Spatial Variation in Crop Response: II. Implications for Water and Nitrogen Management

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Abstract

For agricultural fields with considerable spatial variation, it is almost impossible to manage water and fertilizer inputs in an optimum manner using conventional equipment with uniform applications. Site-specific applications can be made to zones as small as 83 m^2 (9.1 m by 9.1 m.) using modified center pivot systems. Two modified center pivot irrigation systems in Florence, SC, were used to apply variable water and N-fertilizer amounts to corn during a three-year period. Corn grain yields varied for a range of water and N fertilizer inputs during the period, but yield responses were not equal for all years. Yield response to these inputs also varied with soil map unit, demonstrating that yields increased more with increased input for some soils than for others. The differential response to variable input was analyzed to determine economic response. With these data, it should be possible to ultimately develop a management tool to maximize profit and/or optimize resource allocation or utilization.

Introduction

During the last 10-15 years, reasonably-priced technology to measure spatially-indexed crop yields and to apply fertilizers at spatially-variable rates has stimulated increased interest in site-specific farming. Technology to apply irrigation at spatially-variable rates is not commercially available, having lagged fertilizer application. However, it is generally agreed that water and fertilizer are the most important inputs for determining yield and profit. While moving irrigation systems, if modified, could offer great potential for site-specific application of water and nutrients, little is known of crop yield response to these inputs, or the economic implications. Both yield responses and the associated economic implications must be known before optimum dynamic management can be achieved. Availability of commercial equipment for variable-rate applications of water and nutrients to small management areas will accelerate the need for these crop response functions.

A brief summary of the two-decade history of spatial variability and irrigation management research at USDA-ARS, Florence, SC, and the development of two site-specific center pivot irrigation systems was provided by Sadler and Camp (2002, this proceedings). If not already familiar, the reader is strongly encouraged to review that paper for important background and equipment descriptions to fully appreciate this discussion. These center pivot irrigation systems provide a unique capability to determine the crop response functions needed for dynamic management of water and nutrient inputs to a variety of crops. Although corn and soybean were grown in an initial experiment to prove the function of the site-specific center pivot design (1995-1998), corn was selected as the initial crop for determining crop response functions to both water and N fertilizer.

Irrigation production functions were reported by Sadler et al. (2002b) for three years (1999-2001) in an experiment on center pivot #2 (CP2) with typically variable soils. N-fertilizer production functions were

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reported by Camp et al. (2002) for three years (1999-2001) in an experiment on center pivot #1 (CP1) with a relatively uniform soil. Descriptions of both experiments were reported by Sadler and Camp (2002, this proceedings). Sadler et al. (2002b) reported significantly different irrigation production functions for different soil map units. When soil map unit delineations were ignored (Sadler et al., 2002a), they found spatial patterns in both irrigation response and the irrigation amount that produced maximum yield. Camp et al. (2002) reported different N-fertilizer production functions for each irrigation amount and for each of the three years. In an analysis of the corn yield response to water and N-fertilizer for the variable soils on CP2, Lu et al. (2002) reported estimated production functions for water on two N-fertilizer treatments and three years (1999-2001), and calculated the amount of irrigation required for both yield- and profit-maximizing strategies.

Studies during the period 1999-2001 under CP1 and CP2 provide the data used in both the companion paper and this report. The objectives of this paper are to report production functions for both irrigation and N-fertilizer and to discuss implications of these results for the design and management of site-specific applications.

Methods and Materials

The commercial center pivot systems had been modified to make variable-rate irrigation and N-fertilizer applications to individual management zones within the system, each 9.1m by 9.1 m. N fertilizer applications were achieved by injecting UAN 24S into the irrigation stream at a rate to maintain a constant concentration, and variable N-fertilizer rates were obtained by varying the irrigation application. All applications were controlled by a computer interfaced with the commercial pivot control panel and by a PLC control system to control valve operation. Additional details regarding the site-specific center pivot hardware modifications and the control system were reported by Sadler and Camp. (2002) and other reports cited there.

