application methods commonly used on self-propelled sprinkler irrigation systems are high elevation sprinkler (usually impact style) head applications mounted on the top of the main pipe and medium elevation spray application heads (MESA), low elevation spray application heads (LESA) and low energy precision application (LEPA) methods. MESA is the most common method used on self-propelled irrigation systems in northern Great Plains region. Early work on LEPA was directed towards achieving relatively uniform application depths (Lyle and Bordovsky 1981, 1983, 1995; Bordovsky et al. 2003). Schneider (2000) reported that LEPA could potentially achieve application efficiencies greater than 95 % and that MESA was about 85 % depending on management.

Application depths on self-propelled sprinkler systems are generally controlled by the speed of the machine. However, this is not sufficient under site-specific conditions where variable amounts are needed along the length of the machine. It is possible to control every sprinkler individually, but the management level may increase to the point that the system is not practical because growers probably cannot manage areas less than 0.4–0.5 ha within a field in other cultural aspects of their operation. However, individual sprinkler control would allow more accurate site-specific applications to irregularly shaped areas. Increasing the number of sprinklers per bank would decrease cost, but the control system would lose some ability to adequately match pre-selected treatment areas. Controlling sprinkler heads in groups 10–15 m wide is generally a practical compromise to match operational limits (Evans et al. 2000; Sadler et al. 2000).

**Types of SS-VRI Sprinkler Irrigation Systems**. In the past few years some commercial companies began marketing center pivot control panels with an option to change center pivot travel speed in increments ranging from 1 to 10° as the machine rotates around the field. This tactic effectively changes application depths in each defined radial sector of the field, and no additional hardware is needed compared to a standard machine (some may need a GPS). This practice is commonly referred to as speed or sector control. It could also be referred to as variable depth irrigation, although some erroneously refer to it as variable rate irrigation. Nevertheless, field variability seldom occurs in long, narrow triangular-shaped parcels and adjusting machine speed may not always be a sufficient level of control because soil and crop conditions often vary substantially in the radial direction.

Consequently, center pivot manufacturers are also offering site-specific variable rate irrigation systems that can differentially apply water site-specifically to irregularly shaped areas or management zones. This is referred to as zone control. Specialized equipment such as control, panels, many valves, supplemental wiring and a GPS are required to control the irrigation in each management zone. Most zone control SS-VRI systems vary water application depths by various forms of pulse modulation (on–off cycling of spray-type sprinkler heads) for a given machine speed. Valves are located on every sprinkler head or groups of heads. Water is then applied to each zone by controlling water output amounts from each group of heads along the length of the machine depending on their location in the field. Zone control has a larger potential for achieving efficient management of water and energy than speed control, and is the general focus of this paper.

The most common site-specific sprinkler irrigation systems in use today are speed control systems, and it is anticipated that much of the short term growth will likely occur with these types of systems. Speed control technologies are probably being used close to their technical capacity to improve water productivity at this time. However, zone control systems can achieve the same effects provided by speed control, but with greater flexibility and provide more management options (Evans et al. 2012, 2013).

Site-specific control systems manage water application amounts by controlling individual or grouped sprinkler nozzle assemblies. These technologies can be used to treat predefined large areas in a whole field or a range of small areas within a field with simple on/off sprinkler controls. Small area (e.g., 0.5–10 ha) site-specific systems can be used to address issues in well defined, localized problem areas where the cost of a full precision irrigation control system may not be justified such as under the first span from the pivot point to avoid overirrigation or minimize foliar disease incidence in that area. These technologies can also be used to treat diverse areas of varying sizes within a large field by variably controlling groups of sprinkler heads across all spans as the machine moves.

**SS-VRI Systems for Agricultural Research**. There is little doubt that SS-VRI systems are wonderful research tools. They can be used to adjust water applications for artificial variability (e.g., research treatments) on top of natural variability within a field. For example, these systems could serve as an efficient, replicated screening method to identify drought and heat tolerance of various genotypes at a number of different locations to advance crop breeding efforts. SS-VRI systems could also be established to impose a range of abiotic stresses (deficit irrigation) using a line source sprinkler concept to develop water production functions (yields vs. range of available water). Another use would be to evaluate the effects of various degrees of potential climate change in different area on various cropping systems by simulating changing rainfall patterns and other conditions. SS-VRI research systems can be used to develop and test sensor networks that measure crop response to abiotic (e.g., water deficits) and biotic (e.g., insect and disease) stresses for improved management. Data from these types of experiments would also be quite beneficial in developing and testing various models and strategies for automatic control of commercial SS-VRI systems. A case study of a SS-VRI system currently being used for agricultural research is presented below.

