Development of Combined Site-Specific MESA and LEPA Methods on a Linear Move Sprinkler Irrigation System

R. G. Evans, W. M. Iversen, W. B. Stevens, J. D. Jabro

Abstract. *A site-specific controller, hardware and software systems were developed with the capability to switch between either mid-elevation spray application (MESA) or low-energy precision application (LEPA) methods. These systems were field tested and used to manage site-specific irrigations under a linear move sprinkler system and simultaneously varied water application depths by plot as the machine traveled back and forth across the field. The controller and modifications to the water application methods utilized off-the-shelf components as much as possible. The linear move system was modified so that every plot could be irrigated using either MESA or LEPA methods. A programmable logic controller (PLC)-based control system was utilized to activate grouped networks of electric over air-activated control valves. Both the depth and method of irrigation were varied depending on the location of each plot in the field as provided by a low-cost WAAS enabled GPS system mounted on the machine. When not being used, low-cost pneumatic cylinders lifted the LEPA heads above the MESA heads to avoid spray interference when the MESA mode was operating over a specified plot width and length. The control system was used on fifty-six 15- × 24.4-m (50- × 80-ft) plots as well as several other adjacent research projects in which there were a mix of crops and a prescribed set of management experiments. While this particular application was designed specifically for a large, complex agronomic research project to address artificially imposed spatial variability water management, the same controllers, valves and general software could be easily adapted to field scale commercial irrigation.*

Keywords. *Precision irrigation, Precision agriculture, Spatial variability, Variable rate irrigation, Pneumatic controls, Sugarbeet, Barley, GPS.*

Competition for water with municipalities, industries, recreation, and environmental uses is a globally important issue for irrigation managers as water conservation mandates and related litigation is increasing. This will result in the continued refining of water conservation measures including improved efficiency in water delivery, timing of applications, and increased use of various deficit irrigation strategies. Maintaining crop production through more efficient use of rain and irrigation is critical to overcoming these problems, which are complicated because their severity varies in both time and space. In order to maintain profitability, irrigators will have to apply water and agrochemicals in a more efficient manner to reduce the social as well as the economic costs of diverting or pumping water over relatively long distances.

New and improved strategies and practices are needed to increase the cost-effectiveness of crop production, reduce soil erosion, reduce energy requirements, reduce surface and groundwater contamination from agricultural lands, as well as to sustain food production for strategic, economic, and social benefits. Improved technologies will be a major part of the solutions for better management of energy, water, and soil resources in a limited resource future for irrigated agriculture. It is highly likely that site-specific differential irrigation under self-propelled irrigation systems will be a significant part of the future toolbox for many growers (Evans and Sadler, 2008).

Over the past 50 years, the goal of center pivot and linear move irrigation designers has been to have the most uniform water application pattern possible along the entire length of the center pivot or linear move machines. However, considerable yield variations still exist despite the inherent high frequency and relatively uniform applications of self-propelled center pivot and linear move irrigation systems, which are often attributed to spatial variability in soil water holding capacity and nutrient availability due to soil texture, pests, topography and other factors. Runoff and chemical leaching below the root zone can also occur when crop water use is non-uniform. Poor maintenance of the equipment may also be a source on non-uniformity. Thus, because of the non-uniform nature of large fields, designing for uniform and a precise, uniform water application may not always be an advantage, particularly when agrichemicals are applied (Evans et al., 1996; Sadler et al., 2000, 2005; Evans and Sadler, 2008).

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Variations in soil water availability across a field may cause irrigators to: 1) ensure that areas with the smallest water holding capacity receive adequate water; 2) manage the whole field based on average soil water conditions; or 3) limit water application to avoid over-irrigating the wettest areas. All of these cases can cause over-irrigation or under-irrigation of some areas of a field due to the current inability to differentially irrigate based on soil, topography, and plant factors within a single irrigated field (Evans et al., 2000).

Microprocessor-controlled center pivot and linear move irrigation systems are particularly amenable to site-specific approaches because of their current level of automation and large area coverage with a single lateral pipe. These technologies provide a unique control and sensor platform for economical and effective ways to vary agrichemical and water applications to meet the specific needs of a crop in uniquely defined zones within a field. Typical management objectives would include optimizing yield and quality while maintaining environmental benefits and reducing chemical leaching.

Site-Specific Irrigation

In this article, site-specific irrigation is the preferred term rather than precision irrigation or variable rate irrigation. The widely used term precision irrigation has many definitions that do not always include site-specific considerations. For example, precision irrigation is also used to describe the precise amounts of water applied uniformly across an entire field with drip irrigation systems.

Water conservation and environmental objectives may make it necessary to supersede traditional uniformity criteria with the capacity of the irrigation system to have spatially variable water application capabilities to meet particular site-specific requirements of soils, plant growth, reduced leaching, or other criteria such as an agrichemical application within a field. To achieve such capability, a conventional irrigation machine would need variable-rate sprinkler heads of some type, a method of position determination (e.g., GPS), and a microprocessor-based device to control water application amounts from each sprinkler head or groups of sprinkler heads based on specified management criteria. These systems might also require modifications to the water supply delivery system to handle variable-rate water demands as well as the capability for variable-rate nutrient injection, and variable-rate pesticide application. The implications of site-specific technologies on chemigation have been discussed by Duke et al. (1992, 1998, 2000), Evans and Han (1994), Evans et al. (1995), and King et al. (2009).

The development of control and management technologies that can spatially and temporally direct the amount and frequency of water (and appropriate agrichemical) applications by site-specific self-propelled irrigation systems would be a very powerful tool to increase water productivity while reducing water application and minimizing adverse water quality impacts. Site-specific irrigation could also play a major role in maximizing net returns when implementing limited or deficit irrigation strategies in water short areas. These benefits could be enhanced by the use of wireless networks of real-time automated soil water and micro-meteorological sensors or infrared thermometers monitoring of plant temperatures that are strategically distributed to provide continuous feedback to re-calibrate and check various model parameters used in decision support frameworks (Andrade-Sanchez et al., 2007; Kim et al., 2008, 2009; Kim and Evans 2009; O'Shaughnessy and Evett, 2010). Various sensor systems can also be mounted on the machine and provide real-time feedback for decision support as the machines move across a field (Peters and Evett, 2008).

Site-specific application technologies can be used to treat a whole field or to treat small areas of a field with simple on/off sprinkler controls in single span-wide treatment areas. Small area control systems would be used to manage irrigation in well-defined areas where the cost of a complete site-specific irrigation control system is not justified such as rock outcrops, waterways, or under the first span from the pivot. Analysis of field data (Evans et al., 1996) have shown that application depths are normally reduced by either no more than 15% to 20% or by 100% (no application, as would be the case of rock outcroppings or waterways). They also concluded that lesser values would not usually be needed except for chemigation. It should be noted that those conclusions pertain to arid or semi-arid western U.S. conditions, and it is not yet clear that lower flow rates are needed in the humid eastern United States.

