Precision Management with a Site-Specific Center Pivot Irrigation System

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Abstract

Interest in site-specific management of crop inputs such as water and fertilizers has increased during the past few years, primarily because of the availability of yield monitors, which permit farmers to directly observe the effect of varying inputs on crop yield. A commercial center pivot irrigation system was modified in 1995 to provide site-specific water and fertilizer applications to areas as small as 100 m^2. The modified system was used to manage applications during 1995-1998 while the reliability of the control system was improved. A second center pivot, located on a site with widely variable soils, was modified in a similar manner in 1998. In 1999, both modified systems were used to determine the effects of a range of water and N fertilizer application rates on corn growth and yield. Measured soil water values indicate good spatial accuracy in delivery of water applications, good uniformity within the management zones, and a distinct range of soil water contents resulting from various irrigation application rates. Once crop production effects of variable inputs, soils, and economic factors have been determined, site-specific irrigation and N-fertilizer combinations can be developed for soil management zones.

Introduction

The development of global positioning systems with improved spatial resolution and the development of crop yield monitors on harvesting equipment has allowed crop yield mapping that permits the identification of meaningful yield patterns that may be related to numerous agronomic, hydrologic, and climatic factors. These advances have led to further developments for variable-rate application technologies to apply nutrients and agro-chemicals that permit site-specific management. Interest in precision management of water and agricultural chemicals, separately and together, has increased with these developments. Effects of variable water and chemical inputs can now be measured directly by the farmer.

Precision application of fertilizers has been accomplished during recent years using ground-driven applicators, but within a given system, most irrigation is still being applied uniformly. Some commercial traveling irrigation systems (e.g., center pivots) have programmable management systems, which allow variable application rates for sectors by changing the travel speed. To provide dynamic control of water and chemical applications, smaller areas both along the

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traveling section and in the direction of travel must be capable of variable-rate applications and must be adaptable to areas with arbitrary boundaries.

There are several techniques for varying water and chemical application rates via sprinklers and nozzles, but the two most common methods are changes in orifice size and time-based pulsing of water flow. Dynamic changes in flow using orifice size are typically accomplished in a step-wise rather than continuous fashion by switching several sprinklers at a single location, each with a different application rate (McCann and Stark, 1993), or by switching several manifolds, each with a set of sprinklers that provide a different application rate (Roth and Gardner, 1989; Lyle [W. M. Lyle, 1992, personal communication]). King and Kincaid (1996) and King et al. (1997) obtained a more continuous range of application rates by partially inserting and removing a pin into the sprinkler orifice to reduce flow to a minimum of 40%. This provided a time-averaged application rate ranging from about 40 to 100% of maximum flow.

Various application rates through sprinklers and nozzles can be achieved in a more continuous manner by pulsing the water flow, either for individual sprinklers or for a manifold with several sprinklers or nozzles. In this case, the flow rate is determined by the characteristics of the valve, pump, or meter device controlling the pulsing and its rate of operation. Duke et al. (1992) and Fraisse et al. (1992) used this technique to provide variable water and nutrient applications on a linear irrigation system. Sprinklers were mounted on discrete manifolds (21 m in length) along the support truss, and the application rate was determined by the rate at which each manifold was pulsed via switching solenoid valves on and off.

The size of the desired management area can vary widely, depending upon topography, soil properties, and crop variability. For example, Southeastern Coastal Plain soils are often variable, even within small fields. These soils are characterized by a nearly level, sandy surface and a sandy clay subsoil. The landscape includes small depressions of various sizes, where the soil has extensive inclusions of sands and the surface soil texture is generally finer than outside the depression. Many of the soils have compacted layers, which constrain crop rooting depth and limit soil water volume available for uptake by plants. The low water storage and restricted crop rooting combine to severely reduce plant-available water storage. Based on previous studies of spatial patterns of crop growth and yield, water availability appears to be the major factor contributing to yield variability in the Coastal Plain (Karlen et al., 1990; Sadler et al., 1995a; 1995b).

