Development of Site-Specific Irrigation Research under Linear Move Systems
Sidney, Montana

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Abstract

An off-the-shelf PLC-based control system has been developed and field tested to enable site-specific irrigation of multiple 50 ft X 80 ft research plots using either mid-elevation spray heads (MESA) and low energy precision application (LEPA) irrigation methods on linear move sprinkler systems. Both methods were installed on one machine to cover the same areas whereas the second system varies application depths. The irrigation method alternates or applied depths can change depending on irrigation treatment for each 50 ft plot width the machines travel down the field. Electric over air-activated control valves are installed on each gooseneck for each system. The PLC controls allow the variable treatments to be used depending on location which is provided by a low cost WAAS enabled GPS system. Pneumatic cylinders lift the LEPA heads above the MESA heads when the MESA is operating over a given plot width and length.

Keywords: precision irrigation, spatial variability, pneumatic controls, sugarbeets, barley, GPS

Introduction

Competition for water with municipalities, industries, recreation, and environmental uses appears to be a globally important issue, with water conservation mandates and related litigation increasing. The implications of these pressures will necessarily result in continued refining of water conservation measures, through improved efficiency in delivery, timing of applications, and, likely, 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 an efficient manner to reduce the social as well as the economic costs of diverting or pumping water over relatively long distances. Improved technologies continue to be needed to better manage energy, water and soil resources.

Thus, new and improved strategies and practices are needed to reduce surface and groundwater contamination from agricultural lands, and sustain food production for strategic, economic, and social benefits. Innovative irrigation techniques and management systems will be necessary to increase the cost-effectiveness of crop production, reduce soil erosion, and reduce energy requirements while enhancing and sustaining crop production, the environment and water use efficiency. We believe that precision differential irrigation under self-propelled irrigation systems will be a significant part of the future toolbox for many growers.

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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. Microprocessor controlled center pivot and linear move irrigation systems also provide a unique control and sensor platform for economical and effective precision irrigated crop management. These technologies make it potentially possible to vary agrichemical and water applications to meet the specific needs of a crop in each unique zone within a field to optimize crop yield and quality goals while maintaining environmental health (reduced water and agrichemical use) and reduced leaching.

Over the past 50 years, the goal of center pivot and linear move irrigation design engineers has been to have the most uniform water application pattern possible along the entire length of the center pivot or linear move, and they have been relatively successful. Considerable yield variations still exist despite the inherent high frequency and fairly uniform applications of self-propelled center pivot and linear move irrigation systems, which are often attributed to spatial variability in soil water holding capacities and related nutrient availability. Field heterogeneity with respect to soil water holding capacity has been reported in many studies (e.g., Burden and Selim, 1989; Agbu and Olson, 1990, Mallawatantri and Mulla, 1996; Mulla et al. 1996; Evans and Han, 1994). Furthermore, the terrain under center pivot and linear move irrigation systems is often quite variable, causing runoff, channeling, and run-on, which can also profoundly affect crop stand and crop yield.

Terrain variation can also change the system pressure distribution along the lateral pipeline. Intermittent end gun operation can also cause system pressure fluctuations. System pressure changes, in turn, alter the amount of water applied as water pressure varies with applicator orientation and position in the field. While engineering solutions such as flow control nozzles or pressure regulators at each head have somewhat helped this situation, they are still not able to fully compensate for the effects of system pressure changes (Evans et al., 1995; James, 1982; Duke et al., 1997; 1998., 2000). Other factors contributing to non-uniform applications include the types, spacings, and locations of installed nozzles. These factors not only affect the amount of water applied to a given area within the field, but they also compound the problem when applying nutrients across a field. If fertigation is used or if the water supply contains significant nutrients, the nutrient distribution will also not be uniformly distributed across the field (Evans et al., 1995; Duke et al., 2000). As a result of these and other factors, considerable crop yield and leaching variation can occur throughout the field.

