Capabilities of a Center Pivot Irrigation System for Precision Management of Water and Nutrients

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ABSTRACT

Research suggests that spatial yield variability for the southeastern Coastal Plain may be caused primarily by water relations. This causes difficulties in scheduling irrigation for conventional center pivot irrigation systems, which are not capable of applying variable depths of water to small areas of variation within the total system. Thus, the objectives of this work were to design and construct a site-specific center pivot irrigation system that could independently apply variable rates of water and chemicals to 900-ft^2 areas within the irrigation system. A commercial center pivot system was modified by adding three 30-ft manifolds in each of 13 segments along the truss. Nozzles were spaced 5 ft apart along each manifold, and both manifolds and nozzles were sized to provide 1/7, 2/7, and 4/7 of a base application depth at a given tower speed. All combinations of the three manifolds provided eight depths (from 0 to 0.5 in. in 0.07-in. increments) when the outer tower traveled at 50% of full speed. A programmable, computer-controlled management system obtained the positional data from the center pivot controller and switched the appropriate valves to obtain the application rate desired. During 1995-97, the system applied water and N fertilizer in a fixed-boundary field experiment. Initial measurements and observations of water and N-fertilizer application uniformities were acceptable. A second center pivot system is being modified for site-specific water, nutrient, and pesticide management on a field with soil variation (irregular boundaries) typical of the Coastal Plain.

INTRODUCTION

The coarse-textured soils of the southeastern Coastal Plain are often quite variable with a nearly level, sandy surface and a sandy clay subsoil. The landscape includes numerous shallow depressions of variable size, where the soils are sandy loam or loamy sand with extensive inclusions of sands. In these depressions, surface texture is generally finer than that outside. Many of the soils have compacted layers, which restrict root growth to very shallow depths (12 to 18 in.) and limit soil volume available for water removal by plants. The low water-holding capacity and root-restricting layers combine to reduce plant-available water storage.

The climate is humid and subtropical, and it has a mean frost-free growing season of about 250 days. Average annual rainfall in Florence, S.C., is 43 in./yr and normally exceeds crop requirements, but rainfall is often poorly distributed during the year and growing season. Mean monthly rainfall during the growing season is about 5 in./mon, but can vary from lows of about 0.8 in. to highs of

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about 10 in. The combination of high rainfall variability and low water-holding capacity in soils creates a complex management scenario, which results in frequent yield-reducing crop stress in a region that appears to have sufficient rainfall.

Based on observations of spatial patterns in crop growth, the major factor contributing to yield variability for soils in the Coastal Plain appears to be plant-available soil water (Sadler et al., 1995). Results from a study that investigated crop yield for 14 crops during an 11-year period found no useful correlation between yield and several patterns of variation, including soil classification and fertility. Because of the combined effect of climate and soil variability and the uniform application rates of most center pivot irrigation systems, optimum management of irrigation and nutrients applied via an irrigation system is often not possible, even for relatively small systems (Camp et al., 1988).

Consequently, in 1991, a Florence ARS team developed specifications for a computer-controlled, variable-rate center pivot system (Camp and Sadler, 1994). Other research groups have worked independently toward similar goals, including Lyle and Bordovsky (1981, 1983), Roth and Gardner (1989), Duke et al. (1992), Fraisse et al. (1992), and King et al. (1995). The objectives of this paper are to describe the variable-rate center pivot irrigation system developed at Florence and to illustrate its capabilities for application in site-specific management of water and chemicals.

MATERIALS AND METHODS

Two small, three-span, commercial center pivots were purchased in 1993 (Valmont Industries, Inc., Valley, Neb.). Each was 450 ft long and provided an irrigated area of 14 acres. The systems were standard commercial systems except for oversized truss rods to increase the truss load capacity and oversized ports in the system pipe to supply water to individual manifold segments. Both systems also included computer management control systems that could be programmed and controlled either locally or from a remote base station.