The ability to vary water application along the main lateral of the center pivot based on field position allows the irrigation manager to address specific soil and/or slope conditions. 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 (King et al., 1995; Sadler et al., 2000, 2005; King et al., 2009), and fungal disease pressure should also decrease (Neibling and Gallian, 1997). 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. The continually changing positions of individual sprinkler heads in the field can be approximated based on periodic readings from differential GPS, electronic compasses or electronic angle resolvers.

Site-specific irrigation using self-propelled center pivot and linear move systems have been studied by several groups of researchers. These included Fort Collins, Colorado (Duke et al., 1992; Fraisse et al., 1992), Aberdeen, Idaho (King et al., 1997; McCann et al., 1997), Prosser, Washington (Evans et al., 1996), Florence, South Carolina (Camp and Sadler, 1994; Omary et al., 1997; Camp et al., 2002), Tifton, Georgia (Perry et al., 2003, 2004) and and Clemson, South Carolina (Han et al., 2009). The basic control systems developed in Prosser, Washington, were installed on a three-pivot cluster on a commercial farm in south central Washington (Evans and Harting, 1999; Harting, 1999). Similar control systems were later installed on more than seven full-sized center pivot systems in north central Oregon that used real-time radio communications to monitor, download instructions, and start or stop machines as well as controlling pumping stations and main control valves (Harting, 2004). Several of these prior studies were summarize in the proceedings of a 2000 ASAE conference (Buchleiter et al., 2000; Evans et al., 2000; Sadler et al., 2000). Site-specific sprinkler irrigation research is also on-going in Georgia and South Carolina on cotton (Perry et al., 2003, 2004; Dukes and Perry, 2006; Han et al., 2009).

Recent innovative work on site-specific sprinkler irrigation in Washington has also been reported by Pierce et al. (2006) and Chavez et al. (2010a, b). There is also ongoing variable rate sprinkler irrigation research in Brazil (Coelho, 2009) and in Europe (Al-Kufaishi et al., 2006).

Water Application Methods

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). This was later extended into variable-rate, site-specific irrigation (Bordovsky and Lascano, 2003). Schneider (2000) reported that LEPA could potentially achieve application efficiencies greater than 95% and that MESA was about 85% depending on management.

Site-Specific Control of Water Application Depths

Application depths on linear move 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 to 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. Control of sprinklers in banks that are 10 to 15 m (30 to 50 ft) in width are generally a practical compromise to match operational limits (Evans et al., 2000).

Site-specific control systems are linked to nozzle hardware assemblies to manage water application amounts. Basically, three approaches have been used to obtain the variable rate irrigation depths depending on location as the machine moves across the field. These include mechanically adjustable nozzle sizes to change flow rates (King and Kincaid, 1996; King et al., 1997), multiple sprinklers with individual valves at each outlet (Camp and Sadler, 1994; King et al., 1995; Wall et al., 1996; McCann et al., 1997; Omary et al., 1997; King et al., 2009) and pulse modulation (Fraisse et al., 1992; Evans et al., 1996; Evans and Harting, 1999; Perry et al., 2004; Han et al., 2009; Chavez et al., 2010a, b). Each of these techniques has advantages and disadvantages, and each affects the design of the other components and software of the site-specific control system.

Research Objectives

The objective of this article is to describe the design, installation, and testing of a dual, site-specific irrigation system and software at the USDA-ARS, Northern Plains Agricultural Research Laboratory in Sidney, Montana. 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.

Procedures and Methods

This research was conducted on a 4-ha (10-acre) field at the Montana State University (MSU) Eastern Agricultural Research Center (Sidney) farm [near Sidney, Mont. (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 sugarbeet (*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 15 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 15 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- × 24-m (50- × 80-ft) plot including buffers was planted either to sugarbeet 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 (50-ft) alleys across the middle and ends of the block for turning farm equipment, and rototilled 1.2-m (4-ft) alleys between the sides of all plots

In effect, there were two separate irrigation systems on one machine, which allowed treatments to vary either irrigation method or to vary depth water applications as the machine moved through the field. The site-specific controller and software was developed to provide the capability to switch between MESA or LEPA water application methods as well as to simultaneously vary water application depths by plot.

All plots were irrigated with a Valley (Valmont Industries, Inc., Valley, Nebr.) 244-m (800-ft), 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, three 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 (36 psi). Two double direction boom backs

