SPATIAL ANALYSIS OF CORN RESPONSE TO IRRIGATION

E.J. Sadler, C.R. Camp, Jr, D.E. Evans, and J.A. Millen

Coastal Plains Soil, Water, and Plant Research Center
USDA-ARS
Florence, SC

ABSTRACT

To acquire specific crop management recommendations, greater time, labor, and resources are needed. Without, one is forced to base recommendations on theoretical considerations or imprecise data about how the crop might respond to varying inputs in space. The capital expenditure represented by site-specific irrigation equipment makes it particularly difficult to obtain irrigation production functions, but that same expenditure for producers makes the knowledge equally critical. The site-specific center pivot irrigation facility at Florence, SC, offers a unique opportunity to impose varying irrigation and fertilizer treatments on small plots within a single field and irrigation system. In a previous experiment, spatial variation in crop response to irrigation based on soil map unit means showed dramatic differences among soil map unit responses, but analysis of variance indicated significant within-unit differences as well. This work re-analyzes the data from this experiment during 1999-2001, using spatial statistics and disregarding soil map unit classification. The results are crop response curves for all 396 plot locations in the field. The results have the potential to contribute to economic feasibility studies for irrigation, but the shape of the curves in the vicinity of zero irrigation should contribute as well to analysis of many rainfed cultural practices that conserve water.

Keywords: Site-specific irrigation, Production functions

INTRODUCTION

The increasing interest in precision agriculture has created a need for site-specific crop management recommendations, which are time-, labor-, and other resource-intensive to acquire. However, without such data, one is forced to base recommendations for management on theoretical considerations or imprecise data about how the crop might respond to varying inputs in space. Specialized

 Proceedings of the Sixth International Conference on Precision Agriculture.

irrigation equipment to acquire data on which to base recommendations is very expensive, which makes it particularly difficult to obtain irrigation production functions, but the high capitalization for producers investing in irrigation equipment makes the knowledge equally critical.

The site-specific center pivot irrigation facility at Florence, SC, provided a unique opportunity to impose varying irrigation and fertilizer treatments on small plots within a single field and irrigation system. In brief, a commercial center pivot was modified to allow independent irrigation amounts to be applied on plots as small as 9.1x9.1 m. For a given outer tower speed of 50%, application depths could vary from 0 to 12.7 mm in 1.8-mm increments. Details of the equipment can be found in Camp and Sadler (1994), Omary et al. (1997), and Camp et al. (1998).

This facility was used during the 1999-2001 seasons in an experiment to examine the effect of irrigation and nitrogen fertilization on corn grain yield for twelve soil map units in one field. The results from that experiment were reported by Sadler et al. (2002) using analysis of variance by soil map units. Crop response to irrigation showed dramatic differences among map units. However, analysis of variance indicated significant within-unit differences as well. This suggested that a re-analysis on a strictly spatial basis would be justified. This work re-analyzes the data from 1999-2001, using spatial statistics and disregarding soil map unit classification.

MATERIALS AND METHODS

The experiment was conducted during the 1999-2001 corn growing seasons using the site-specific center pivot irrigation facility at Florence, SC (34.25 N, 79.80 W). Soils at this site had been mapped on a 1:1200 scale by USDA-NRCS staff in 1984 (USDA-SCS, 1986); The United States Department of Agriculture (USDA) - Natural Resource Conservation Service (NRCS). Descriptions of the soil map units and background information on the field site before the pivot was installed can be found in Karlen et al. (1990) and Sadler et al. (1995). The experimental design was a combination of randomized complete and incomplete blocks, each within individual soil map unit boundaries. It included 39 randomized complete blocks of the 2x4 factorial design using 135 and 225 kg/ha N and 0%, 50%, 100%, and 150% of normal irrigation. Where soil map units were too small for RCB's, RICB's were imposed in 19 areas. The total number of plots was 396, each nominally 9.1 m x 9.1 m at the outer boundaries and 6.1 m x 6.1 m in the central control areas. Irrigation was applied to all irrigated plots when tensiometers in selected 100% plots exceeded 30 kPa tension, with irrigation amounts adjusted to reflect the varied depths for the designated treatment. The plot diagram and the soils map are shown in Figure 1.