The variable-rate water application system was designed, constructed, and installed on Center Pivot 1 (CP1) in cooperation with Coastal Plain Experiment Station, University of Georgia, Tifton, Ga. The center pivot length was divided into 13 segments, each 30 ft long, starting with the outer tower. Each segment had three parallel, 30-ft manifolds, each with six industrial spray nozzles spaced 5 ft apart, and all were 10 ft above the ground surface. Water was supplied to each set of three manifolds (one segment) from the system pipe via 2-in.-diameter ports, distribution manifolds, and drop hoses. Each manifold had a solenoid valve to control flow, a pressure regulator, a vacuum breaker, and a low pressure drain. The three manifolds and nozzles were sized to provide 1/7, 2/7, and 4/7 of a base application depth. All combinations of the three manifolds provided 0, 1/7, 2/7, 3/7, ...7/7 (or 100%) of the base depth, which was 0.5 in. when the outer tower was operated at 50% duty cycle. Additional details regarding construction, evaluation, and operation of this variable-rate application system were reported by Omary et al. (1997). When applying N fertilizer, flexible tubes were attached around each nozzle to deliver water near the ground surface.

The variable-rate application system was controlled by an 80386 PC (Horner Electric, Indianapolis, Ind.) with hard disk drive, floppy drive, serial ports, and peripheral connectors, which was mounted on the programmable logic controller (PLC) backplane (GE Fanuc model 90-30, Charlottesville, Va.)

and connected via the system buss. The PLC was mounted on the mobile portion of the system about 15 ft from the pivot. It controlled all manifold solenoids. Angular location of the truss was obtained from the C:A:M:S™ (Valmont Industries, Inc., Valley, Neb.) management system via short-range, radio-frequency modems (900 MHZ, spread-spectrum modems; Comrad Corp., Indianapolis, Ind.) between the mobile PC and the stationary management system.

The PC controlled the PLC using custom software. Based on both stored and continuously-collected positional data, the PC signaled the PLC to switch on the appropriate solenoids to provide the desired application depth within each field element. If one of several system variables (pressure, flow rate, position, voltage, etc.) was reported as out of the specified range, the PLC controller closed all solenoid valves and stopped the center pivot drive system. The problem was recorded to a log file for user information. Additional details regarding the control system and overall center pivot operation were reported by Camp et al. (1997).

The nutrient injection system on the modified center pivot system is based on the principle of maintaining a constant nutrient concentration in the water supply line. Therefore, variable nutrient application amounts can be applied to each segment by varying the water application depth. Because water flow rate varies frequently, depending upon the number of solenoids switched on at any time, the nutrient injection rate must vary with water flow rate to achieve constant nutrient concentration. This was achieved with a variable-rate, four-head injection pump (Ozawa R & D, Inc. model 40320, Ontario, Oreg.) located at the pivot center. Nitrogen fertilizer solution from an adjacent storage tank was injected into the pivot water supply pipe. The injection rate was varied by the number of pump heads in use and the pump speed, which was controlled by adjusting the 0-5 VDC signal sent to the pump controller. To keep the nutrient concentration constant, the on-board PC calculated the water flow rate, calculated the required nutrient injection rate, computed the 0-5 DC voltage setting required to provide the required injection rate, and reported it to either the operator or the PLC controller. In 1995 and 1996, fertilizer injection was controlled by the operator manually entering voltage values in a CR7 data logger/controller (Campbell Scientific Inc., Logan, Utah). In 1997, the 0-5 VDC value was transmitted directly from the on-board computer to the pump controller via the PLC control system. The nutrient injection system was used to apply all sidedress N [urea ammonium nitrate (UAN 24S)] for corn during the 1995-97 growing seasons. The spatially-variable nutrient applications were accomplished using a minimum-depth, spatially-variable water application.

The modified center pivot system (CP1) was sited on a relatively uniform soil area. Because of the relatively good soil uniformity, a traditional field experiment with fixed plot boundaries was selected for fine-tuning the technology under more controlled conditions than the highly variable soil conditions where CP2 was sited. Treatments included were three rotations (corn-corn, corn-soybean, and soybean-corn), two tillage practices (subsoiled and not subsoiled), three water managements (rainfed, tensiometer-controlled and crop-stress-controlled irrigation), two nitrogen regimes (single sidedress and multiple sidedress), and four replications, which provided a total of 144 plots. All rows were planted, and all subsequent operations were performed in a circular pattern that coincided with the travel pattern of the center pivot system. Individual plots were established in a regular 7.5° by 30-ft pattern, which made the minimum plot length 30 ft in segment 8, and 45 ft in segment 13.