To address this problem, plans were initiated in 1991 to develop a computer-controlled, variable-rate center-pivot irrigation system at the ARS laboratory in Florence, SC. Two commercial center-pivot systems were purchased in 1993 and were modified to allow variable-rate water applications. These systems have been evaluated and improved in the intervening period while being used to manage water and nutrient applications for fixed-boundary experimental plots. The objectives of this paper are to briefly describe the variable-rate center pivot irrigation system developed at Florence and to illustrate its capabilities for precision management of water and chemicals.

System Description

Two small, three-span, commercial center pivots were purchased in 1993 (Valmont Industries, Inc., Valley, NE[2]). Each system was 137 m long and provided an irrigated area of 5.8 ha. Both systems included computer management control systems that could be programmed and controlled either locally or from a remote base station.

One system (CP1) was modified in 1995 for testing and further development. To fine tune the site-specific management technology, a traditional field experiment with fixed 7.5° by 9.1-m plot boundaries was implemented on CP1, which was sited on a relatively uniform soil area. The second system (CP2) was modified in 1998 with a water and nutrient application system similar to that used for CP1. CP2 was sited on a highly variable soil area that reflects the conditions found in a typical, highly-variable Coastal Plain field.

The variable-rate water application system on both systems consisted of 13 segments along the truss, each 9.1 m long, ending on the outer tower. Each segment had three parallel, 9.1-m manifolds with six industrial spray nozzles spaced 1.5 m apart and 3 m above the ground surface. For each segment, water was supplied to each set of three manifolds from the system pipe via 5-cm-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 12.7 mm when the outer tower was operated at 50% duty cycle. Manifolds, nozzles, and controls for one segment are illustrated in Figure 1. Additional details regarding construction, evaluation, and operation of this variable-rate application system were reported by Omary et al. (1997).

Nutrient Delivery System. The nutrient application system was based on the principle of maintaining a constant nutrient concentration in the water supply line and varying nutrient application amounts to each segment by varying the water application depth. This required nutrient injection into the water supply in proportion to the flow rate, which was achieved with a variable-rate, four-head injection pump (Ozawa R & D, Inc. model 40320, Ontario, OR) located at the pivot center. The on-board PC calculated the injection rate based on water flow rate and transmitted the appropriate control signal to the pump.

Control System. The variable-rate application system was controlled by a computer, 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 5 m from the pivot center, from which it controlled all manifold

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[2] Mention of trademark, proprietary product, or vendor does not constitute a guarantee or warranty of the product by the U.S. Department of Agriculture and does not imply its approval to the exclusion of other products or vendors that may also be suitable.

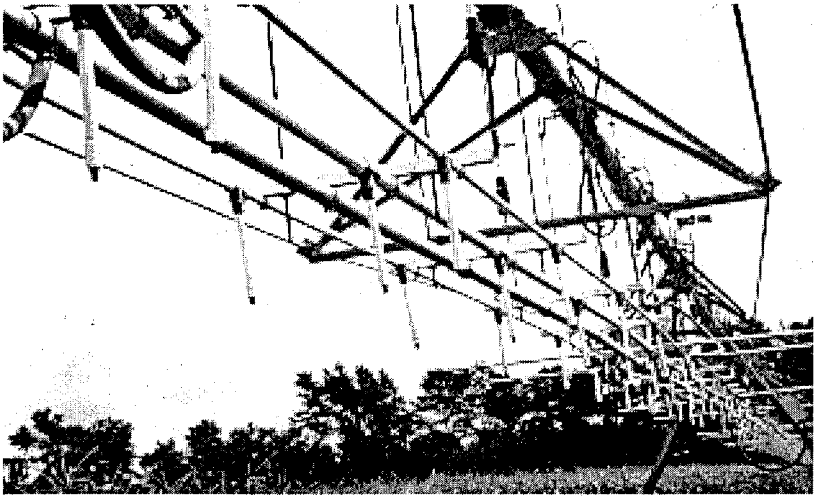


Figure 1. Photograph of modified center pivot irrigation system showing a single element with three manifolds for water application and a fourth conduit for electronic cables.

solenoid valves. Angular location of the truss was obtained from the C:A:M:S™ (Valmont Industries, Inc., Valley, NE) management system. Initially, communication between the mobile PC and the stationary management system was accomplished via short-range, radio-frequency modems (900 MHZ, spread-spectrum modems; Comrad Corp., Indianapolis, IN). Later, a direct cable connection was used to increase communication reliability. Using custom software developed in house, stored data, and continually-collected positional data, the PC controlled the PLC to operate the appropriate solenoid valves to provide the desired application depth within each field element. The control software included checks for out-of-range values and fail-safe operation. Additional details regarding the control system and overall center pivot operation were reported by Camp et al. (1998).