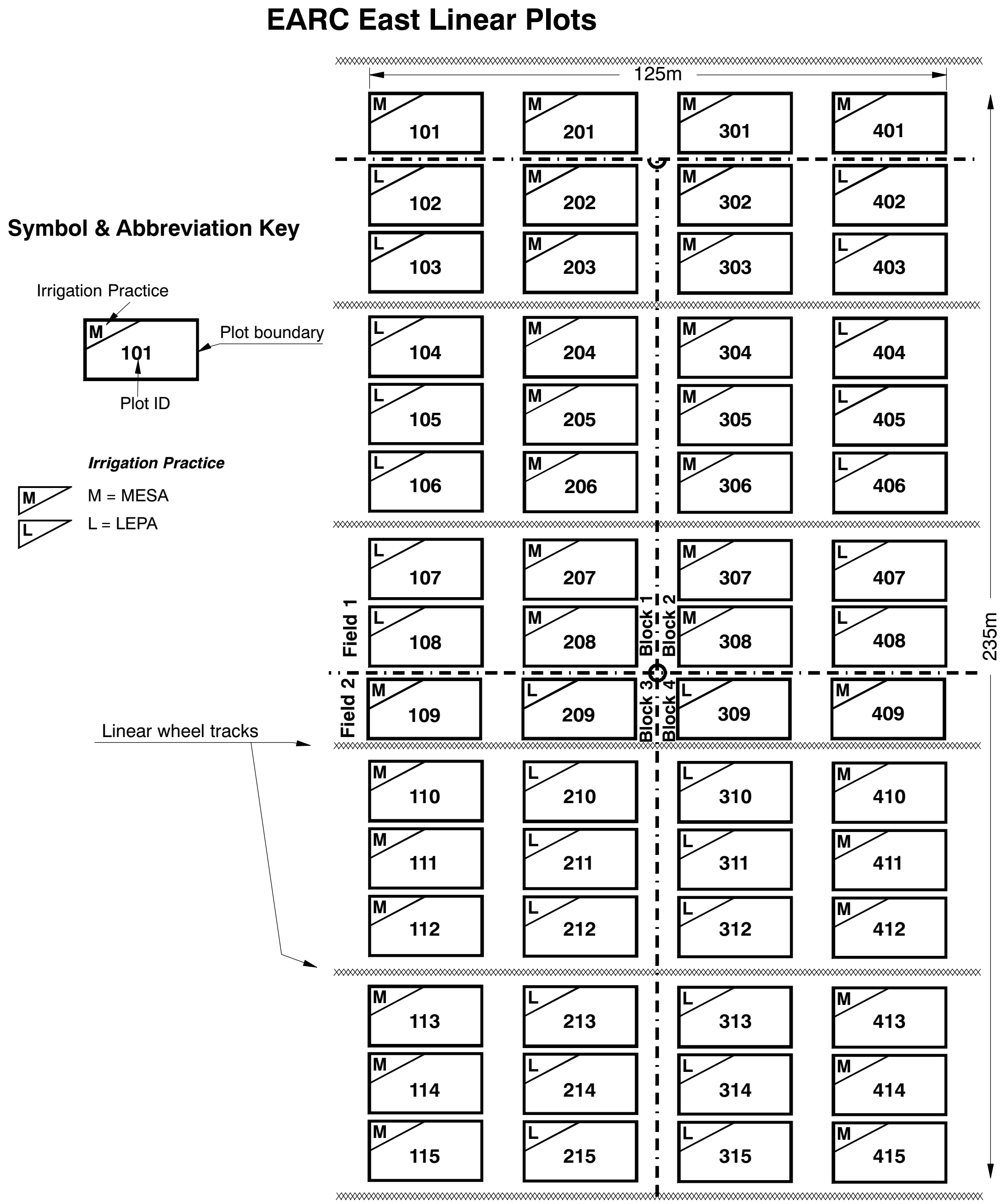


Figure 1. Plot layout diagram of the field where the site-specific controls were first implemented.

were installed at each of the towers (although not at the cart) because the machine irrigated in both directions. Spans were 48.8 m (160 ft) in length except for the center span with the guidance system which was a 47.5-m (156-ft) span. The machine moved at about 2.1 m min^{-1} (7 ft min^{-1}) at the100% setting.

A Valley CAMS Pro control panel (Valmont Industries, Valley, Nebr.) was used to turn the machine on or off and control machine ground speed. A separate controller, described later, 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 5 MESA or 12 LEPA heads [15-m (50-ft) wide strips]. 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 (ET_a, NDAWN, 2009) of each crop using data from a nearby agricultural weather station reconciled with weekly neutron probe soil moisture readings. Equivalent depths of water were applied for both irrigation methods for the same crop.

Conversion to a Site-Specific Irrigation System

The existing linear move irrigation system was converted to make groups of individual sprinkler nozzles electronically controllable by attaching a PLC, solenoids, air valves, and GPS. As much as possible, the site-specific sprinkler irrigation and control system utilized off the shelf components.

The PLC (S7-226, Siemens, Johnson City, Tenn.) with three relay expansion modules was mounted in a panel on the main cart. The controller relay modules activated ASCO electric solenoids (U8325B1V, ASCO, Florham Park, N.J.). The 24-Vdc electric ASCO valves, in turn, activated a pneumatic system to close normally-open 19-mm (¾-in.) plastic diaphragm-actuated globe valves (Bermad, Model 205, Anaheim, Calif.). Thirty banks of sprinklers were controlled with this system (15 MESA banks, 15 LEPA banks). The electric ASCO solenoid valves were grouped into clusters of six valves and placed on a weather tight fiberglass enclosure at each tower and the cart. Seven conductor 14 gauge wire in a shielded UV resistant cable with a common ground was used between the controller and the actuators (on longer machines, a 12-gauge wire cable was used). The cables were terminated in the control panels at the cart and the solenoid boxes on each of the towers. Plastic tubing [6.4 mm (1/4 in.) diameter] commonly used for air brakes on heavy trucks connected an ASCO valve to the respective groups of Bermad valves (fig. 2). Figure 3 shows the arrangement of valves mounted on the sprinkler lateral pipe. Machine travel speed was set by the Valley panel, which established the maximum application depth and the PCL controller managed the sprinkler heads.

MESA sprinkler heads were spaced every 3 m (10 ft) with Nelson S3000 spinner with #31 nozzles (Nelson Irrigation, Walla Walla, Wash.) with 100-kPa (15-psi) regulators. These heads supplied about 0.40 L s^{-1} (6.41 gpm) and were about 107 cm (42 in.) above the ground on flexible drops with 0.45-kg (1-lb) weights below each regulator. Part-circle sprinkler heads were placed at the edges of each 15-m (50-ft) wide plot to minimize spray onto adjacent plots. The air-activated Bermad valves were located on the gooseneck above each drop to each head in groups of five, and were individually connected to the ASCO valves for control. Figure 3 presents a schematic diagram of the water application system for a single span on the site-specific linear move system.

The LEPA system used the bubbler style Senninger Quad-Spray® heads (Senninger Irrigation, Inc., Clermont, Fla.) with 70-kPa (10-psi) regulators (#10.5 nozzles) and sliding 0.9-kg (2-lb) weights above each regulator. The head supplied about 0.16 L s^{-1} (2.49 gpm). The drops were spaced every 122 cm (48 in.) along sub-manifolds suspended from the truss rods (not a recommended practice). The bottom Quad-Sprays were about 15 cm (6 in.) above the furrow surface when operating. The Bermad valves were located on three goosenecks that supplied water to the submanifolds for the 12 LEPA heads per 15-m (50-ft) wide research strip.

Figure 2. Photograph showing the pneumatically-activated valves, control and power wiring and air lines along sprinkler lateral pipe.

A pulse modulation approach was used to control water application depths because of the greater flexibility in the range of application depths, installation simplicity, and reduced costs compared to more complex multiple sprinkler heads with individual valves or variable nozzle control. The ground speed of the machine established the maximum application depth and treatments were a percentage of maximum by varying sprinkler on-times in a 60-s cycle interval. The software allowed easy changes to the cycle time if there was a need to make adjustments.

Because the Bermad control valves were located on top of the pipe (see fig. 2) both the MESA and LEPA heads had some drainage between pulses, which was limited to the volume in the drop tubes. This was not an issue for the LEPA, but did result in some minor non-uniformity in the MESA applications.

Cycle time is defined as the sum of total on and off times during one pulse cycle. For example, a total off time of 12 s out of every 60 s would result in an 80% of maximum application depth. Evans et al. (1996) used a 250-s cycle time with rotator MESA heads whereas Duke et al. (1998) and Harting (1999) used a 60-s cycle time with MESA spray heads.

Normally open valves were used on the heads since the failure mode would leave the sprinklers on; which would be more representative of grower practice. Air was used as the control fluid for these valves because air was much cleaner than the irrigation water and minimized the potential for foreign material to plug the small orifices in the control valves. Another advantage was that air does not freeze and the control system did not need to be flushed or drained for winterization. Any moisture in the air system was eventually vented to the atmosphere through normal operation. There were random problems with occasional failure of the Bermad valve membranes that could be replaced without removing the valves from the manifold, but troubleshooting the exact problem valve was often time consuming.

A 1-HP, 3-phase, 480-V air compressor was installed to provide air for actuating the Bermad control valves. The compressor was located at the main cart for easy maintenance with a 9.5-mm (3/8-in.) plastic airline running the length of machine. Air [about 19-L (5 US-gal)] accumulators were located at each tower near the bank of electrically actuated ASCO valves to ensure rapid and uniform sprinkler head operation (fig. 4).

Because there were three 15-m (50-ft) strips in each span, each bank of six ASCO valves on each tower controlled the Bermad valves on six groups (three MESA and three LEPA) for a single span. Air was applied to close the Bermad valves for brief periods for cycling to control the depth of application or for longer intervals to change irrigation method for a particular plot (fig. 4).