Water distribution uniformity was measured when a target rate of 0.28 in. (2/7-base-depth manifold at 25% full speed) was applied to a single element (30 by 30 ft) surrounded on all adjacent sides with elements that had no irrigation. Water was collected in 50 cups spaced 1 ft apart on the soil surface along a system radius. Water was also collected in 50 cups placed along the travel pathway (tangential to the circle), alternatively in either of two lines, one under a nozzle and one midway between nozzles, so that they were spaced 2 ft apart within each line. Water volume was measured and the depth calculated from cup diameter. For the tangential test, the manifolds were switched on when the manifolds reached the cup at 10 ft and switched off when they reached the cup at 40 ft, providing an on-cycle travel distance of 30 ft. Each test was repeated three times. Uniformity coefficient (UC), as defined by Christiansen (1942), was calculated for each test using the measured water depths for appropriate zones.

N-fertilizer application uniformity was measured in 1997 for a single element (30 by 30 ft) at the same time as water application uniformity was being measured. After water volume in each container was measured, a small water sample was collected from cups spaced 3 ft apart. These samples were analyzed in the laboratory for nitrate and ammonia using colorimetric methods (Technicon Instrument Corp., Tarrytown, NY). The N-fertilizer (UAN 24S) contained three forms of nitrogen (ammonia, nitrate, and urea), but the samples were analyzed for only ammonia and nitrate. By assuming the concentration ratio of the three sources remains constant for a given batch of UAN 24S during the irrigation application, the urea concentration in the water sample can be calculated from the two measured values.

RESULTS AND DISCUSSION

A commercial center pivot irrigation system was converted to a site-specific center pivot irrigation system by installation of a three-manifold, multiple-segment water application system, a PC-based PLC control system, and control software. The control software evolved during the 1995 growing season through experience and modification so that by the end of the season, the system operated unattended, except for monitoring via the remote C:A:M:S™ base station. Improvements in radio communication reliability between the moving and stationary components during the 1996 growing season made system operation even more reliable. Acceptable application uniformity within control elements and expected border effects between elements with different application depths had been measured previously (Omary et al., 1997). Observations during the 1995-97 seasons indicated that the border width was not different from that measured previously. Water ponding and surface redistribution had been a concern during design, because of the relatively high instantaneous application rates caused by the small wetted diameter of the industrial spray nozzle. However, even when nozzle discharge was collected in a 1.5-in.-diameter flexible hose and discharged near the ground surface during N-fertilizer application, excessive local ponding and runoff did not occur.

Water application depths (mean of three tests) along a radius under a single segment operating alone are shown in figure 1. As expected from individual nozzle tests (Omary et al., 1997), the spray pattern and drift caused an area about 10 ft on either side of the segment length (30 ft) to be irrigated at depths less than the target depth of 0.28 in. Water depths were more uniform within the control zone (center 20 ft of segment) and much closer to the target depth. Uniformity coefficients for the control zone ranged from 87.0 to 92.6 for the three tests. Considerable variance among the three