During the period 1999-2001, corn was grown with a range of water and N-fertilizer applications on both site-specific center pivot irrigation systems. Treatments on CP1 were 0, 75%, and 150% of normal irrigation and 50%, 75%, 100%, and 125% of a N-fertilizer base rate, which was 135 kg/ha for rainfed and 225 kg/ha for irrigated. Treatments for CP2 were 0, 50%, 100%, and 150% of normal irrigation, two N-fertilizer rates (135 or 225 kg/ha), and 12 soil map units. More detailed descriptions of these experiments were reported by Sadler and Camp (2002) and other references cited there.

Crop response curves or production functions were determined for both water and N-fertilizer in both experiments by plotting corn grain yield as a function of either total water (rainfall + irrigation) or total N-fertilizer applied. Although the range in treatment variables suggest that water production functions are more reliable for CP2 (four vs. three water rates for CP1) and that N-fertilizer production functions are more reliable for CP1 (four vs. two N-fertilizer rates For CP2), data from both experiments are discussed. Using spatial statistics and disregarding soil map unit classification, quadratic crop response curves were determined for each of 396 plots in CP2 (Sadler et al., 2000a). From these response curves, maximum yield was determined for each plot (derivative of zero or end point). Irrigation amounts at maximum yield for each plot were then mapped.

In a similar manner, the marginal corn yield benefit to an incremental increase in N fertilizer at the 150% irrigation rate was calculated for both pivots in all years. The marginal yield benefit was determined by dividing the corn yield difference at two N-fertilizer rates by the difference in the N-fertilizer rates. The selected N-fertilizer rates on CP1 were 169 and 225 kg/ha, which correspond to the 75% and 100% rates. On CP2, the rates were 134 kg/ha and 225 kg/ha.. Using current prices for N fertilizer and corn grain, the breakeven point is about 5 kg/ha corn grain per 1 kg/ha of N fertilizer.

Results and Discussion

Crop response to irrigation and N fertilizer. In CP2, the irrigation variable was consistently dominant in all three years, even in best rainfall year. Both linear and quadratic forms of the irrigation effect were significant at the 1% level, and deviation from the quadratic form was not significant in any year. Also, variation among soil map units was significant in all years, at the 1% level in 1999 and 5% level in the latter two years. However, the variation within soil map unit was also significant at the 1% level. These results are more easily visualized in a graphical presentation. For example, corn yield response curves to water for 12 soil map units are shown in Fig. 1, averaged across N treatments. It is obvious from the curves that both the means are different and the ranked order of yields under rainfed (0 IBR) and irrigated conditions is quite different for the soil map units. Similar results were obtained each year but the rank order change was most apparent in the first two years. Response to irrigation, as defined by greatest corn grain yield minus rainfed yield, was quite different across the soil map units. In 1999, responses to irrigation varied from 3.9 to 7.2 Mg/ha for the soil map unit means. Responses in 2000 were similar (2.2 to 8.0 Mg/ha) but were much lower in 2001 (1.3 to 4.0 Mg/ha). Measures of variation from the quadratic curve indicated the best fit in 1999 (r^2 values ranged from 0.39 to 0.99) and 2000, and a much lower goodness of fit in 2001, reflecting the smaller range of yields.