System Evaluation

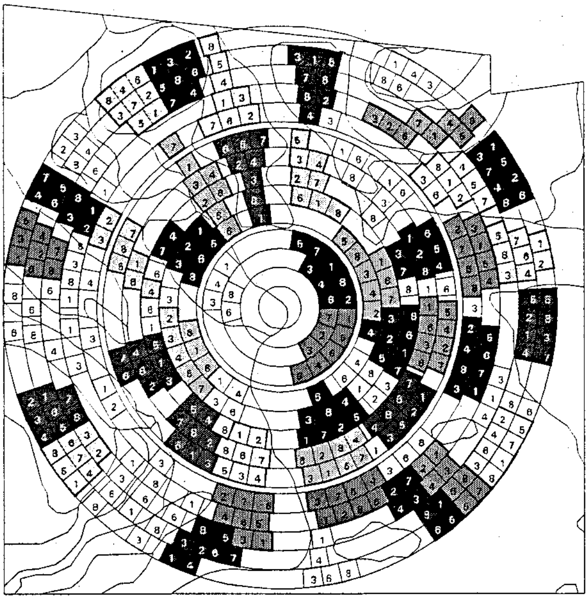
Water Distribution Uniformity. Uniformity coefficient (UC) values (Christiansen, 1942) were determined for selected segments operating alone. Values of UC indicate acceptable system performance, especially for the control zone within each element (UC=87 to 95%), which is the center 6 m of the 9.1-m width. The UC values measured in the radial direction (parallel to manifolds) were similar to those measured in the tangential direction (travel direction). When adjacent elements had different application depths, about 1.5 m at the edge of each element had reduced uniformity, as expected from the prototype evaluation (Omary et al., 1997). However, when adjacent elements had the same application depth, simulated UC values for the entire element were about 92%.

Water and Nutrient Applications to Fixed-Boundary Plots. During the period 1995-1998, CP1 was used to manage water and nutrient applications for a replicated experiment with 144 regular 7.5° by 9.1-m fixed-boundary plots. One objective was to evaluate system reliability and uniformity while simultaneously modifying the control system to enhance performance and reliability. Another objective was to evaluate water, nutrient, and tillage variables in a corn-soybean rotation experiment. Plot boundaries were fixed at 7.5° increments in the rotational (travel) direction and 9.1 m along the radius. Consequently, plot dimensions varied in size, increasing with distance from the center, but were at least 85 m^2. Predetermined water and nutrient amounts were applied to each treatment with timing of water applications determined by tensiometers.

With the demonstrated reliability of system operation during the previous four years, research projects on both center pivots were initiated in 1999 to determine yield production functions required for site-specific management of spatial variability. CP1 was used to apply water and nutrients to 144 fixed-boundary plots (same as in previous experiment) in a replicated experiment with corn. The objective of this experiment was to determine the effects of water and N fertilizer rates on corn yield for three antecedent crop-conservation tillage conditions. Treatments included all combinations of 0.50, 0.75, 1.0, and 1.25 recommended N fertilizer rate and irrigation to replace 0, 0.75, and 1.5 of a base rate determined using tensiometers. Water and fertilizer were applied in the same manner as in the previous experiment.

CP2 was used to apply water and nitrogen fertilizer to fixed-boundary plots within several soil mapping units. The objective of this experiment was to determine the effect of water and nitrogen fertilizer rate on corn yield for several soil mapping units under conventional tillage. Irrigation treatments included irrigation to replace 0, 0.5, 1.0, and 1.5 of the base rate determined using tensiometers. N fertilizer rates were 135 kg/ha (recommended rate for rainfed production) and 225 kg/ha (recommended rate for irrigated production). The number of treatment combinations and number of replications within each mapping unit varied, depending upon the available land area within a specific soil mapping unit. This provided a total of 396 plots as shown in Figure 3. All plots were about 9 m by 9 m in size, but boundaries were adjusted in 1° increments. Plot areas that included portions of two soil mapping units were not irrigated and received the lower N fertilizer rate. Each plot was 12 rows wide, which provided sufficient area for collecting reliable yield data both using a commercial combine equipped with a yield monitor and using a plot combine to obtain discrete samples that were manually weighed individually.