In the past, to improve in-season operational efficiencies on a whole-field basis, managers have resorted to practices such as manually changing sprinkler heads to match pre- and post-emergence conditions. Labor costs make this technique unreasonably expensive. For within-field variation in demand during the season, irrigators have had to vary end tower run speeds to adjust water applications. This modifies water applications to more closely meet water requirements of the field for a given angle of rotation. Until computerized center pivot panels became available, the field manager was required to either be at the controller when a speed change was needed or to use a switch at the pivot point and a second percent timer to vary the end tower speed. Now, with the use of a computerized center pivot control panel, the end tower speed can be changed based on a preprogrammed position in the field. This has greatly enhanced the ability of the field manager to apply water to meet spatially variable demand in wedge-shaped segments, but it still assumes an average demand across each wedge-shaped treatment area. Thus, areas of the field continue to be over- or under-irrigated, causing plant stress, reducing yield and quality and increasing potential for leaching water and chemicals.

Precision Irrigation

The term precision irrigation predates site-specific agriculture. Its general meaning in the irrigation industry connotes a precise amount of water applied at the correct time, but uniformly across the field (Evans et al. 2000). In this paper, precision irrigation is further defined to replace the uniformity criteria with the capacity of the irrigation system to have a spatially variable capability. To achieve such capability, an otherwise conventional irrigation machine would potentially need variable-rate sprinklers of some type, position determination (e.g., GPS), modification to the water supply delivery system to handle variable-rate water demands as well as the capability for variable-rate nutrient injection (probably), and variable-rate pesticide application (possibly).

The ability to vary water application along the main lateral of the center pivot based on position in the field allows the field 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 de-percolation and surface run off. Reducing excess water applications will decrease the potential to move nutrients past the plant root zone (King et al., 1995), and the fungal disease pressure should also decrease (Neibling and Gallian, 1997). Precision 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. Position in the field can be determined by differential GPS, electronic compasses or electronic resolvers.

The development of control and management technologies that can spatially and temporally direct the amount and frequency of water (and appropriate agrochemical) applications by “precision” self-propelled irrigation systems would be a very powerful tool that would increase productivity and minimize adverse water quality impacts. There is also a need to develop more efficient methods of applying crop amendments (e.g., nutrients, pesticides) that will reduce usage, improve profit margins and reduce environmental impacts.

Variations in precision irrigation using self-propelled center pivot and linear move irrigation machines have been started by researchers in four groups embarked on research to develop site-specific irrigation machines. These were in Ft. Collins, CO (Fraisse et al. 1992; Duke et al. 1992), Aberdeen, ID (McCann and Stark, 1993; King et al. 1995; McCann et al. 1997), Prosser, WA (Evans et al. 1996), and Florence, SC (Camp and Sadler, 1994; Sadler et al., 2002a, 2002b; Camp et al. 2002; Omary et al. 1997). The methods developed in Prosser, WA, were installed on a 3-pivot cluster in a commercial farm in south central Washington state and north central Oregon (Harting 1999; Evans and Harting, 2000).

Some recent examples of variable irrigation achieved on self-propelled irrigation systems in the last five years include: Al-Karadsheh et al. (2002), Perry et al. (2002, 2004), Perry (2003), and Klocke et al. (2003) and on fixed systems by Ohyama et al. (2005), Coates and Brown (2004), and Rodriguez-de-Miranda (2003). From these studies, three major needs are recognized: that some sort of wireless communication among the controllers is required in order to optimize the hydraulic operation of the irrigation system (Sadler and Camp, 2005c, Ohyama et al., 2005, Coates and Brown, 2004, and Rodriguez-de-Miranda, 2003); that in-field variable soil water holding capacities demand remote spatial soil moisture monitoring in specific areas within the field, thus requiring an integrated irrigation control and monitoring system (Evans et al., 2000); and critical research needs to include improved decision support systems and monitoring and feedback to irrigation control in real time (Sadler et al., 2005b). Zhang (2004) has discussed the importance of wireless sensor networks in precision irrigation control.