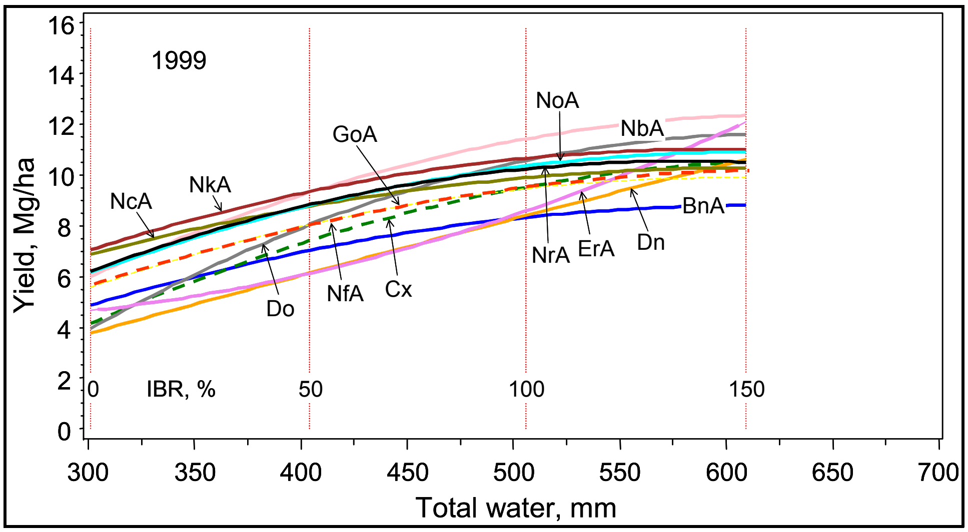

Figure 1. Corn yield response to total water on twelve soils during 1999 under CP2. IBR is irrigation base rate (Sadler et al., 2002b).

While stability of corn response curves would be desirable in order to predict the effect of management, two different types of curves were obtained during this experiment. These can be seen in the mean corn yield response curves for the predominant soil (Norfolk ls, NkA) in all three years (Fig. 2). N treatments were averaged in 1999

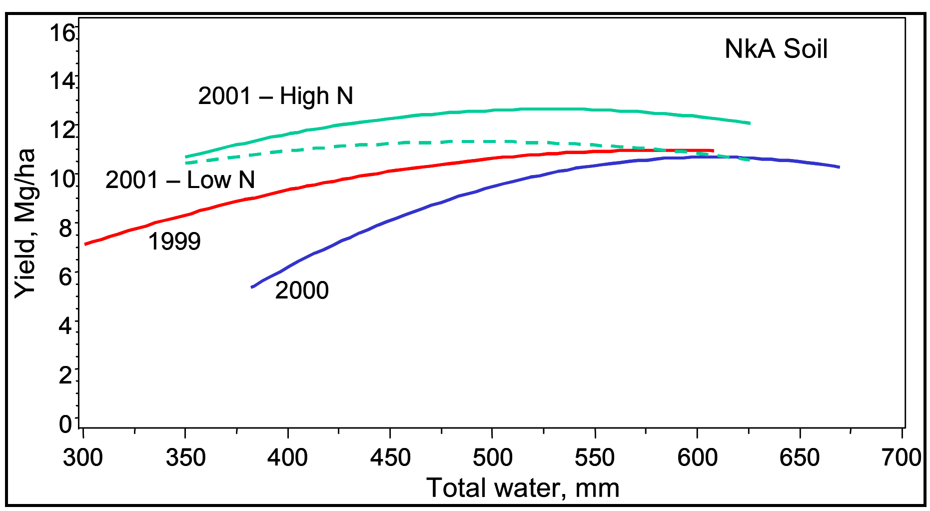

Figure 2. Corn yield response to total water during 1999-2001 for the Norfolk loamy sand (Sadler et al., 2002b).

and 2000 when they were not different. The curves for 1999 and 2000 were similar, rising from a low value with no irrigation to a high, near-plateau value for the greatest irrigation amount. However, in 2001, the corn response for either N treatment was nearly flat across all irrigation treatments. For the NkA soil, r^2 values were 0.73, 0.68, and 0.42 for 1999, 2000, and 2001, respectively.

On CP2 in 2000, the amount of irrigation water that produced the maximum corn yield is shown in Fig. 3. The large areas between 280 and 290 mm indicate that for many locations, a maximum yield (i.e., derivative of equation at zero value) was not obtained within the range of irrigation applied. Extrapolation above the greatest irrigation amount applied (288 mm) is not appropriate. This result is somewhat surprising, especially when the greatest irrigation amount was 150% of normal irrigation. It is also noteworthy that these patterns do not correspond to soil map unit boundaries or any other measured soil property. A similar pattern, but with distinct differences, was obtained in 1999 (See Sadler and Camp, 2002, Fig. 5).