Lifting Mechanism for the LEPA Heads

A system of pneumatically operated cylinders was designed and tested to lift the LEPA heads above the MESA heads when the MESA treatments were operating. This

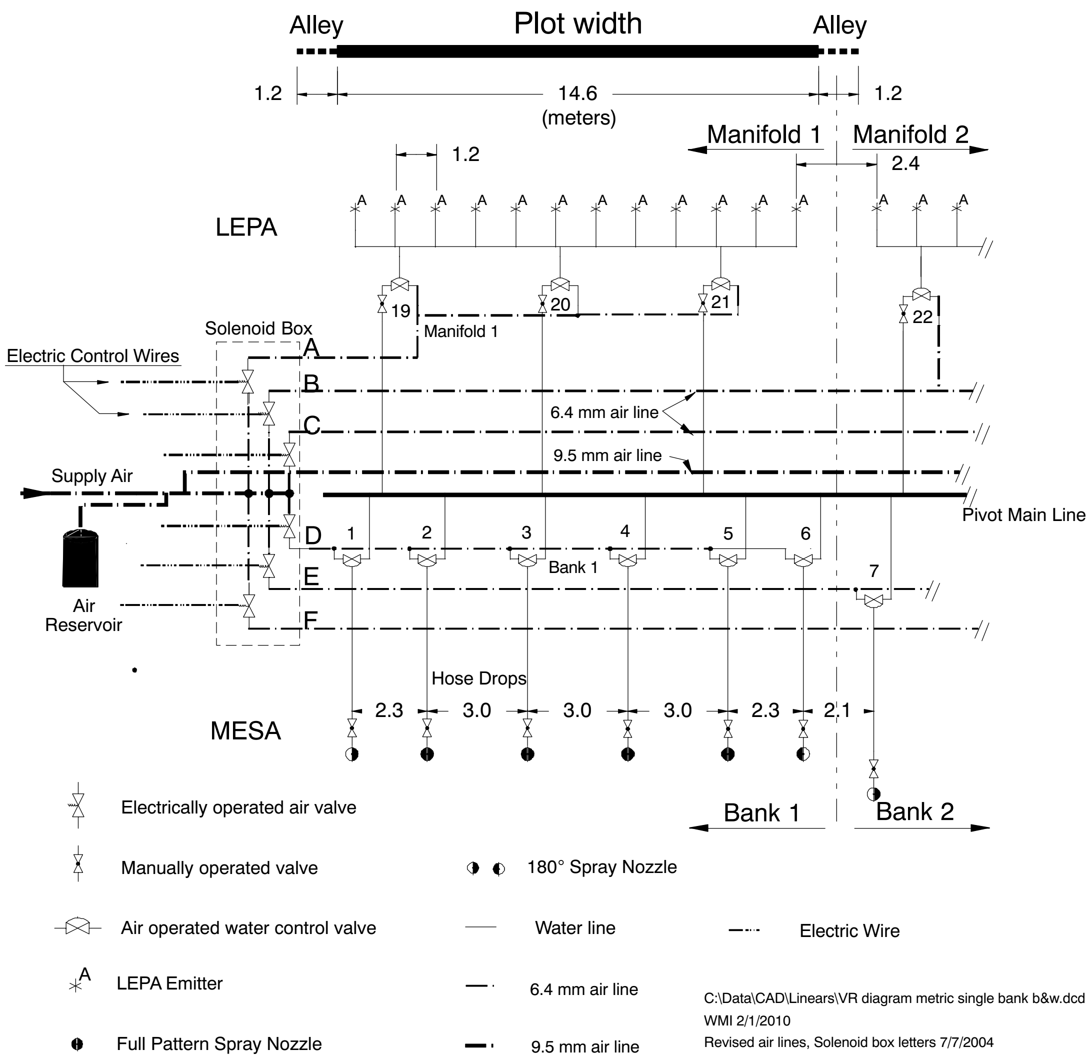


Figure 3. Basic schematic of the water distribution systems for both methods on a single plot, which was duplicated 15 times along the length of the linear move machine.

served to minimize interference with the MESA spray patterns as well as keep the LEPA heads out of the canopy. Raising the LEPA heads above the crop canopy when MESA was utilized was also necessary because part of the study was comparing the prevalence of leaf diseases under each system, and dragging the LEPA heads through the crop canopy might spread diseases from one treatment to another. Figure 5 shows the system in operation.

Closing the normally open valves on the LEPA heads also started to activate the LEPA lift system. When air was applied to the solenoid valves (turning them off) on the LEPA manifolds, the pneumatic cylinders were simultaneously activated, lifting the LEPA heads, which required about 20 s. When the air supply to the valves was shut off, the LEPA heads were turned on and would descend as the air was vented from the pneumatic cylinder. This system worked well when the requirement was only to change irrigation treatments from plot to plot. It was also easy to trouble shoot because even with the system running dry, the rise and fall of the LEPA heads gave a visual indication of the status of the solenoid and air delivery to a particular bank of nozzles. The drawback was that if the cycle time of the LEPA system occurred at very short intervals, the lift system would not have time to respond because it would take 10 to 15 s to pressurize or vent the cylinder. During this "change of state" time the LEPA heads would not be at their desired position, and the air compressor couldn't maintain adequate pressure for the control system. This system was modified in 2009 so the application rates of the LEPA banks could be varied by pulsing as previously described. A separate solenoid was added to control air to the lift cylinder only, and the original solenoid was used just for the air supplied to the Bermad valves controlling the water flow. The PLC program was also modified so that the lifting or lowering was controlled independently of water application.

The 1.52-m (5-ft) long single acting pneumatic lifting cylinders were built out of 6.35-cm (2.5-in.) extruded aluminum sprinkler tubing. End plugs about 5-cm (2-in.) long with O-rings were fabricated and installed at each end. The cylinder end plugs on the rod end were drilled and tapped to receive a swivel 90° 0.635-cm (¼-in.) tube × 0.3175-cm (1/8-in.) MNPT air hose fitting. A 1.31-cm (33/64-in.) hole was drilled through the center of this plate, and a 2.54-cm (1-in.) hole was counter bored ¼-in. deep on the inside of