Early work on low-energy precision application (LEPA) in Lubbock-Halfway, TX, (Lyle and Bordovsky, 1981, 1983) was used to conduct non-spatial irrigation research on cotton (Bordovsky et al. 1992), corn (Lyle and Bordovsky, 1995) and sorghum (Bordovsky and Lyle 1996), and was extended into variable-rate irrigation (Bordovsky, 2000,Bordovsky and Lascano, 2003).

Controlling Water 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, and varying output from sprinklers depending on location in the field may be a viable option. Nevertheless, adjusting water application depths just based on soil conditions to fine-tune the water management while considering spatial variability of soils and topography can be a significant challenge.

It is possible to control every sprinkler individually, but the cost increases past the point that the system is economically feasible. On the other hand, it would be possible to increase the number of sprinklers per bank, which would decrease cost, but the control system would lose some ability to match pre-selected treatment areas. In addition, individual control of heads may not be feasible since growers can not practically manage areas less than 0.4 to 0.5 ha within a field in other cultural aspects of their operation. Since sprinklers are mounted every 2.5 to 3 m with wetted diameters ranging from 6 to 10 m or more, banks of 3 to 5 heads tends to match these practical operational limits.

Several innovative technologies have been developed to variably apply irrigation water to meet anticipated whole field management needs in precision irrigation, primarily with center pivot and lateral move irrigation systems. Most of these systems use standard, off-the- shelf equipment with much of the research effort directed towards developing the appropriate control systems. Roth and Gardner (1989) used various sized sprinklers along a lateral move to apply different depths of water as the machine moved. McCann et al. (1997) used either two or three boom systems on center pivots which used combinations of two sprinklers sized to deliver or a 0, 1/3 and 2/3 or 0, 2/5 and 3/5 of the maximum application rate to achieve a targeted application depth in an area. Omary et al (1997), Camp et al. (1998) and Sadler et al. (1996) employed a similar approach utilizing combinations of two or three sprinklers applying 0, 1/3 and 2/3 or 0, 1/7, 2/7 and 4/7 (eight steps) of the maximum application depth. King and Kincaid (1996, 2004) developed an approach based on a needle valve concept where the sizes of the nozzle orifices are modified to achieve different discharge rates on a regular irrigation spray head but it required very precise control and high quality water.

It is also possible to apply different depths by pulsing flow and varying cycle times. Other investigators have relied on pulsing individual sprinklers or several sprinkler heads on a manifold to vary the application depths (Fraisse et al., 1992; Evans et al., 1996; Duke et al., 1997,1998). For this project, we have chosen the pulsing approach because of the greater flexibility in application depths, installation simplicity and reduced costs since complicated sprinkler heads or extra sprinklers and multiple valves are not required.

Cycle time is defined as the sum of total on and off times during one pulse cycle for calculation purposes. For example, a total off time of 50 seconds out of every 250 seconds would result in an 80% of maximum application depth (this could be 5 off times of 10 seconds each or whatever other combination is desired depending on the equipment). Evans et al. (1996) used a 250 second cycle time with rotator heads whereas Duke et al. (1998) and Harting (1999) used a 60 second cycle time with spray heads. We are also using a 60 second cycle time in this project, though our software allows us to easily change the cycle time if we need to make changes..

We are utilizing the site-specific implementation of a pulsed system on an artificially imposed spatial variability, such as a field of small research plots in which there are a mix of crops and a prescribed set of water management experiments. Application of these technologies over the top of natural variability is certainly more complicated and more demanding than general site specific field irrigation. Our water management treatments vary either irrigation method or depth water applications as the machine moves through the field. The objective of this paper is to describe the design, installation and testing of a site-specific irrigation system at the USDA-ARS, Northern Plains Agricultural Research Laboratory in Sidney, Montana.

The Sidney Site-Specific Irrigation System

An irrigated sugarbeet-barley crop rotation and tillage research study by irrigation method (LEPA vs MESA) was established near Sidney, MT under an 800 ft linear move irrigation system in 2004. The focus of the project is to assess the environmental impacts of cultural practices and improved management of water, nutrient and chemical applications. This is part of a multi-year team project involving several scientists from ARS and Montana State University. The soils in the field were grid sampled and analyzed for various physical and chemical characteristics prior to the initiation of the project.