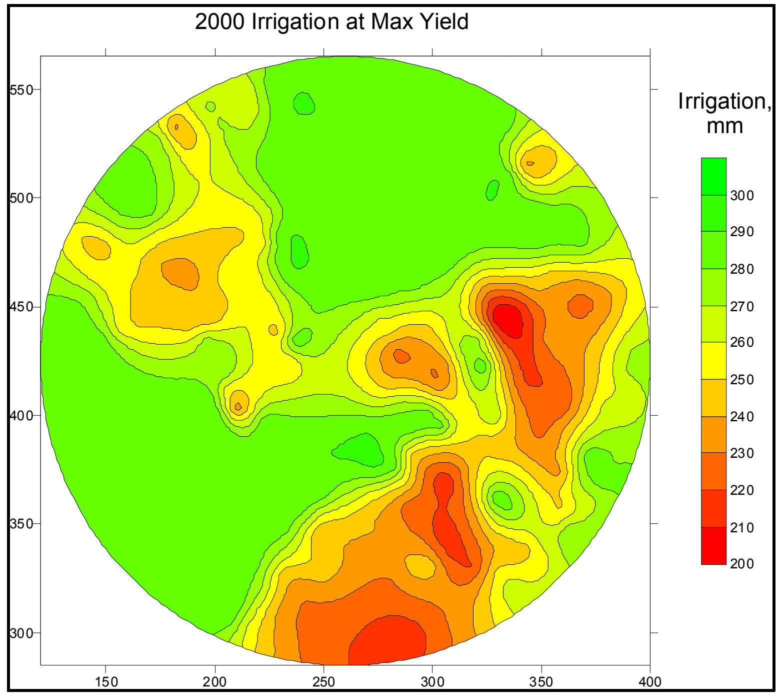

Figure 3. Irrigation amount that produced maximum yield.

Using corn grain yield, irrigation, and N-fertilizer data from the 1999-2001 experiment on CP2, and current prices for water and corn in the south-eastern U. S., Lu et al. (2002) calculated corn production functions for a range of irrigation amounts and two N-fertilizer treatments. All production functions were quadratic in form, were different for each year and for each N-fertilizer treatment, and had r^2 values ranging from 0.51 to 0.65 in 1999 and 2000, and from 0.11 to 0.13 in 2001. They found that profit-maximizing strategies required much less water and produced larger gross margins (total returns minus total variable costs) than yield-maximizing strategies. For example, for the high N-fertilizer rate in 1999, the profit-maximizing strategy required 280 mm of water to produce \$197/ha of gross margins, whereas the yield-maximizing strategy used 351 mm of water to produce only \$173/ha of gross margins. The differences in optimal levels of irrigation water and gross margins between the two strategies become even more significant when the relative water/corn price ratios increase. Finally, they also calculated demand functions and demand elasticities for water, which measures the responsiveness of irrigation water quantity to changes in the price of water. They found that demand for irrigation amount was not very responsive to changes in the price of water at the current price. However, at high water prices, demand for irrigation water became more responsive to changes in water prices.

Corn grain yield responses to N fertilizer for both rainfed and irrigated conditions on CP1 during 1999-2001 are shown in Fig. 4. Irrigated response curves are the means of the two irrigation rates. The linear forms of the N fertilizer effect were significant at the 1% level for both rainfed and irrigated in all years except for irrigated in 1999 (5% level). The quadratic form was also significant for irrigated in 1999 at 5% level and in 2000 at 1%

level. The deviation from quadratic was not significant for any treatment in any year. As with corn response to irrigation, N response curves were different among the three years. Corn response to N fertilizer under irrigation was greatest in 2000, ranging from about 7 Mg/ha to a near-plateau level of about 12 Mg/ha. The response in 2001 was slightly less, ranging from about 8.5 Mg/ha to a maximum of about 12.5 Mg/ha. The response in 1999 was quadratic in form but ranged between 9 and 10 Mg/ha. The low response in 1999 was probably caused, at least in part, by residual soil N from antecedent soybean crops. Corn yields were much lower for rainfed conditions than for irrigated conditions in 1999 and 2000, and increased slightly with N fertilizer, ranging from 5-6 Mg/ha to about 7 Mg/ha. However, in 2001, corn yields for rainfed were similar to those for irrigated because of the favorable rainfall distribution, and sharply increased with N fertilizer, ranging from 7.5 to about 10.5 Mg/ha.