## 6 Case Study of SS-VRI Systems for Agricultural Research

An example of research using SS-VRI system for research is a project conducted on a 4 ha field at the Montana State University (MSU) Eastern Agricultural Research Center) farm (near Sidney, MT (**47.73° N, 104.15° W**) **over five years from 2005 through 2009**. The site-specific irrigation control system was designed to implement research comparing tillage method (strip till vs clean, conventional till) by irrigation method (LEPA vs MESA) in a two year, irrigated crop rotation of sugar beet (*Beta vulgaris* L.) and malting barley (*Hordeum vulgare*). The soil was classified as a relatively heavy Savage clay loam (fine, smectitic, frigid Vertic Argiustolls) with 21 % sand, 46 % silt, and 33 % clay. Average field slope was about 0.5 % to the east.

The research was laid out in fifteen east–west strips parallel to the bi-directional travel of the linear move irrigation system (Fig. 1). Fourteen of these strips were used for research, but all fifteen were capable of site-specific irrigation. Each research strip was divided into four plots with two plots irrigated with MESA and two with LEPA for a total of 56 plots. Each 15 m by 24 m plot including buffers was planted either to sugar beet or malting barley, which alternated from year to year. Half of the plots were irrigated with MESA and the others with LEPA each year. There were 15 m alleys across the middle and ends of the block for turning farm equipment, and 1.2 m wide alleys between the sides of all plots.

All plots were irrigated with a Valley (Valmont Industries, Inc., Valley, NE) 244 m, 5 span, self-propelled linear move sprinkler irrigation system including the cart, which was installed in the spring of 2003. A diesel engine powered an electrical generator (480 V, 3 phase) was located on the cart that provided electricity for the tower motors, cart motors, irrigation water pump, air compressor and control valves. A buried wire alignment system was used with antennas located in the middle of the machine. The linear move machine used a screened floating pump intake in a level ditch as its water supply. Nominal operating pressure was about 250 kPa. Two double direction boom backs were installed at each of the towers (although not at the cart) because the machine irrigated in both directions. Spans were 48.8 m in length except for the center span with the guidance system which was a 47.5 m span. The machine moved at about 2.1 m $\text{min}^{-1}$ at the 100 % setting.

A Valley CAMS Pro control panel (Valmont Industries, Valley, NE) was used to turn the machine on or off and control machine ground speed. A separate programmable logic controller (PLC) was designed and fabricated with the purpose of being able to irrigate every plot with either MESA or with LEPA. Individual, pneumatically activated solenoid valves were installed on every sprinkler head and controlled in banks of five MESA or thirteen LEPA heads.

The PLC-based control system activated grouped networks of electric over air-activated control valves. Thirty 15-meter wide banks of sprinklers were controlled with this system (15 MESA banks, 15 LEPA banks.) Both the depth and method of irrigation were varied depending on the location of each plot in the field. When not being used, low-cost pneumatic cylinders lifted the LEPA heads above the MESA heads to avoid spray interference when the MESA is operating over a given plot width and length (Fig. 2).

The amount of water applied was adjusted by pulsing heads on and off (pulse modulation) to achieve a target depth based on a digital map stored in the PLC (or in a remote base computer) of depths for each nozzle location as the machine moved down the field. Water was applied to meet the calculated actual evapotranspiration of each crop using data from a nearby agricultural weather station