The nine acre field is laid out in 14 strips in the direction of travel. Each strip is planted either to sugar beets or malting barley, which alternates from year to year. There are a total of 56 plots with the individual plots being 50 ft wide and 80 ft long including buffers. Each strip is divided into four plots with two plots being irrigated with MESA and two with LEPA that are blocked by replication. Water is applied to meet the calculated ET_a of each crop strip (backed up with soil moisture readings) using data from a nearby weather station. Equivalent depths of water are applied for both irrigation methods. Sugar beets are on 24 inch rows and the malting barley is on 8 inch row spacing.

Figure 1. Precison irrigatton system at Sidney, 2005.

We are using a Valley[4] (six tower system including the cart) diesel machine with an electrical generator set (480 v, 3 phase) on the cart that provides power for the tower motors, cart motors and the pump. A buried wire alignment system is used with the antennas located in the middle of the machine. The linear move machine uses a screened floating pump intake in a level ditch as its water supply. Nominal operating pressure is about 36 psi. Two double direction boom backs are installed at each of the towers (although not at the cart). Spans are 160 ft in length except for the center span with the guidance system which is a 156 foot span. The machine moves at about 7 ft/min at the100% setting.

A Valley CAMS Pro control panel is used to turn the machine on or off and control machine ground speed. A separate controller, described later, was designed and fabricated to control the precision water applications including irrigation method (and water application depths.)

The Nesson Valley Precision Site-Specific Irrigation System

While not the main topic of this paper, a second PLC control system has also been installed on a 1300 foot (366 m) buried wire-guided Valley linear move irrigation system (160 ft spans except for 156 ft center span and overhangs at both ends). This machine was installed on about 40 acres (16 ha) of the he new North Dakota State University farm in the Nesson Valley area, about 30 km

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[4] Mention of product names or company names is for informational purposes only and does not imply any endorsement by the USDA, Agricultural Research Service over products not mentioned.

east of Williston, ND near the Missouri River. Water is supplied either from a well or from the river. The site-specific irrigation control system is similar to the Sidney system except that it is being used to evaluate irrigation frequency effects on sugarbeet-potato-barley rotations using only MESA heads on a 60 inch (1.5m) spacing. Water depth is varied by plot during the season to match the respective crop ET as the machines moves down the field.

There are three separate sets of experiments under this machine that all irrigated differentially. The differing irrigation requirements of all of the plots can be met by inputting the required information in the control panel. The irrigation frequency study consists of 72 plots (each 50ft x 80 ft) arranged in a 4 x 18 matrix on a potato, sugarbeet and malting barley rotation. These plots are irrigated on two different frequencies (approximatelyg1 in or 2 inch ET_a replacement). Each of the 18 strips has two of the three crops and each crop is irrigated to match its respective ET_a throughout the season. We also apply nitrogen fertilizer to the beets and potatoes through the system.

To the south of the irrigation frequency study, there are 6 groups of replicated soil quality study plots, which requires half of them to be irrigated and half non-irrigated. To the west of the irrigation frequency set of plots is a barley phosphorus study that extended nearly the length of the linear. All of the plots in each of the three experiments are irrigated with a single pass of the linear move.

Figure 2. Nesson Valley research site, 2005

Positioning System

At both locations, we are using a WAAS enabled Garmin 17HVS GPS with a DGPS positional accuracy of <3 meters, 95% of the time. It is located at the cart for determining and tracking machine position as it moves across the plots, The GPS readings are used to switch between either the LEPA or MESA treatments (Sidney) or to differentially apply water to the different crops (Nesson) depending on treatments.

Sprinkler arrangement-Sidney

MESA sprinkler heads are spaced every 10 ft with Nelson S3000 spinner (#31 nozzles) with 15 psi regulators. These heads are about 42 inches above the ground on flexible drops with 1 lb weights below each regulator.

Figure 3. Valve arrangement, control wires and pneumatic tubing on the Sidney system for both the spray heads and LEPA application methods.