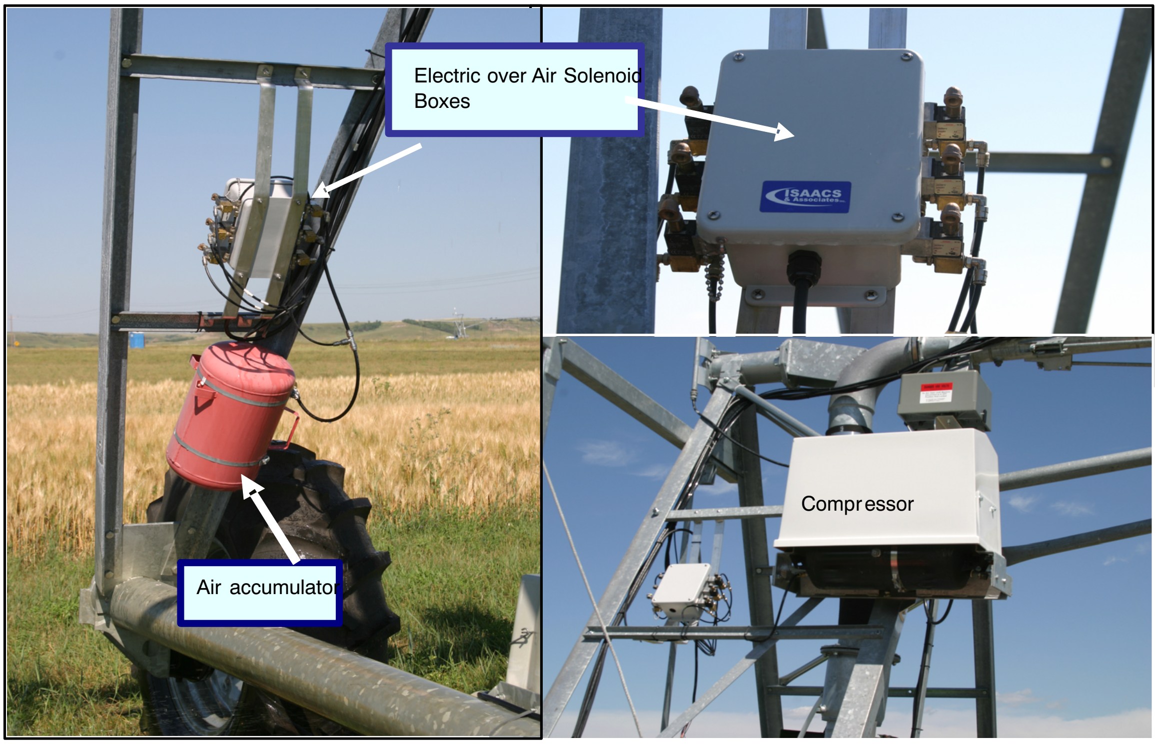


Figure 4. Photographs showing the air compressor at the cart and an air accumulator and valve box, which were located at each tower

this plate to receive a ½-in. ID × 1-in. OD × ¼-in. high Buna-N U-cup for the cylinder rod. The cylinder cap or plate on the other end was fitted with a breather to allow the air to escape from the non-pressurized end of the cylinder and to prevent dirt and insects from entering. The breathers are of the style commonly used on agricultural gear boxes. The 149-cm (58.5-in.) long plunger rod was 1.27-cm (0.5-in.) aluminum and was threaded into a piston machined from an acetyl plastic material. The piston was fitted with a 6.03-cm (2-3/8-in.) OD × 5.08-cm (2-in.) ID Buna-N 60 O-ring. The first prototype used the more commonly available Buna-N 70 O-rings, but these rings were deemed too stiff. If the ring groove was made shallow enough to prevent air leakage, the piston wouldn't slide easily enough to allow the force of

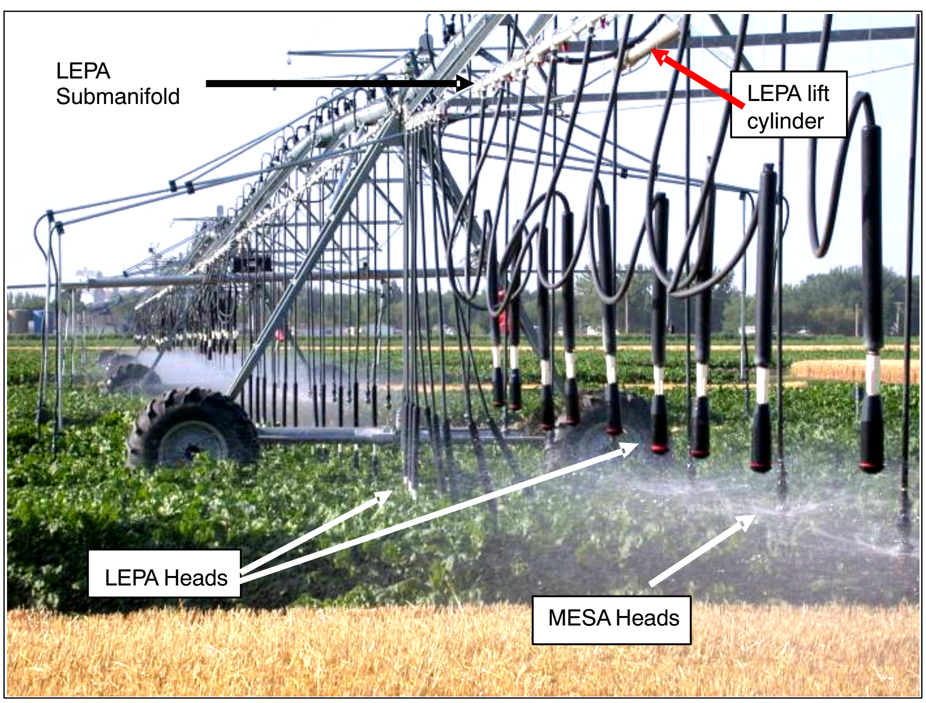


Figure 5. Photograph of the LEPA heads lifted above the crop canopy and avoiding interference with the MESA spray head water distribution patterns and LEPA heads in operation in the adjacent strip.

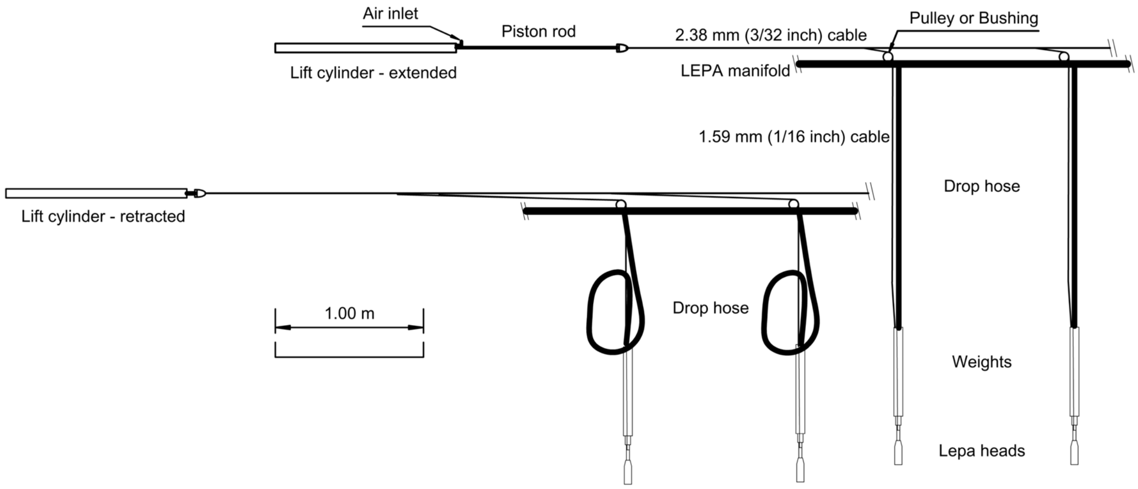


Figure 6. Schematic of the operation of the LEPA head lift cylinder and pulley system in the both the extended and retracted modes.

gravity to lower the LEPA heads. Softer O-rings of Buna-N 60 material were used in the final version because they could be compressed about 10% of their diameter and still allow the piston to slide with less than 7 kg (15 lb) of force applied. Prior to installation each cylinder was coated with a light film of grease and then pressurized to 38.5 kPa (80 psi) and monitored for leakage. A pressure drop of less than 14 kPa (2 psi) per min was considered acceptable.