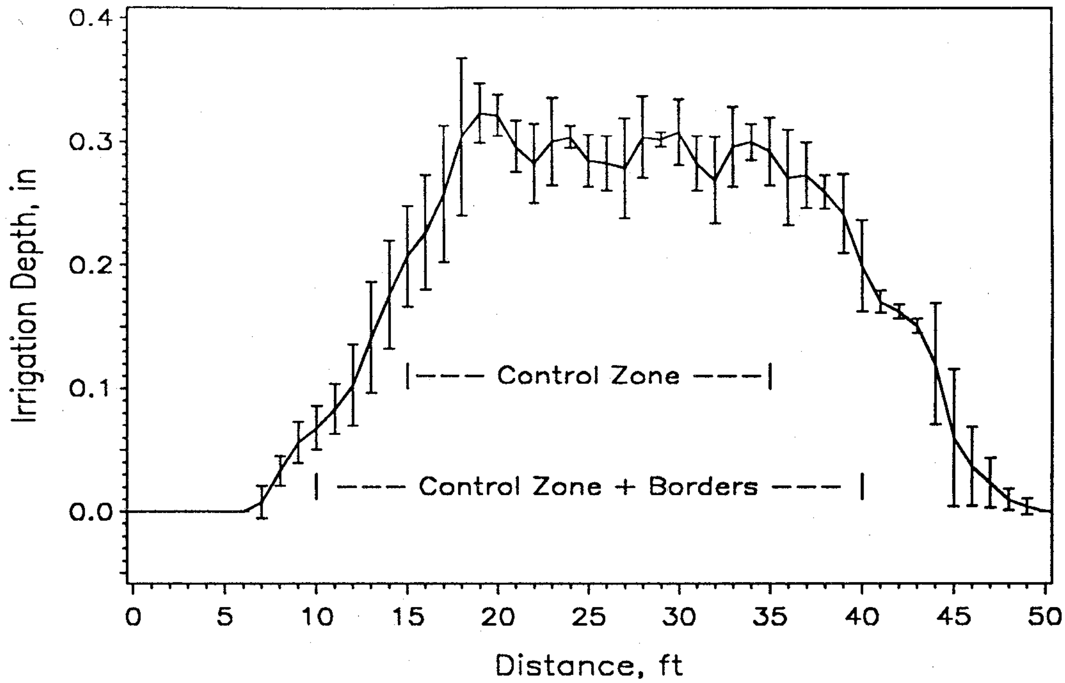

Figure 1. Water depth distribution along a system radius for segment 11 with one 30-ft manifold operating and cycle timer at 25% (2/7 or 0.28-in. target depth). Each data point is the mean of three measurements, with error bars indicating one standard deviation.

tests, caused primarily by wind variations, is reflected by the standard deviation bars (fig. 1). In a previous evaluation of another segment, uniformity coefficients ranged from 89.0 to 90.8 for three tests (Camp et al., 1997). In that study, the effect of having segments on either side irrigating at the same rate was simulated by adding appropriate measured water depths to those for the segment being evaluated. Mean UC values for three tests were essentially equal (91.8 - 92.2) for zone widths of 20, 30, and 50 ft, which correspond to the control zone, control zone plus borders, and full measurement area, respectively. This indicates good uniformity for the entire width when all segments are applying the same depth.

Water application depths (mean of three tests) along a line tangent to the circle (direction of travel) under a single segment operating alone are shown in figure 2. The variance, as indicated by the standard deviation bars, and uniformity within the control zone (20 ft) were similar to that for the radial case. Again, the primary reason for the variance was wind. Uniformity coefficient values for the control zone in the tangential case ranged from 88.8 to 94.7 for the three tests. In a previous evaluation of another segment, uniformity coefficients ranged from 89.3 to 92.0 for three tests (Camp et al., 1997).

Sidedress N-fertilizer applications to field research plots were made using the 2/7 manifold, which delivered 0.28 in. water at 25% duty cycle, 0.14 in. at 50%, and 0.07 in. at 100%. Nitrate concentration of the samples collected during one test of water uniformity in 1997 were 169 and 163