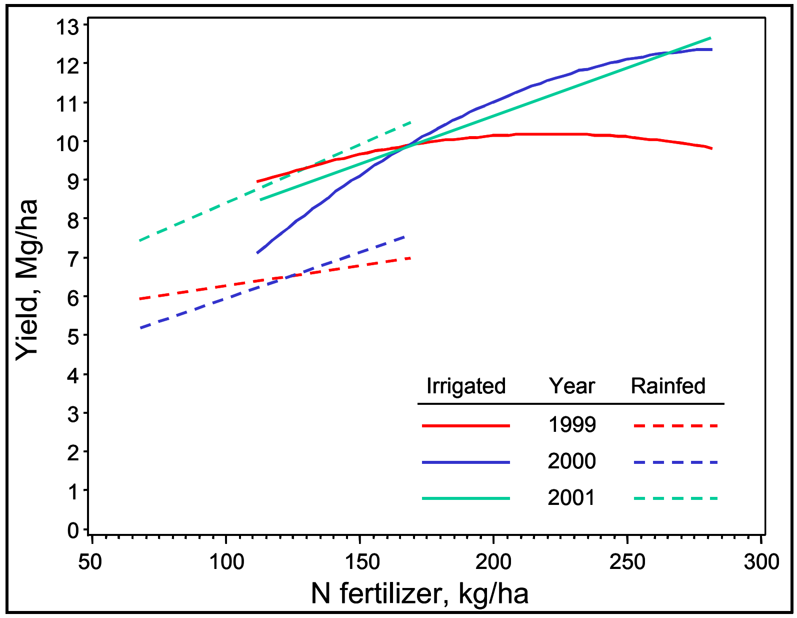

Figure 4. Corn yield response to N fertilizer for both rainfed and irrigated conditions on CP1 during 1999-2001 (Camp et al., 2002).

The marginal corn yield benefit to an incremental increase in N fertilizer at the 150% irrigation rate for CP1 during 2000 and 2001 are shown in graphical form in Figs. 5 and 6. Because the breakeven value is about 5 kg corn/kg N (using current N fertilizer cost and corn grain value), the darker shades of green above that point indicate increasing return while the darker shades of red below that point indicate decreasing return. It is interesting to note that the marginal benefit patterns are distinctly different for the two years and that the

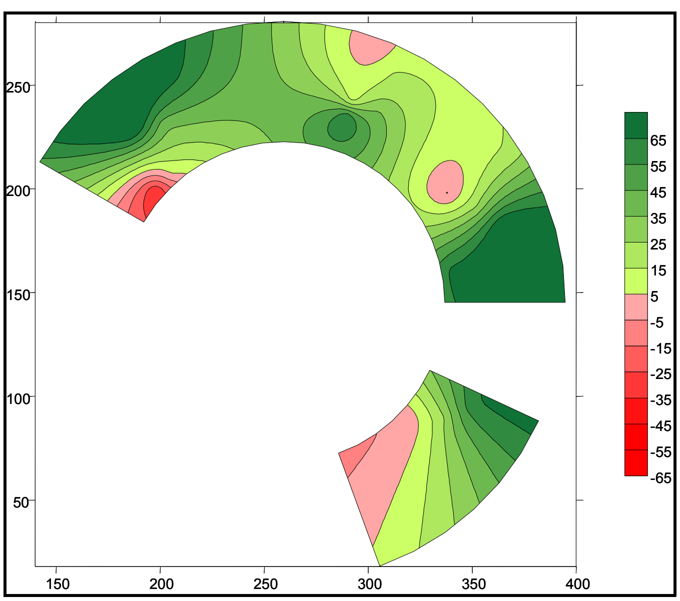

Figure 5. Marginal corn yield benefit from N fertilizer with 150% irrigation on CP1 in 2000 (kg corn/kg N).