Surface tillage methods that were used included initial diskings, broadcast dry granular fertilizer applications, and a combined pre-plant herbicide application and incorporation. Corn (Zea mays) (Pioneer 3163) was planted around the pivot circle with a 6-row planter that had in-row subsoilers to a depth of 40 cm. Row spacing was 0.76 m, and the final plant populations in the three years ranged from 6.4 to 6.6 plants m^{-2}, intermediate between

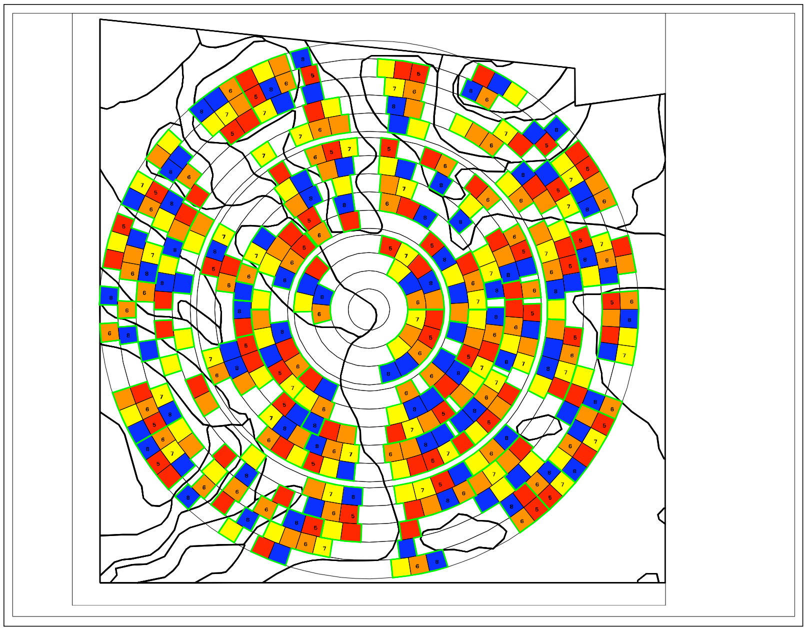

Fig. 1. Experimental design for 1999-2001 corn yield response.

recommendations for rainfed and irrigated corn. Pre-plant and post-emergence herbicides and a banded insecticide were applied as recommended by South Carolina Cooperative Extension Service. Each year, a 6.1-m length of two rows near the center of each plot was harvested using a plot combine. The harvested grain was weighed, corrected to 15.5% moisture, and expressed as mass per unit ground area, in Mg/ha.

For each year, the spatial yield data were separated into four files corresponding to irrigation treatments (For this analysis, the N treatment, found to be insignificant during 1999-2000, was disregarded). Then, data in each file was interpolated over the whole field using the kriging option of SURFER (Golden Software, Golden, CO), with nugget and spherical components to the modeled variogram. This was done on 1-m grid spacings and the estimates corresponding to the positions of the centers of the plots were extracted. Thus, in each of four files, there was an estimate corresponding to an individual irrigation treatment at all 396 plot locations. These four files were then combined to create the source data for quadratic regression of yield and irrigation treatment, which was done using SAS (SAS Institute, Inc., 1990). For each year, the results from the regression analysis comprised a family of 396 quadratic equations describing yield as a function of irrigation amount (Irr in mm) (Eqn 1).

$$Yield = A_0 + A_1 \cdot Irr + A_2 \cdot Irr^2 \qquad (1)$$

Spatial representation of these curves is difficult, so several specific characteristics of these curves were extracted for presentation. These include the slope evaluated at zero irrigation, the maximum yield, the maximum response to irrigation, the irrigation amount at maximum yield, and the irrigation water use efficiency at that maximum. These values were also computed in SAS. A graphical representation of the analytical procedure is given in Figure 2.