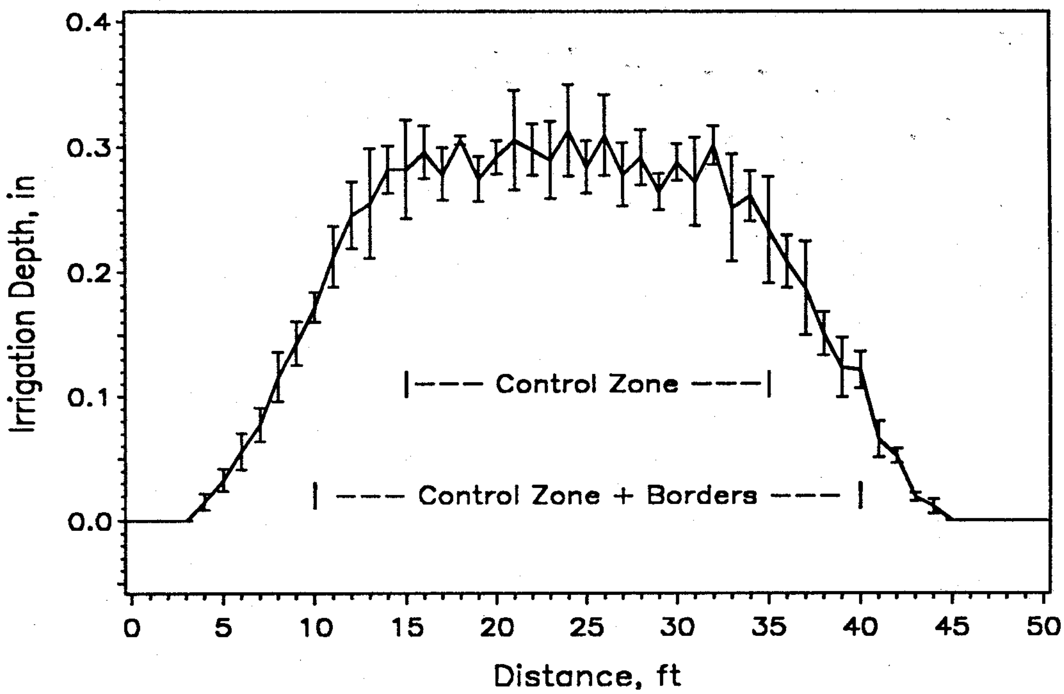

Figure 2. Water depth distribution along a system tangent for segment 11 with one 30-ft manifold operating and cycle timer at 25% (2/7 or 0.28-in. target depth). Each data point is the mean of three measurements, with error bars indicating one standard deviation.

ppm for the radial and tangential directions, respectively, with standard deviation values of 3.1 and 81.2 ppm and coefficient of variation values of 2.5% and 34.6%, respectively. While the mean nitrate concentrations were similar for the two directions, variation was much greater for the tangential direction. Variations in tangential nitrate concentration values were probably caused by temporal concentration variations within the water supply and spatial effects, while variations in radial values were caused primarily by spatial effects. Nitrate concentrations measured in 1995 by collecting full discharge from randomly selected nozzles when applying N fertilizer to field plots on each of two dates were 244 and 270 ppm, respectively, with standard deviation values of 17.8 and 13.6 ppm (Camp et al., 1997). These values indicate relatively uniform nitrate concentrations among the nozzles sampled, both in space and time after manifold pressurization. Further testing will be required before conclusions can be reached.

A prototype pesticide application system developed by Valmont Industries, Inc. has been modified and installed on CP1. This system operates independently of the water application system, using the center pivot only as a transport vehicle. Application uniformity of this system will be evaluated in 1997. Center Pivot 2, sited on highly-variable soils typical of many southeastern Coastal Plain fields, is currently being modified using the same water application and control systems used on CP1. A similar pesticide application system will be installed on CP2. When completed, CP2 will represent full implementation of variable-rate management of water, nutrients, and pesticides for small areas of variation with irregular boundaries, which reflect the conditions found in a typical, highly-variable Coastal Plain field.

The management software will also be modified to approximate irregular soil unit boundaries with a series of fixed-boundary areas of variable width (angular direction) and to optimize water and chemical applications for each segment in relation to the location of each soil unit. Infrared thermometers have been mounted on both center pivot systems to provide real-time or near-real-time feedback of crop conditions. They may also be used for mapping soil variation. Generally, these sensors should allow improvement in crop management and detection of dynamic crop variation during the season.

SUMMARY AND CONCLUSIONS

Modifications to a commercial center pivot irrigation system produced a system that provides site-specific, variable-rate applications of water and nutrients. The system has 13 segments, each 30 ft in length, along the truss, which allow variable application rates of water and nutrients to control areas of about 900-ft^2. Seven different depths can be applied independently within each segment. Based on stored and measured data, a programmable, computer-controlled management system opens the appropriate valves to obtain the desired application rates for specific areas. Water and nitrogen applications to a fixed-boundary field experiment were successfully accomplished during 1995-97. Measured water and N-fertilizer application uniformities indicate acceptable system performance. However, more extensive evaluation of the water, nutrient, and pesticide application systems will be required before definitive conclusions can be reached with regard to system performance. An IRT system should provide useful information for crop stress and soil mapping and feedback for near-real-time management of water and chemicals. A second commercial center pivot irrigation system is being modified for site-specific water, nutrient, and pesticide management on a site with variation (irregular boundaries) typical of Coastal Plain fields.

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