The LEPA system uses Senninger Quad-Spray® heads with 10 psi regulators (#10 nozzles) and sliding 2 lb weights above each regulator. The drops are spaced every 48 inches along submanifolds suspended from the truss rods. The bottom Quad-Sprays are about 6 inches above the furrow surface.

Sprinkler arrangement-Nesson

MESA heads are spaced every 5 ft using Senninger LDN (#12 nozzles) with 10 psi regulators. The nozzles are about 42 inches above the ground on flexible drops with 2 lb weights above each regulator.

Figure 4. Valve arrangement , control wires and pneumatic tubing layout for the Nesson precision irrigation system.

Lifting Mechanism for the LEPA Heads (Sidney). A system of pneumatically operated cylinders have been designed and tested to lift the LEPA heads above the MESA heads when the MESA treatments are operating. This serves to minimize interference with the MESA spray patterns as well as keep the LEPA heads out of the canopy. When air is applied to solenoid valves (turning them off) on the LEPA manifolds, the cylinders are activated, lifting the LEPA heads.

The 4 foot long pneumatic cylinders have been built out of 2.5 inch aluminum sprinkler tubing. End plates with O-rings were fabricated and installed at each end. The 5 foot plunger rod is 0.5 inch stainless steel and is threaded into a piston machined from acetal. The cylinders are attached to the truss and are hooked to a series of cables and pulleys that lift the LEPA heads. This lifting system was designed in Spring 2005 but was not installed and tested until Fall 2005.

PLC Control System Development

Both the Sidney and Nesson Valley systems utilize the same basic control and valve systems, which are off the shelf components throughout. The PLC controller (Siemens 226 with 3 relay expansion modules) activates electric solenoids (ASCO U8325B1V, 24 volt, 6.9 watt) to control banks of sprinklers or LEPA heads. The ASCO valve, in turn, activates a pneumatic system to close normally-open, ¾-inch plastic globe valves (Bermad, model 205). In the case of the MESA heads, the Bermad valves are located on the gooseneck above each drop to each head in groups of five (at Sidney) or ten (at Nesson). The air-activated Bermad valves are located on three goosenecks that supply water to the submanifolds for the LEPA heads. The ASCO valves were grouped into clusters of six valves and placed on a weather tight plastic enclosure at each tower and the cart. One-quarter inch tubing connects the ASCO valve to the respective grouped Bermad valves. Normally open valves were used on the heads since the failure mode would leave the sprinklers on, however, this also increased the risk with the dual system at Sidney since both the MESA and LEPA heads would be on if the air system failed (although we would probably get a low pressure cutoff at the pump shut the machine down in that case.)

Air was used as the control fluid in both systems since air was much cleaner than the irrigation water from surface supplies, and eliminated foreign material in the water supply from plugging the 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 is eventually vented to the atmosphere through the normal operation. A 1 HP, 3 phase, 480 volt air compressor was located at each cart for easy maintenance with a 3/8 inch line running the length of machine. Air reservoirs were located at each tower to ensure rapid and uniform valve operation.

The wiring cabinets for the PLC and add-ons were custom built (about $6K) using 36 inch steel, water proof enclosures (Figure 1). The software for the PLC and an operator interface panel (UniOp BKDR-16-0045) provides a means to control and monitor the PLC without the need for a laptop computer. The panel’s LCD screen displays 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 if a crop or study area will be irrigated. The interface panel is also used to input timer settings that determine the application rate for each crop or study area, turn off the irrigation for a particular crop or study area, or manually override the GPS unit for demonstration or troubleshooting purposes. The layout of the physical addressing used in the Sidney project is shown in Figure 6.