The slope at zero irrigation, *SZI*, can be viewed as an estimate of the marginal benefit to yield accrued by saving a unit amount of rain under rainfed conditions. The value, of course, is the derivative of equation 1 evaluated at zero irrigation, or simply the A_1 coefficient (Eqn 2).

$$SZI = A_1 + 2 \cdot A_2 \cdot Irr \Big|_{Irr=0} = A_1 \qquad (2)$$

The maximum response to irrigation is defined as the maximum yield within the imposed treatment range minus the intercept, A_0. To find the maximum yield, one must first locate the x coordinate corresponding to the maximum yield. For concave-down forms ($A_2<0$), the maximum will be either the point where the derivative is zero or an endpoint. If the former, the value of irrigation that results in the derivative being zero is shown in equation 3. If a zero derivative did not exist within the range, the endpoint was chosen.

$$Irrmx = \frac{-A_1}{2 \cdot A_2} \qquad (3)$$

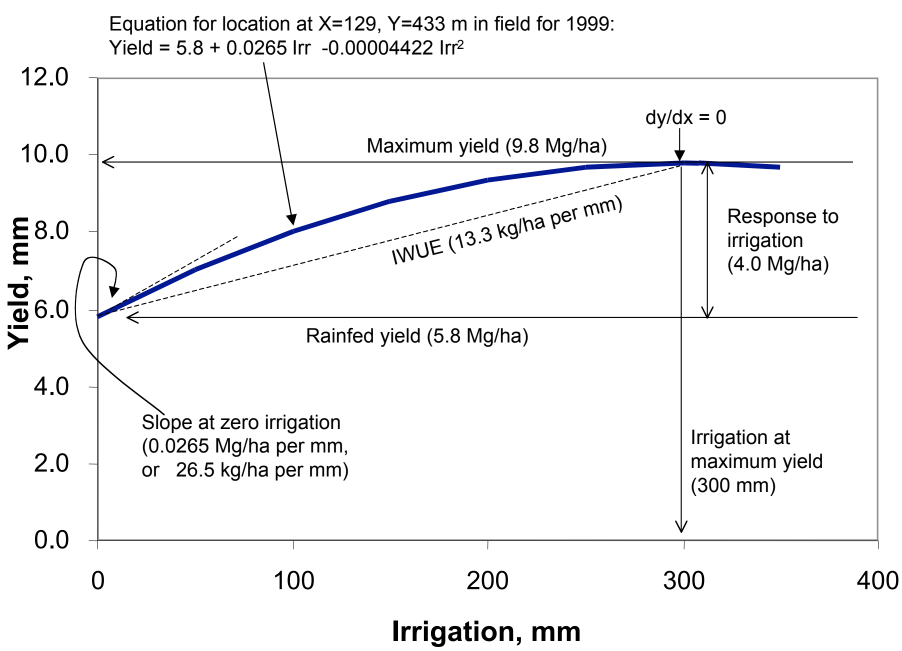

Fig. 2. Graphical presentation of the analytical procedure.

The quadratic equation was then evaluated at *Irrmx* to obtain the maximum yield, *Ymx*. The maximum response to irrigation, *Rmx*, was then found by subtracting the intercept, A_0, from *Ymx*.

The maximum irrigation water use efficiency, *IWUE*, was found by dividing the maximum response to irrigation by *Irrmx* (Eqn 4).

$$IWUE = \frac{Rmx}{Irrmx} \tag{4}$$

The 396 values of *SZI, Irrmx, Rmx*, and *IWUE* were then read into SURFER, gridded using kriging defaults, and mapped for presentation here.

RESULTS AND DISCUSSION

Space constraints preclude presenting all maps for all years, so data for 1999 will be presented, with some selected results for 2000 presented for comparison. As seen in Figure 3, rainfed yields for 1999 were typical of a fairly dry season for corn, ranging from approximately 3.5 to 8.0 Mg/ha. For comparison, in 2000, the range was from 3.4 to 6.4 Mg/ha (data not shown), indicating a slightly more severe drought. In this and the following figures, the circle indicates the boundary of the center pivot, and coordinates are meters SE (X) and NW (Y) in the local coordinate system.

For either of these years, it would be expected that, on average, a large yield response to irrigation would be obtained, and in general, this was true. However, spatial variation in this response has not been documented, although it is commonly assumed that irrigation will reduce the yield variation within a field. For 1999, there was approximately 4.5 Mg/ha range in the rainfed yield, and as seen in Figure 4, the range in the maximum yield is reduced, but only somewhat, to approximately 3.5 Mg/ha. For 2000, the range was 3 Mg/ha for both rainfed and maximum yields.