Soil and Crop Mapping. To aid in detecting and mapping soil and crop variation, infrared thermometers (IRT) were installed on aluminum booms and masts that were attached to each center pivot system. The booms extended about 3 m in front of the water application system and the masts allowed adjustment of each IRT 1.5 m above or below the boom, which was 3 m above the ground surface. One IRT was installed for each of the 13 segments on CP1 with the measurement area centered within the 9.1-m segment. Two IRTs were installed on each segment on the second system (CP2) with measurement areas located about 3 m inside the ends of the segments. The IRTs were Exergen Irt/c .3X with 3:1 field of view (~17°) and type K



Treatment Codes		
	Nitrogen (kg/ha)	
%BR	135	225
0	1	5
50	2	6
100	3	7
150	4	8

Figure 2. Schematic diagram of irrigation and fertilizer treatment areas in a site-specific center pivot irrigation system on a site in Florence, SC, that includes several soil mapping units.

thermocouple leads (Exergen Corp., Watertown, MA). Initially, the thermocouples were read using analog cards on the PLC, and the data were stored on the PC. Because of impedance matching problems, thermocouples were later read using a data logger (Campbell Scientific, Inc., Logan, UT) with a type K thermocouple input card and reference temperature source. A thermal scan of corn canopy late in the grain fill period in the fixed-boundary water and nitrogen fertilizer rate experiment on CP2 is shown in Figure 3. Canopy temperature clearly shows that a wide range of crop stress levels occurred because of the various irrigation application rates. This map of canopy temperature used the difference between individual canopy temperatures and the mean of all measurements along the center pivot truss at that time (T_c - T_{mean}). This normalization helped remove variations caused by increasing ambient temperature and brief periods of cloudiness, while retaining the relative temperature effects of the treatments.

Spatial Uniformity and Accuracy. To determine spatial accuracy of water applications and soil water uniformity within target areas during 1999, the center of each plot in CP2 was marked when the center of each segment of the center pivot truss passed over a location and the resolver indicated the appropriate azimuth. From the marked plot centers, volumetric soil water content of the 0- to 6-cm depth was determined every 0.3 m along transects both parallel and perpendicular to the travel path using a soil moisture probe (Theta Meter, type HH1, Delta-T Devices, Cambridge, England). These data were evaluated for uniformity within each plot (about 9 m by 9 m) and within the central control area of each plot (about 6 m by 6 m). These data were also analyzed to determine the spatial application accuracy by comparing changes in soil water content at plot boundaries.

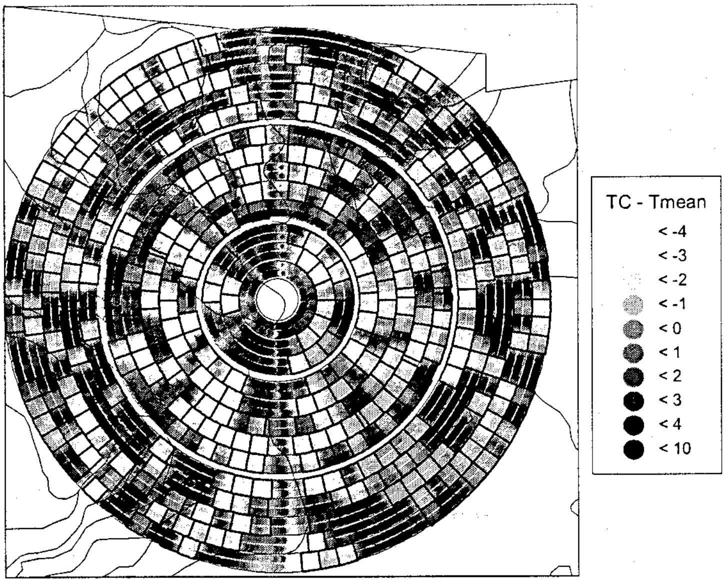


Figure 3. Thermal map of crop temperature (T_c - T_{mean}) for corn during late grain fill with a range of irrigation and fertilizer application rates managed by a site-specific center pivot irrigation system in Florence, SC.