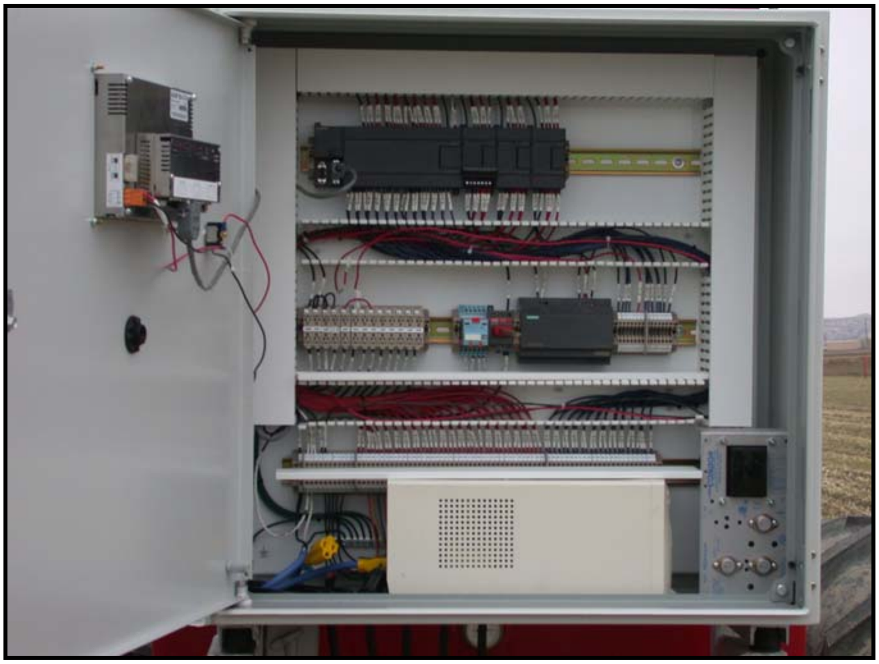

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Figure 5. Photograph of the interior of the wiring cabinet showing the PLC, power supplies, wiring and front interface panel.

Future Directions

One way to achieve the desired level of control would be the use of real-time soil water and micrometeorological sensors distributed across a field for continuously re-calibrating various decision-making model parameters during irrigation events. This type of integrated feedback is necessary because of the tremendous complexities and time constraints involved in solving real-time 3-dimensional modeling of the systems. Simplified assumptions may be used to increase computational speed and the predictive decision support models do not have the opportunity to drift very far from actual conditions since operating parameters are frequently re-initialized and the models rerun from more accurate baselines. Coupling real-time micro-weather stations, plant-based sensors (e.g., fixed canopy level reflectance, infrared temperature or video) and numerous real-time soil water sensors scattered around the field at critical locations with a set of good predictive models into a decision support system also minimizes the need for continuous and expensive agronomic oversight. Assessment of the environmental impacts of best management or “normal” irrigation practices from the integrated set of models in this configuration with real-time feedback will be more realistic and acceptable to both producers and regulators.

We are working on the use of distributed instrumentation (strategically placed, real-time soil water and micro-meteorological sensors distributed or moving across a field to provide continuous feedback) tied to control systems for spatially-varied water applications (using wireless communications technologies). We believe that a synergistic mix of remote sensing and on-the-go within field sensing of soil and plant status can decrease water and energy use through better timing of inputs for water, nutrient and pest management.