The more surprising result is that the patterns of variation are not necessarily coincident between the rainfed and maximum yields, resulting in a more complex pattern of spatial variation in the maximum response to irrigation, as seen in Figure 5 for 1999. As a result of the shifts in patterns, the range of variation in response to irrigation is from 2.6 to nearly 7.0 Mg/ha, which is as large as the variation in rainfed yield. The corresponding data for 2000 are shown in Figure 6. The range was approximately 3 Mg/ha, from 3.2 to 6.4 Mg/ha. The patterns of response were similar in areas of the field, notably along the diagonal running from middle left to center bottom, but quite different in other areas, particularly just right of the center.

The amount of irrigation water that produced the maximum yield for the 1999 season is shown in Figure 7. The large areas of values between 300 and 310 mm reflect that for many locations, a maximum (i.e., zero derivative in the equation) was not obtained within the range of irrigation. Extrapolation above the highest irrigation amount applied (308 mm) is not warranted, so the 308 mm value was assigned to those locations. A similar, but not coincident pattern was obtained in 2000, with the irrigation amounts varying somewhat less, from 200 to 288 mm (the maximum applied).

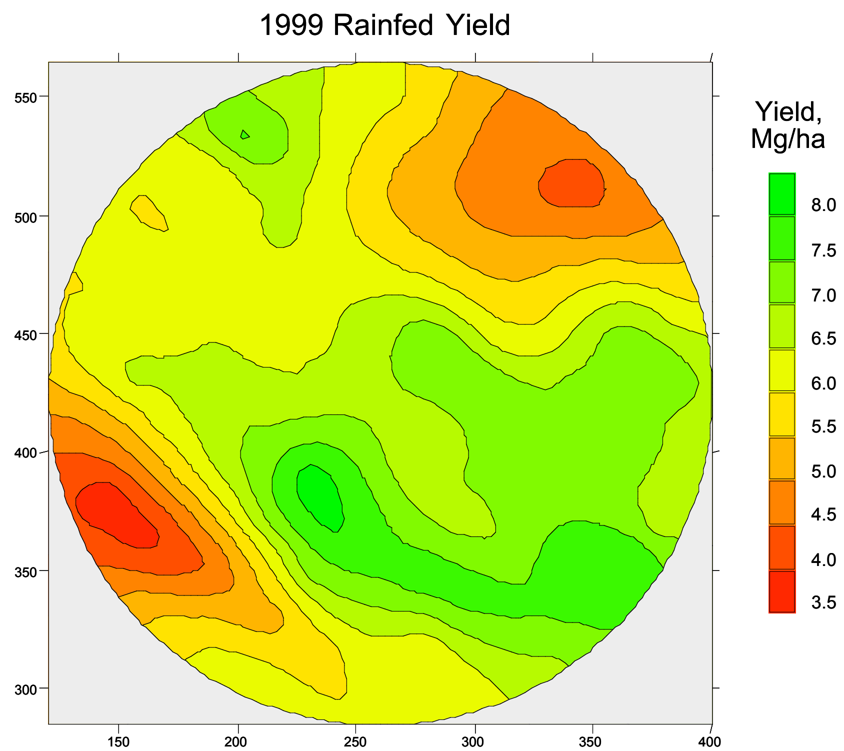

Fig. 3. Rainfed yield (intercept) for 1999 corn.