The cylinders were attached to the span trusses and hooked to a series of cables and pulleys that lifted the LEPA heads (fig. 6). This lifting system was designed in the spring of 2005, fabricated over the summer and installed and tested in fall 2005. Individual heads were lifted by a 1.59-mm (1/16-in.) cable running though the weight on the sprinkler drop hose and then to a 4.4-cm (1-3/4-in.) split bracket pulley which was mounted to the truss rod with a U-bolt. The 1.59-mm (1/16-in.) cable then was connected to a 2.38-mm (3/32-in.) cable running parallel to the truss rod that connected to a steel D-ring attached to the lift cylinder piston rod.

Several changes were made to the lift system as operational problems were encountered during testing. Nylon rope was originally used instead of the steel cable but it stretched and did not acceptably raise the LEPA heads to the proper height over time. The split bracket pulleys worked satisfactorily for most of the heads but near the end of the linear span the truss rods curved rapidly. This caused misalignment issues between the cable and the pulley, and often the cable would become wedged between the pulley and bracket. This was solved by replacing the pulleys near the end of the trusses with bushings made from 31.8-mm (1-1/4-in.) diameter UHMW rod. The rod was cut into 25.4-mm (1-in.) long pieces and a 6.35-mm (1/4-in.) hole was drilled through the center. Starting half way along the length of the piece, the 6.35-mm (¼-in.) hole was enlarged to the edge of the rod, creating a smooth transition for the 90° change in direction. A groove was machined on the outside of the bushing to accept the hose clamp which was used to attach the bushing to the truss rod.

Positioning System

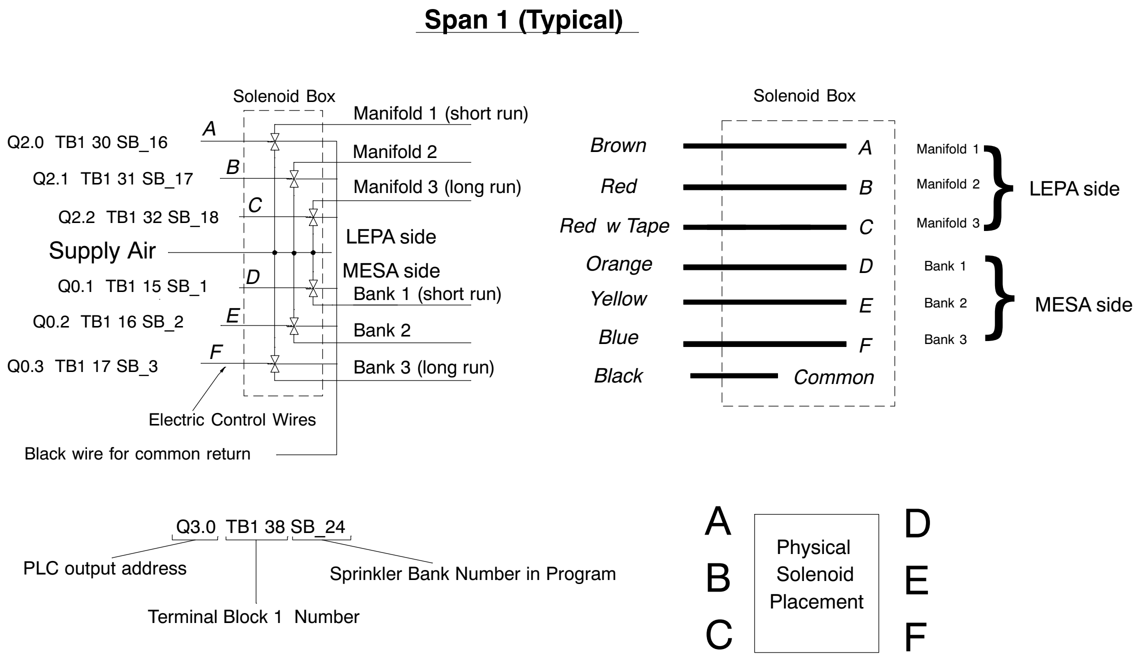
A WAAS-enabled Garmin 17HVS global positioning system (GPS, Garmin International Inc., Olathe, Kans.) with a differential GPS positional accuracy of < 3 m (10 ft), 95% of the time was used to monitor machine location. It was located at the cart for determining and tracking machine position as it moved across the plots. A running average of GPS readings was used to estimate sprinkler head position to control application depths in each plot and to switch between either the LEPA or MESA treatments. The 3-m (10-ft) accuracy of the GPS was more than adequate to transition irrigation methods or application depths between plots as the machine crossed the 15-m (50-ft) wide alleys. The GPS was tied directly to the PLC controller and was transmitted over the wireless link to a monitoring computer about 0.8 km (0.5 mile) away (Kim et al., 2008, 2009; Kim and Evans, 2009). As the linear move sprinkler system moved across the field, the GPS-enabled continuously updated geo-referenced information of the position of sprinkler nozzles.

PLC Control System Development

Site-specific operation was controlled by a programmable logic controller (PLC) (S7-226, Siemens AG, Germany) located on the cart. The PLC managed the activation of electric over pneumatic solenoids to control 30 banks of 5 to 10 sprinklers each. Variable-rate applications were implemented by controlling the on/off times for groups of spray or LEPA nozzles. The layout of the electrical addressing used in this project is shown in figure 7.

The wiring cabinet for the PLC and add-ons was custom built using a 91-cm (36-in.) square steel, waterproof enclosure (fig. 8). The software for the PLC and an operator interface panel (UniOp BKDR-16-0045. Sitek SpA, Verona, Italy) provided a means to control and monitor the PLC without the need for a laptop computer. The interface panel's LCD screen displayed the status of each bank of sprinklers, the GPS position and associated GPS parameters, the application rate timer settings for each crop and plot area, and whether a crop or study area was scheduled to be irrigated. The touch screen on the interface panel was also used to input timer settings that determined the application rate for each crop or study area, turn off the irrigation for a particular crop or study area, and/or manually override the GPS unit for demonstration or troubleshooting purposes.