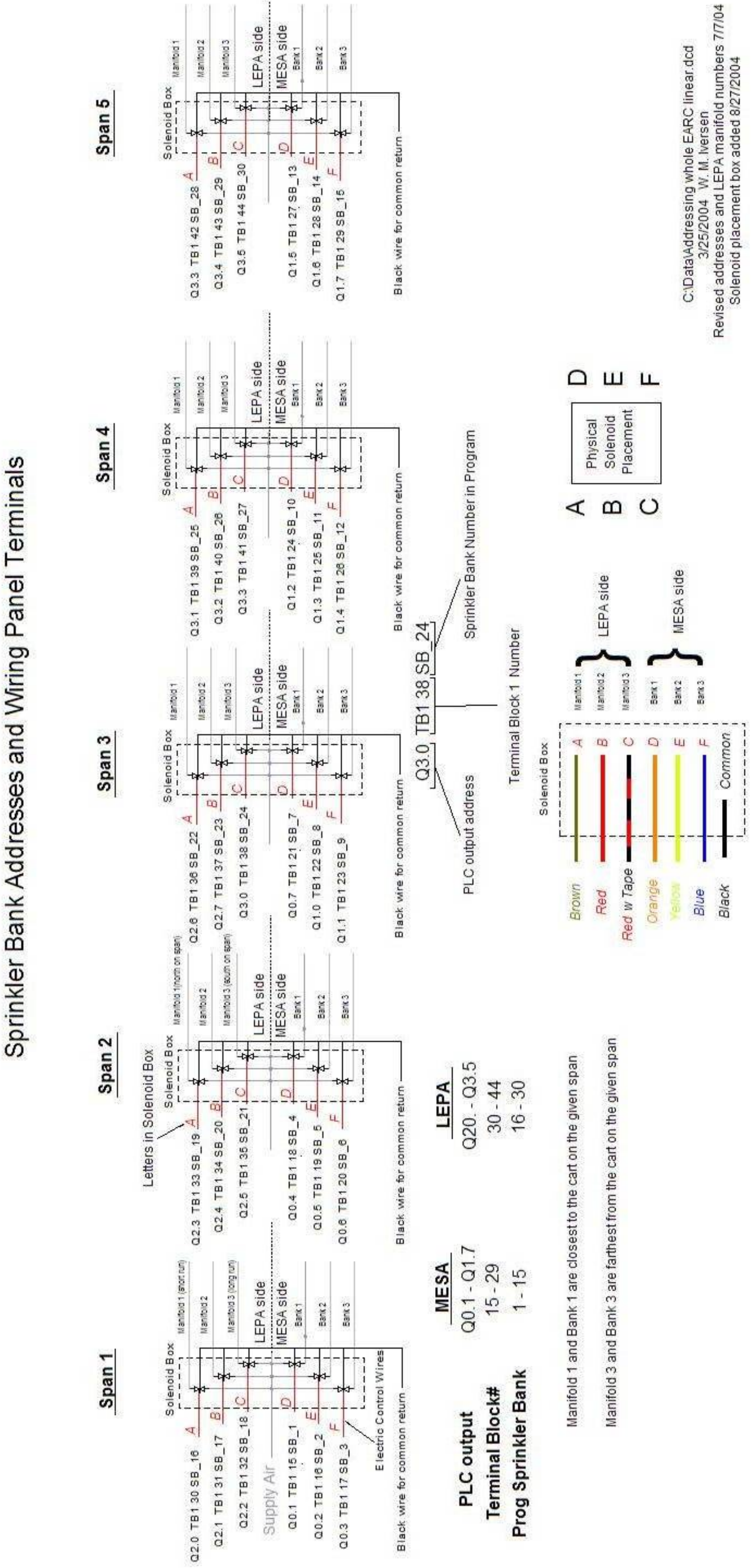

Figure 6. Addressing system used for each span of the Sidney linear move irrigation experiment.

Ultimately, because of the vagaries of “real” field conditions, we will probably need to use strategically placed, real-time soil water and micro-meteorological sensors distributed or moving across a field to provide continuous feedback to re-calibrate and check various model parameters in a decision support framework. There is a real need to improve procedures so that the fewest number of various soil water sensors and sensor systems would be placed for maximum impact to improve water quality.

Conclusions

A precision site-specific irrigation system has been designed, installed and tested on a linear move irrigation system. The PLC-based system has worked for two years (2004-2005). The system successfully switches between MESA and LEPA irrigation methods (Sidney) as it moves down the field. Water application depths can also be varied for each crop (Nesson) depending on location as determined by a GPS system at the cart. Position can be determined by low cost GPS systems but it may also be economically feasible to use physical passive radio tag markers in the field to give even greater precision. This equipment greatly increases our research flexibility and allows us to address multiple experiments under the same machine, greatly maximizing results and utility of these expensive machines.

This project shows it is possible to economically 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 capabilities. The ability to vary water application along the main lateral of the linear move based on position in the field allows the 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.

It should also be mentioned that both the Sidney and Nesson Valley projects are also developing and evaluating minimum tillage practices suitable for self-propelled irrigation systems on these rotations to reduce energy (e.g., tractor fuel) costs and improve soil quality.

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