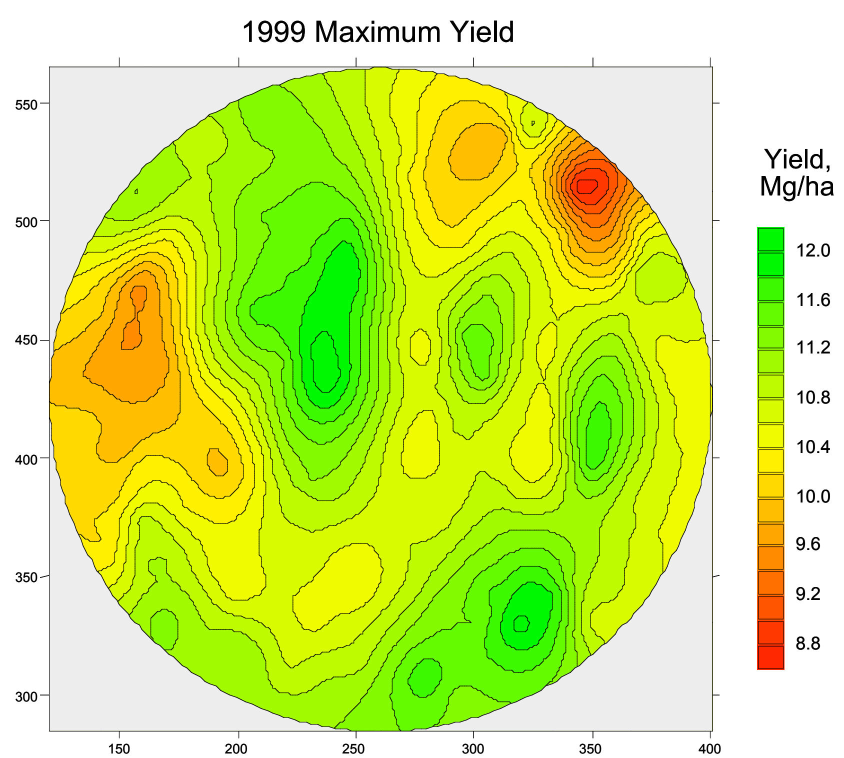

Fig. 4. Maximum corn yield observed.

The usual representation of yield increase for irrigation is as irrigation water use efficiency, *IWUE*, as defined above. For the 1999 season, Figure 8 shows the spatial pattern obtained for *IWUE*, expressed here as kg/ha of yield increase per mm irrigation water applied. The spatial pattern is understandably related to that for maximum response to irrigation shown in Figure 5, since the irrigation amount corresponding to maximum yield (Figure 4) was less variable. The pattern of IWUE for 2000 was similar to that for 1999, with the range raised slightly, from 12 to 29 kg/ha per mm irrigation water applied.

Irrigation water use efficiency, presented above as the maximum response divided by the irrigation amount that obtained it, has the units of yield per unit water, which in Figure 8, has been presented in kg/ha per mm. Mathematically, it is the average slope from the rainfed yield to the maximum response. The slope of the production function, therefore, also has units of yield per unit water, stated originally as Mg/ha per mm water. While the average slope from rainfed yield to maximum response is of critical interest to irrigated culture, one can also make inferences about rainfed culture under the conditions obtained in this experiment.

Rainfed conditions prevailed at zero irrigation, so the slope at that point pertains to this discussion. The meaning of the values for SZI shown in Figure 9 is that one could have expected that amount of yield increase per mm additional water. If one assumes that the source of water need not have been irrigation, one can broaden the interpretation to include water-conserving management such as surface residue and conservation tillage, which have been shown to retain more rainfall than conventional tillage employed here.

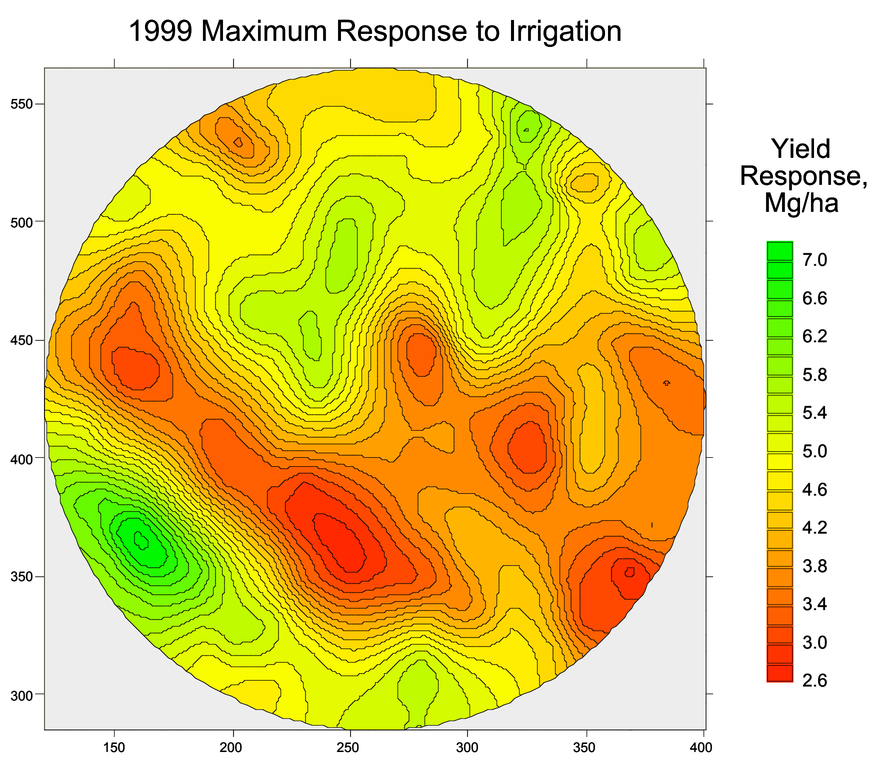

Fig. 5. Maximum response to irrigation for 1999.