Soil water contents for five treatment areas along the travel path in one soil mapping unit are shown in Figures 4 and 5. The crop was corn, late in the grain fill period, and the treatment areas had been irrigated both the day before and earlier on the day of measurement. In the first case (Figure 4), where the two irrigation treatments were no irrigation and 150% of base, the transition in soil water content was well defined and occurred at the correct location in the field. In the next case (Figure 5), the irrigation transition was from a 150% of base plot to a 50% of base plot then back to another 150% of base plot. Positional accuracy of irrigation applications appeared to be very good as indicated by changes in soil water contents at plot boundaries. As applied, the spray pattern in all border areas affected the water content up to 2 m from the plot boundary. Soil water content was very low where there was no irrigation. The variation in irrigated areas was acceptable (CV = 11 - 30%), especially when considering the canopy interference with water application and the limited time for water redistribution in the soil profile. Mean soil water contents for the two irrigation treatments indicate reasonably good treatment consistency among the same treatment and a distinct difference between the two irrigation treatments.

Mean management zone soil water contents for several irrigation amounts and three soil mapping units are shown in Figure 6. Although there is considerable variation in water content, a distinct difference caused by irrigation is evident for all soils. These areas were irrigated both the day before and earlier on the day measurements were made except for the Dunbar soil, which was not irrigated the day measurements were made. This partially explains why the soil water contents for this soil were lower than for the other soils. From these data, it is evident that a range of irrigation application rates was provided by the site-specific center pivot irrigation system.

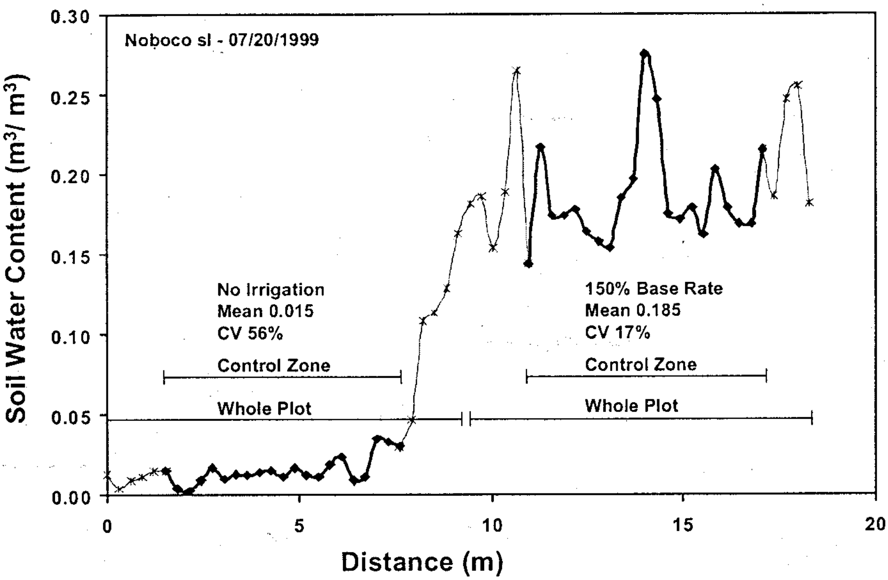


Figure 4. Soil water content for two irrigation treatments along a tangential transect (travel direction) on a site-specific center pivot irrigation system in Florence, SC.