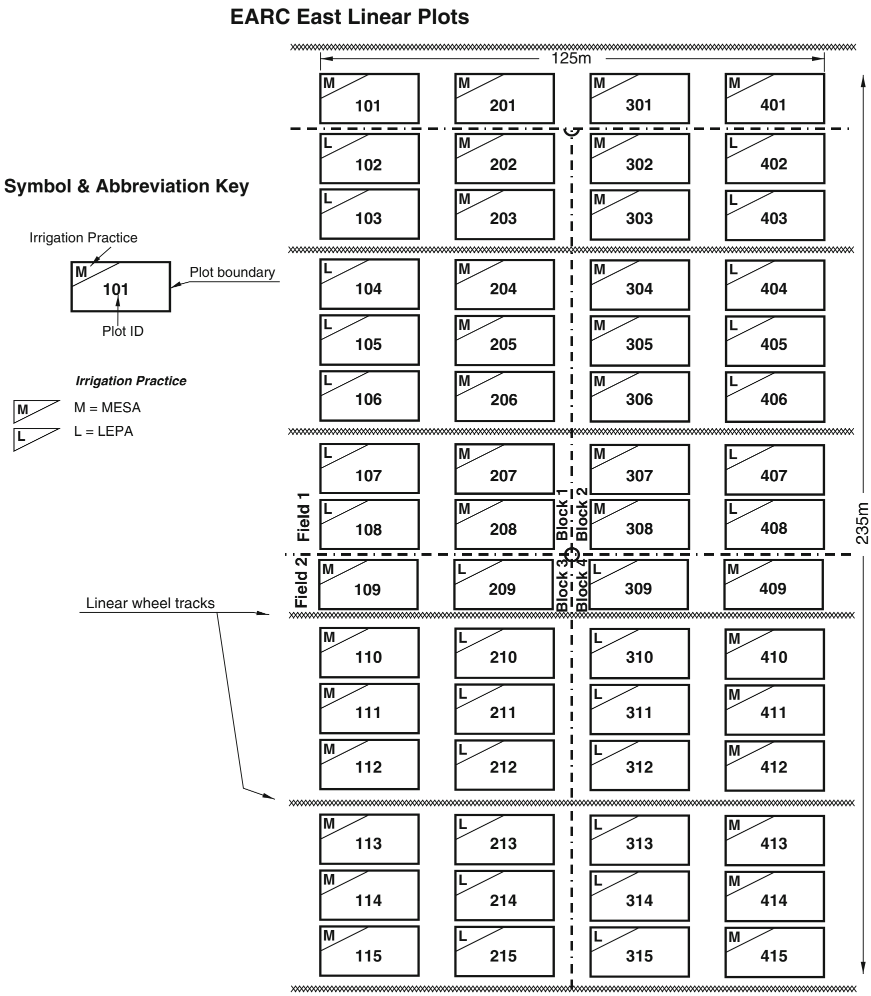

**Fig. 1** Plot layout diagram of the field where the site-specific controls were implemented (Evans et al. 2010)

reconciled with weekly neutron probe soil moisture readings. Equivalent depths of water were applied for both irrigation methods for the same crop.

**Distributed Sensor Systems and Control**. A distributed wireless sensor network (WSN) was integrated into the existing site-specific linear move sprinkler irrigation system described above. Field conditions were monitored by six in-field sensor stations with Campbell CR200 dataloggers (Campbell Scientific, Inc, Logan, UT) distributed across the field based on a soil property map and monitored soil moisture, soil temperature, and air temperature. The CS616 water content reflectometers (Campbell Scientific, Inc, Logan, UT) were calibrated with a

**Fig. 2** Photograph of the LEPA heads lifted above the crop canopy and avoiding interference with the MESA spray head water distribution patterns and LEPA heads in operation in the adjacent strip (Evans et al. 2010)

neutron probe and individually identified for their response ranges at each zone. All in-field sensory data were sampled on 10 s intervals. A nearby weather station monitors micrometeorological information on the field, i.e., air temperature, relative humidity, precipitation, wind speed, wind direction, and solar radiation. Communication signals from the sensor network, weather station and PLC irrigation controller to the base station were successfully interfaced using low-cost Bluetooth wireless radio communication.

**Results**. The overall focus of the project was to assess the environmental impacts of cultural practices and improved management of water, nutrient, and chemical applications as part of a multi-year team project involving several scientists from the location. Practical application of site-specific irrigation technologies with the variability of the research combined with natural variability is certainly more complicated and more challenging than general site-specific field irrigation.

This project illustrates it is possible to effectively install and operate precision site-specific irrigation systems on self-propelled linear move and center pivot systems. The knowledge of soil variability within a field is fundamental to the development of site-specific management areas since different soils have different water holding capacities. The ability to vary water application along the main lateral of the linear move based on position in the field allows researchers as well as producers to address specific soil, crop, and/or special research conditions/ treatments. By aligning irrigation water applications with variable water requirements in the field, total water use may be reduced, decreasing deep percolation and surface run off. Reducing excess water applications will decrease the potential to move nutrients past the plant root zone and fungal disease pressure should also decrease. Cropping systems that more efficiently utilize soil water have been shown to reduce costs and energy use as well as reduce water quality concerns. There is still a need to develop more efficient methods of site-specifically applying crop amendments (e.g., nutrients, pesticides) through self-propelled sprinkler irrigation systems to reduce total amounts applied, improve profit margins and reduce adverse environmental impacts.