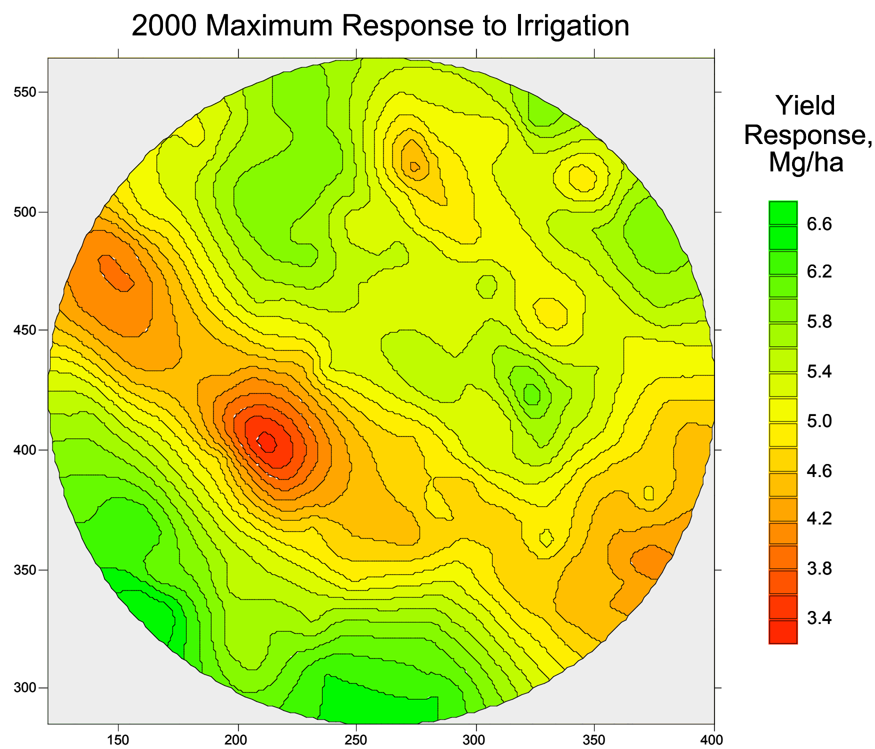

Fig. 6. Maximum response to irrigation for 2000.