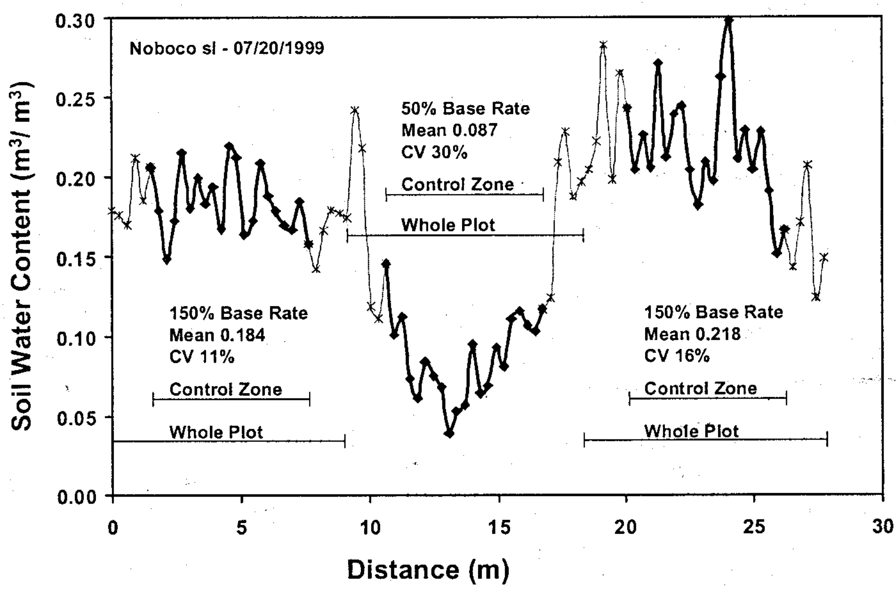


Figure 5. Soil water content for three irrigation treatments along a tangential transect (travel direction) on a site-specific center pivot irrigation system in Florence, SC.

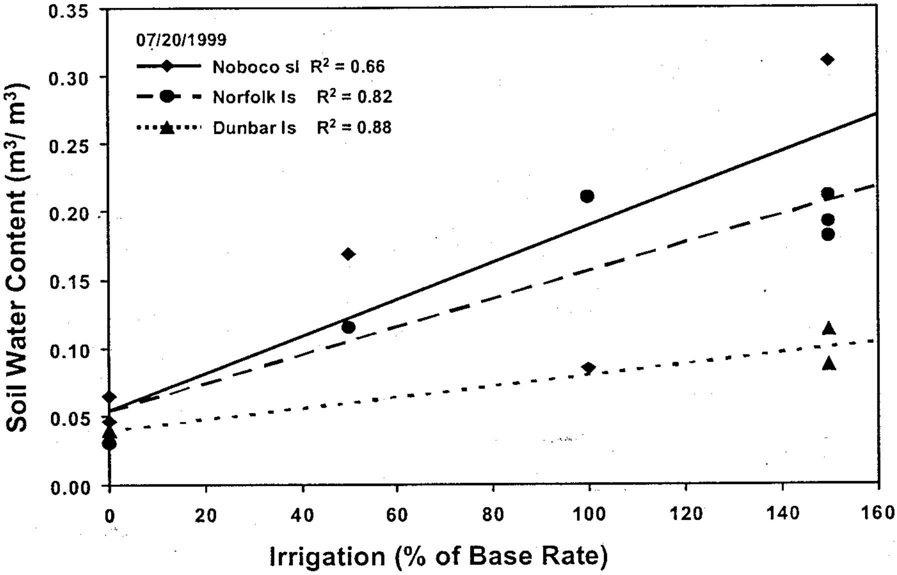


Figure 6. Soil water content for several irrigation treatments along a tangential transect (travel direction) on three soils. Variable irrigation amounts were applied using a site-specific center pivot irrigation system in Florence, SC.

Summary

Commercial center pivot irrigation systems with programmable management systems were modified to provide site-specific water and nutrient management. A control system was developed and improved during a four-year experiment where one modified center pivot system was used to manage water and N-fertilizer applications to a field experiment. A second center pivot was modified in 1998 to provide the same capabilities on a site with variable soils. Beginning in 1999, both modified center pivots were used in experiments to determine the relative effects of water and N fertilizer levels on corn growth and yield. Additionally, the effects of water and N-fertilizer rates will be determined for several soil mapping units at one location. Soil water content measurements during 1999 indicated good spatial accuracy in delivery of irrigation to designated areas, good uniformity within the management area, and a distinct range of irrigation application rates. Canopy temperature data indicate a wide range of plant stress levels caused by the variable irrigation treatments imposed during the growing season. Once crop production effects of variable inputs, soils, and economic factors have been determined, site-specific irrigation and N fertilizer combinations can be developed for soil management zones.

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