## References

Bordovsky JP, Lascano RJ (2003) Variable rate irrigation using low energy precision application (LEPA). In: 2003 Proceedings of the Beltwide Cotton Conference, Nashville, Tenn

Evans RG, Buchleiter GW, Sadler EJ, King BA, Harting GB (2000) Controls for precision irrigation with self-propelled systems. In: Evans RG, Benham BL, Trooien TP (eds) Proceedings of 4th decennial national irrigation symposium, ASAE, St. Joseph, MI. pp 322–331

Evans RG, Iversen WM, Stevens WB, Jabro JD (2010) Development of combined site specific MESA and LEPA methods on a linear move sprinkler irrigation system. Applied Eng Agric 26(5):883–895

Evans RG, King BA (2012) Site-specific sprinkler irrigation in a water limited future. Trans ASABE 55(2):493–504

Evans RG, Iversen WM, Kim Y (2012) Integrated decision support, sensor networks and adaptive control for wireless site-specific sprinkler irrigation. Appl Engr Agric 28(3):377–387

Evans RG, LaRue J, Stone KC, King BA (2013) Adoption of site-specific variable rate sprinkler irrigation systems. Irrig Sci. 31(4):871–887. doi:10.1007/s00271-012-0365-x

Hoffman GJ, Evans RG, Jensen ME, Martin DL, Elliott RL (eds) (2007) Design and operation of farm irrigation systems, 2nd edn. ASABE. St. Joseph, MI, p 863

King BA, Wall RW, Karsky TF (2009) Center-pivot irrigation system for independent site-specific management of water and chemical applications. Applied Eng Agric 25(2):187–198

Kranz WL, Evans RG, Lamm FR, O'Shaughnessy SA, Peters RT (2012) A review of mechanical move sprinkler irrigation control and automation technologies. Appl Engr Agric (in press)

Lamm FR, Ayars JE, Nakayama FS (eds) (2007) Microirrigation for crop production. developments in agriculture series, vol 13. Elsevier, Amsterdam, The Netherlands, p 618

Lyle WM, Bordovsky JP (1981) Low energy precision application (LEPA) irrigation system. Trans ASAE 24(5):1241–1245

Lyle WM, Bordovsky JP (1983) LEPA irrigation system evaluation. Trans ASAE 26(3):776–781

Lyle WM, Bordovsky JP (1995) LEPA corn irrigation with limited water supplies. Trans ASAE 38(2):455–462

Postel S (1999) Pillar of sand: can the irrigation miracle last?. Worldwatch Books, W. W. Norton & Co, New York, N.Y, p 325

Sadler EJ, Evans RG, Buchleiter GW, King BA, Camp CR (2000) Site-specific irrigation—management and control. In: Evans RG, Benham BL, Trooien TP (eds) Proceedings of 4th decennial national irrigation symposium, ASAE. St Joseph, MI, pp 304–315

Sadler EJ, Evans RG, Stone KC, Camp CR (2005) Opportunities for conservation with precision irrigation. J Soil Water Conserv 60(6):371–379

Schneider AD (2000) Efficiency and uniformity of LEPA and spray spinner methods: a review. Trans ASAE 43(4):937–944

Schütze N, Schmitz GH (2009) A neuro-dynamic programming approach for optimal scheduling and feedback control of deficit irrigation systems. In: Proceedings of European geoscience union general assembly 2009. European Geosciences Union, Munich, Germany Available at: http://citeseerx.istpsu.edu/viewdoc/download?doi=10.1.1.149.2226&rep=rep1&type=pdf. Accessed 27 June 2011

Siyal AA, van Genuchten MT, Skaggs TH (2009) Performance of a pitcher irrigation system. Soil Sci 174(6):312–320

Turral H, Svendsen M, Faures JM (2010) Investing in irrigation: reviewing the past and looking to the future. Agric Water Manag 97(2):551–560