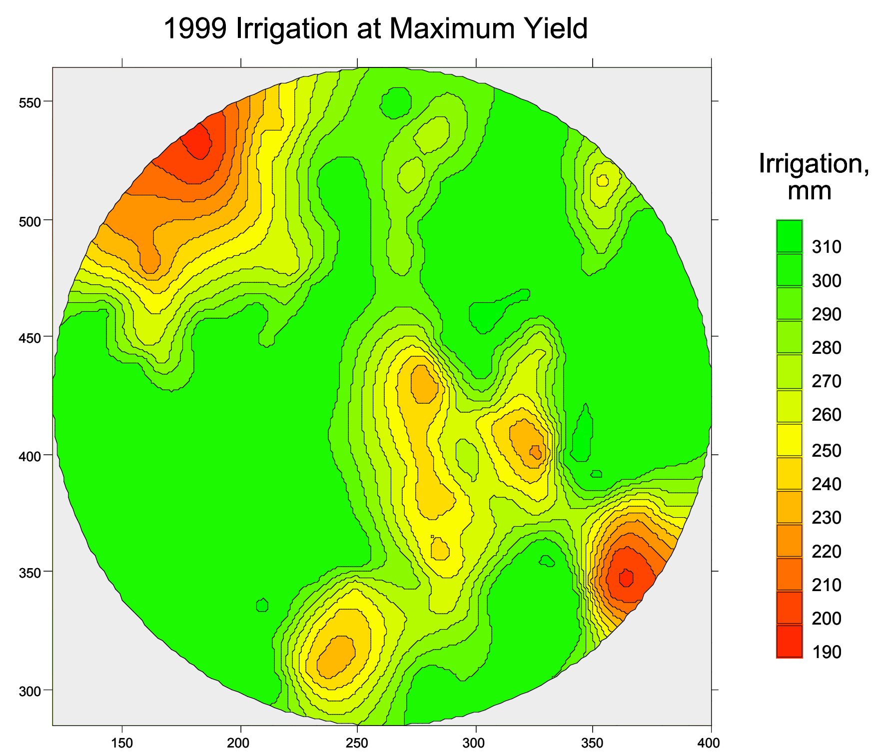

Fig. 7. Irrigation amount that produced the maximum yield.

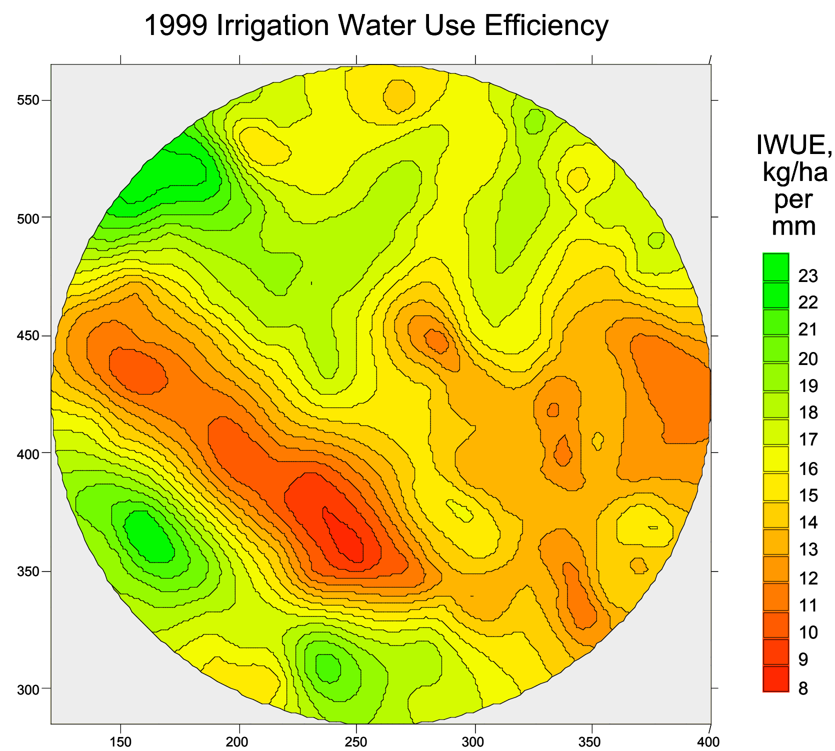

Fig. 8. Irrigation water use efficiency.