The PLC updates the GPS position of the irrigation machine every second from the differential GPS. The PLC



	MESA	LEPA
PLC output	Q0.1 – Q1.7	Q2.0 – Q3.5
Terminal Block#	15 – 29	30 – 44
Prog Sprinkler Bank	1 – 15	16 – 30

Figure 7. Basic addressing system used for each span of the Sidney MESA-LEPA irrigation experiment, which was repeated five times along the length of the linear move machine.

can operate in a stand alone mode or work under the control of an off-site base computer. Instructions are downloaded from a laptop computer or enter via the interface panel. In the off-site mode, the PLC wirelessly transmits the machine position to the base station via a Bluetooth or other type of radio transmitter. The off-site mode can also accept feedback

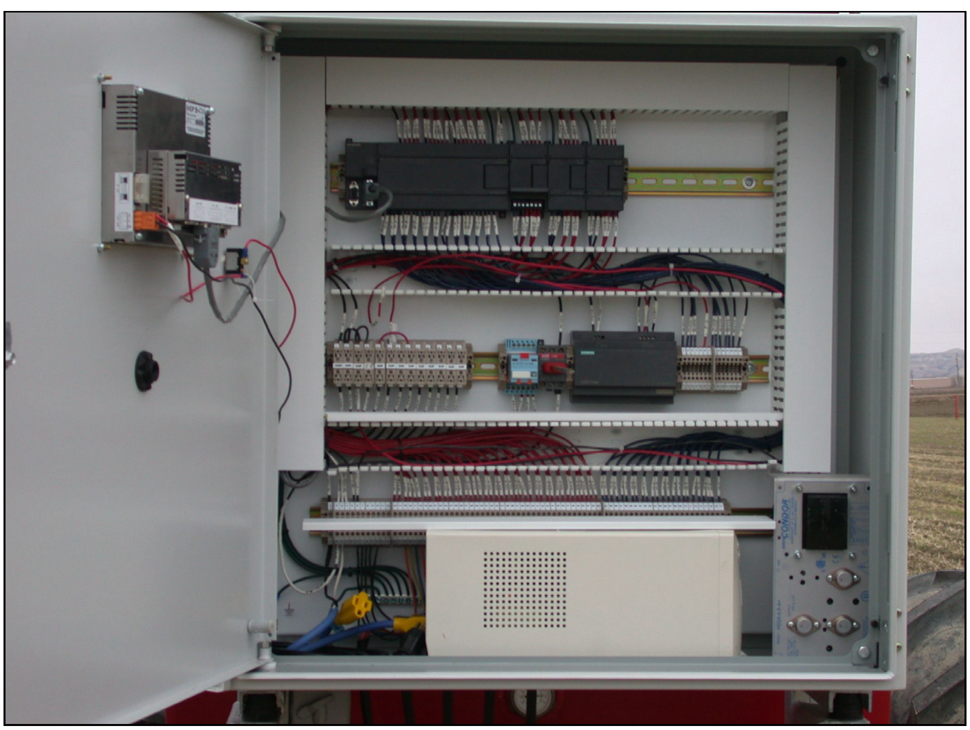


Figure 8. Photograph of the interior of the wiring cabinet showing the PLC, relay expansion modules, power supplies, basic wiring, and the back of the front interface panel.

from in-field soil water and micrometeorological stations (Kim et al., 2008, 2009).

PLC Software

PLCs could be programmed, activated, and monitored in the field as well as over a wireless communications link to a base computer. However, the ability to switch between two separate irrigation systems on the same machine provided some unique challenges. The software was capable of potentially controlling variable rate irrigations on up to eight different crops simultaneously with either LEPA or MESA, if necessary.

The software was specifically designed for the control of a long-term irrigated cropping systems research project. The software from Harting (1999) and Evans and Harting (1999) was studied, but only the method of capturing the GPS signal with the PLC was used from this earlier software. The existing software examples were also written for a pivot and not a linear, so modifications had to be made for our system and setup. The existing systems also required a computer to input the data (although some functions could also be monitored on the panel at the cart). It was desirable to have a system that allowed the person starting the irrigation to easily change the amount being applied to each crop and whether that crop would be watered or not. Several different people operate the machines, and it would be cumbersome for all of them to have access to a laptop with the required software.

Variable rate water application systems reported in the literature often only address changing application amounts depending on what large area of the field the machine was irrigating based on the GPS coordinates of the sprinklers. However, this research required that the method of irrigation be randomized by plot, so that some plots would be irrigated under MESA and others under LEPA at the same time. According to our assessment, the available variable rate systems used for other projects could not accommodate this dual irrigation system requirement. Another drawback of earlier software designs was that they divided the field into a number of regularly spaced small cells (or pixels) based on a grid or angular degree pattern. This works well for field scale applications, but a very large number of cells would be required to provide the necessary resolution for research when there are variable plot sizes and alley widths. For example, to achieve a 1.5-m resolution, one 24- × 15-m plot would be subdivided into sixteen 1.5- × 15-m cells and editing the application values for each cell in a large set of plots would be tedious and error prone.

Consequently, a boundary-based system was used where the entire plot was between two boundary lines so only a single entry was needed to describe the application for the entire plot. In the boundary system, the current GPS reading was compared to a list of entered boundary values, and the PLC would set a binary bit to "1" in a memory location that was unique for each area that lay between two boundary values. This "1" bit would in turn call one or more subroutines that would determine which outputs of the PLC would be powered on or off based on the crop, irrigation type, and inputs from the interface panel. Another advantage of the boundary method was that a single boundary line could be placed in the center of the 15-m (50-ft) wide alley between the plots to ensure sufficient overlap for uniform applications in the plots by the sprinklers in both directions. Cell-based systems would generally not allow that operation because the edge of the cell would not necessarily fall in the center of the alley, unless individual cell sizes were quite small.

Multiple studies with different dimensions and plot sizes could be co-located under the same linear move irrigation system, and their respective irrigation amounts could be varied simultaneously by the software using the boundary-based method. Plot sizes of different potential studies could be adjusted to match each other in some cases, but one study on this site required different farm equipment and thus different plot and alley dimensions. In order to maximize land use and irrigation efficiency, these two sets of plots needed to be placed along the long axis of the linear (perpendicular to the strips) and not in the direction of travel. A separate set of boundaries was used for these plots, which were written as a different network within the PLC program than the main set of plots, and only those groups of sprinkler banks over that particular study was controlled by the corresponding boundaries. The software was designed so that only the boundaries pertinent to a given study are considered by the decision making structure, so the entire plot area of any study could still be addressed by a single variable.

The touch screen interface panel (fig. 9) could be used for monitoring machine status as well as for selecting the crops to be irrigated or otherwise modifying the current program in the field. The interface panel had multiple screen pages with different functions on each page. Pages were available for setting application rate, crop on/off, viewing sprinkler status, troubleshooting, GPS information, and a page where the GPS could be overridden with manual inputs for demonstration purposes. The touch panel had 14 function keys, and each one could be programmed for a different function on each page. For example, the F8 key could toggle the tillage study plots on or off on screen page 2, input a predefined longitude number for demonstration purposes on screen page 7, or turn off a block of plots on the delayed fertilizer study illustrated on screen page 9.

The interface panel also had a numeric keypad, which was used to input timer settings for different application amounts. The main timer controlled the time base for all crops. It was adjustable from 1 to 999 s, but was generally set at 60 s. Each crop or study profile had its own timer. The "on" time for each

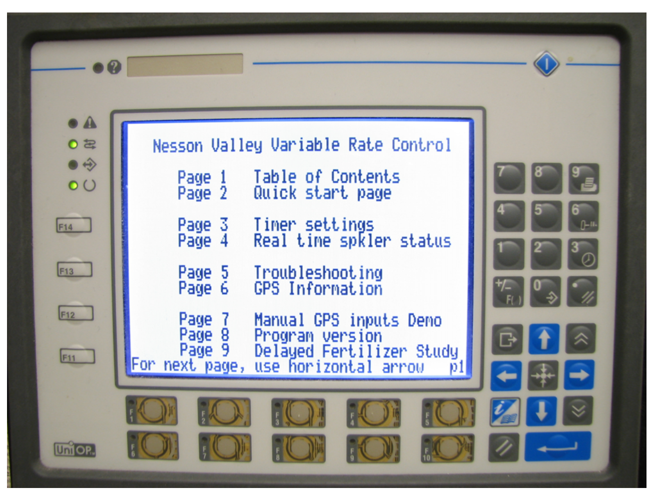


Figure 9. Photograph of the interface panel and touch screen for monitoring and manually inputting changes, if necessary.

of these timers could be inputted from the keypad in a few seconds. The ratio of "on" time to the main timer's setting determined how much water was to be applied. If the main Valley control panel for the linear move system was set to apply 3 cm (1.2 in.), and the PLC timer setting for barley was 30 s with the main PLC timer at 60 s, the amount of water applied to the barley was 1.5 cm (0.6 in.).

Results and Discussion

In general, the system has worked very well and has proven to be very dependable and easy to operate. The same basic control system, hardware and software has also been installed on four other 390-m long linear move sprinkler systems for irrigation research (MESA only) in North Dakota. Table 1 presents the cost of supplies and materials for installing the double system, but does not include labor to install or the cost of the linear move machine and associated infrastructure.

The PLC interface panel mounted on the linear has been the preferred method of parameter input by the technicians responsible for irrigating. It takes only a minute or two to toggle crops on or off and change the amount applied. Someone must be present to start the engines on the linear move irrigation systems and to prime the floating pump (or move the hose so it was convenient to input the irrigation settings in the field at this time). The page on the panel that showed the status of the sprinkler banks was a valuable troubleshooting aid because sometimes water would not be applied as specified at start-up. Knowledge of the PLC output status in the field enabled rapid isolation and correction of related problems.

Five sets of catch can tests were conducted on the MESA heads to determine the accuracy of meeting targeted application depths of either 10 or 25 mm. Various blocks of heads (15-m width) were programmed for 25%, 50%, 75%, and 100% of the targeted amount. The irrigation machine was then moved through the can sites and the data recorded. LEPA head tests did not use catch cans, but were individually measured with buckets and a stop watch to measure the applied volumes for the various programmed depths. Weather data were recorded at an antomated agricultural weather station at the edge of the field. Average wind speed ranged from 2.7 to 7 km h^{-1} during these tests. The catch can data were correlated to the programmed amount of the variable rate irrigation and, in all cases, had an r^2 value ranging from 0.94 to 0.98 (Kim et al., 2006, 2009).

Table 1. Approximate 2004 cost of the dual MESA-LEPA irrigation systems, controls and parts.[a]

Control System, Not Including Wireless	Costs ($)
Cabinet with PLC and HMI panel	6,000
Solenoids and enclosures	1,575
Air over water valves, tubing	3,950
Air compressor, lines, fittings	4,823
Wire, transformer, electrical supplies	2,383
Panel mounts, misc hardware	1,026
Total	19,757
LEPA Manifold, Drops, Heads, Piping	
Senninger quad spray with 10-psi pressure regulator	2,109
Concave quad spray pad	367
Senninger LDN cage	79
#10.5 spray nozzle	77
Barbs and hose clamps	100
3/4-in. U-pipe male × male	90
250-ft rolls of 3/4-in. drop hose	390
PVC pipe and fittings	603
Total	3,815

[a] Does not include the linear mover irrigation system and associated infrastructure costs or labor costs for installation.

System failures have mostly been associated with the pneumatically operated Bermad valves and the electronic solenoid valves, which appear to be interrelated. Failure of the Bermad valve diaphragms was the most common problem with the system. Disassembly of the failed valves usually revealed a small split in the diaphragm near the hard plastic core of the valve. Visual inspection seemed to suggest that the failures were fatigue related because the valves that cycled several hundred times a week failed at about a 2% rate, whereas the ones that only cycled a few times each week were failing at a rate of about 0.5% per year. The failure rate of the valves also increased the longer the valves were in service.

The second most common equipment malfunction was the electric solenoids. It is suspected that that the failure of these was often, though by no means always, hastened by the water introduced to the solenoid by failure of the diaphragm in a Bermad valve. When a hole developed in the diaphragm, the water would travel through the air line and exit through the solenoid vent when the system was in its default mode of no air applied to the valves. When air was applied, the air pressure was higher than the water pressure so no water would exit through the solenoid. If the system was cycling a bank of nozzles on 60-s intervals, the water in the air line combined with the rapid depressurization when the solenoid was opened would produce a cloud of mist at the solenoid vent. The introduction of dirty water to the solenoid plunger assembly with its close tolerances could cause the solenoid to become inoperable. The only other type of failure was due to an open coil.

Position of the machine in the field can be determined by low-cost GPS systems, but it could also be economically feasible to use physical passive radio tag markers in the field to give even greater precision. However, static radio tags may be damaged by field equipment or may create problems by interfering with some cultural operations.

Windows-Based Controls, a Windows-based system, was also developed for off-site control of the research plots for the site-specific sprinkler methods using a personal computer (Kim et al., 2008, 2009; Kim and Evans, 2009). The PC software evolved into a combination of a cell and boundary-based system. Cells across the plots could be different sizes. The cell size for a column of cells could be adjusted by clicking and dragging the boundary. Cells were assigned to crop specific modules so all of the cells for a given crop could be changed with one edit. For example, clicking on a cell would select LEPA, MESA, or OFF. Due to the port limitations on the PLC, either the Windows system or the interface panel could be used, but not both at the same time. The Windows-based system was also useful for logging of irrigations and monitoring machine status.

Conclusions

A site-specific irrigation system has been designed, installed, and successfully tested on a linear move sprinkler irrigation system. The PLC-based system has worked well for a 5-year period (2004-2008). The system successfully switches between MESA and LEPA irrigation methods (Sidney) as it moved down the field. Water application depths were also varied for each crop (Nesson) depending on location as determined by a GPS system at the cart. This equipment greatly increased our research flexibility and allowed researchers to address multiple experiments under the same linear move system, greatly maximizing results and utility of these expensive machines. A total of four site-specific irrigation systems based on the same general controls and equipment designs were operational and being used in the spring of 2009 with a 5th to be added in 2010. It is also important to note that the same controllers, valves and general software could easily be adapted to field scale, commercial self propelled center pivot irrigation systems.

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.

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