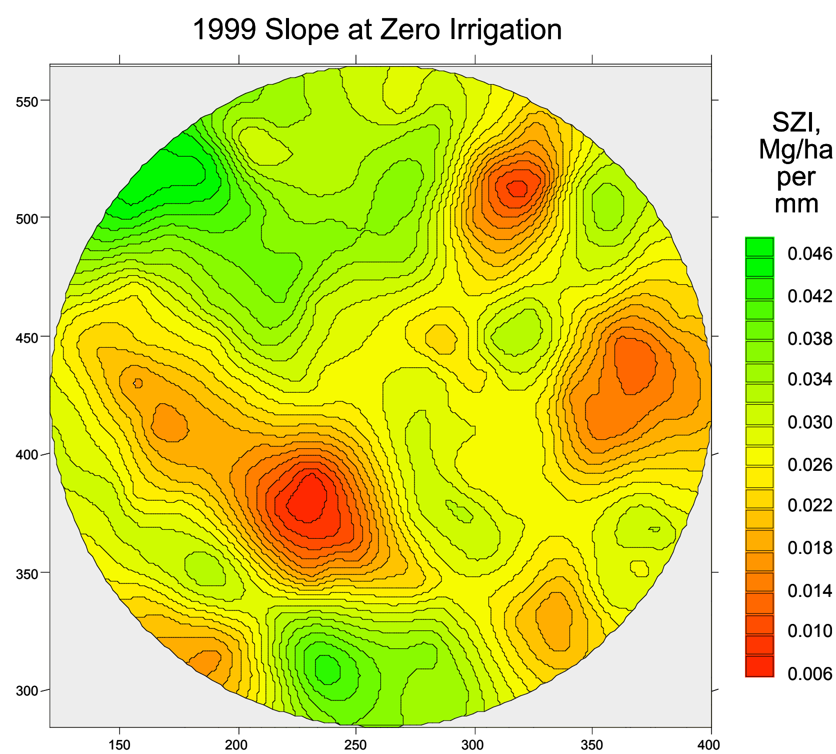

Fig. 9. Slope of the production function at zero irrigation, pertaining to the rainfed condition.

As seen in Figure 9, in 1999 on this field, one additional mm of rainfall conserved would have been expected to raise rainfed yield by a value that varied spatially, from 6 to 46 kg/ha. At prevailing corn prices, that represents approximately \$0.46 to \$3.60 per ha economic benefit per mm of water conserved. While the mathematically exact value of the average slope of a concave-down equation declines slightly as one moves away from the origin, it is reasonable to assume the slope at the origin could represent the first several mm of water conserved. Therefore, multiplying those dollar values by, say, 5 mm of water conserved by surface residue management makes a possible benefit of \$2.30 to \$18.00 per ha. These hypothetical but representative values are not insignificant relative to producer's margins.

SUMMARY AND CONCLUSIONS

Corn response to irrigation varied spatially, with both rainfed yield and maximum irrigated yield contributing to the spatial patterns. Further, the amount of irrigation that produced the maximum yield varied spatially, resulting in a complex pattern of maximum irrigation water use efficiency. These results would appear to support further examination of water as a limiting factor, even in humid regions, that causes significant spatial variation in yield. The practical implications of this finding impact both design and management of irrigation systems.

While the objective of this experiment was to analyze irrigation production functions for corn, the information obtained also provided insights into the expected yield benefit of water conservation technologies under rainfed culture. This somewhat unplanned result may contribute to economic analyses of the economic benefits of conservation programs.

To our knowledge, the spatial response of corn to irrigation presented herein is the first of its kind. The unique capabilities of the site-specific center pivot irrigation facility at the Florence ARS laboratory made the experiment possible, and the information obtained provides significant new interpretations and documents important relationships applicable to precision farming, specifically for the sandy soils of the SE US Coastal Plain and similar regions, but also to agriculture in general.

REFERENCES

Camp, C. R., and E. J. Sadler. 1994. Center pivot irrigation system for site-specific water and nutrient management. ASAE Paper #94-1586. 9 pp. ASAE, St. Joseph, MI.

Camp, C. R., E. J. Sadler, D. E. Evans, L. J. Usrey, and M. Omary. 1998. Modified center pivot system for precision management of water and nutrient. Applied Engineering in Agriculture. 14(1):23-31.

Karlen, D. L., E. J. Sadler, and W. J. Busscher. 1990.Crop yield variation associated with Coastal Plain soil map units. Soil Sci. Soc. Amer. J. 54:859-865.

Omary, M., C. R. Camp, and E. J. Sadler. 1997. Center pivot irrigation system modification to provide variable water application depths. Applied Engr. in Agric. 13(2):235-239.

Sadler, E. J., C. R. Camp, D. E. Evans, and J. A. Millen. 2002. Spatial Variation of Corn Response to Irrigation. Trans ASAE (In review)

Sadler, E. J., W. J. Busscher, and D. L. Karlen. 1995. Site-specific yield histories on a SE Coastal Plain field. Ch 11. pp. 154-166. *In* Robert, P. C., R. H. Rust, and W. E. Larson (ed.) Site-specific Management for Agricultural Systems. Proc. 2nd Int'l Conf. March 27-30, 1994, Minneapolis, MN. ASA/CSSA/SSSA Madison, WI.

SAS Institute Inc. 1990. *SAS/GRAPH Software: Reference. Version 6, First edition*. Vols. 1-2. Cary, NC: SAS Institute Inc.

USDA-SCS. 1986. Classification and correlation of the soils of Coastal Plains Research Center, ARS, Florence, South Carolina. USDA-SCS South National Technical Center, Ft. Worth, TX.