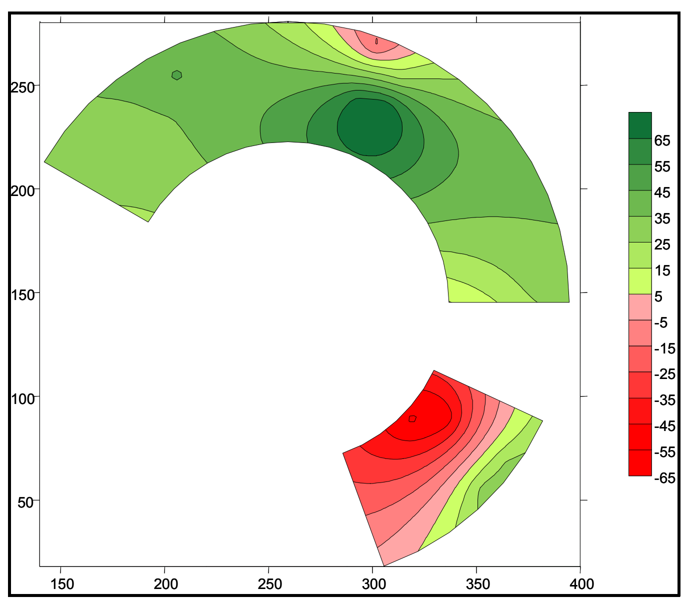

Figure 6. Marginal corn yield benefit from N fertilizer with 150% irrigation on CP1 in 2001 (kg corn/kg N).

patterns do not correspond to soil map unit boundaries or any other known soil property. Since the 150% irrigation treatment was used for this analysis, water should not have been limiting in either year. However, in view of the irrigation deficiency for CP2 discussed previously, it is possible, however remote, that the corn in some portions of this experiment did not receive the optimum amount of water in 2001.

The marginal corn yield benefit to an incremental increase in N fertilizer at the 150% irrigation rate for CP2 during 2000 and 2001 are shown in graphical form in Figs. 7 and 8. The breakeven point and color gradients are the same as in Figs. 5 and 6. In the case of CP2, there were fewer N-fertilizer rates (only two) but many more treatment locations (396 vs. 144), and the entire area within the center pivot was included. Again, the spatial patterns of marginal corn yield benefit were different for the two years although there were some similarities and consistencies, but none of the patterns coincided with any known soil property or map unit boundary. The range of values was less for this experiment than for the experiment on CP1 (-40 to 55 vs. –65 to 65 kg corn/kg N). These results indicate extreme spatial variability in response to N fertilizer, for both relatively uniform (CP1) and variable (CP2) soil map unit classifications.

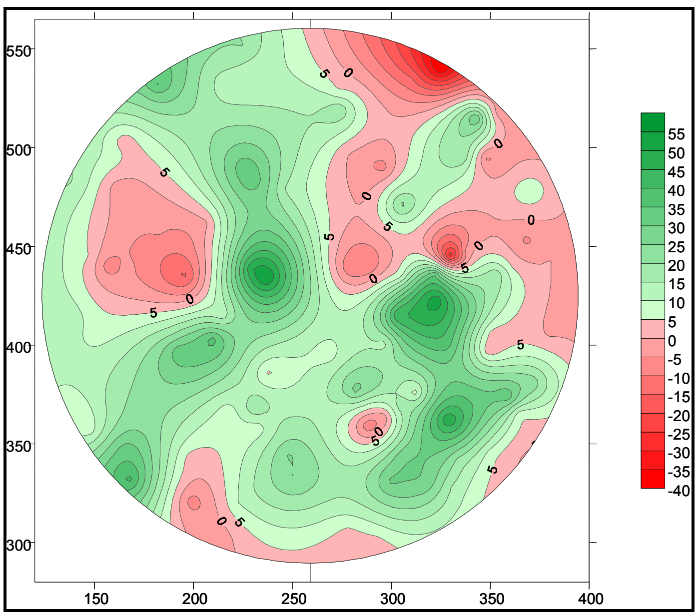

Figure 7. Marginal corn yield benefit to N fertilizer with 150% irrigation on CP2 during 2000 (kg corn/kg N).

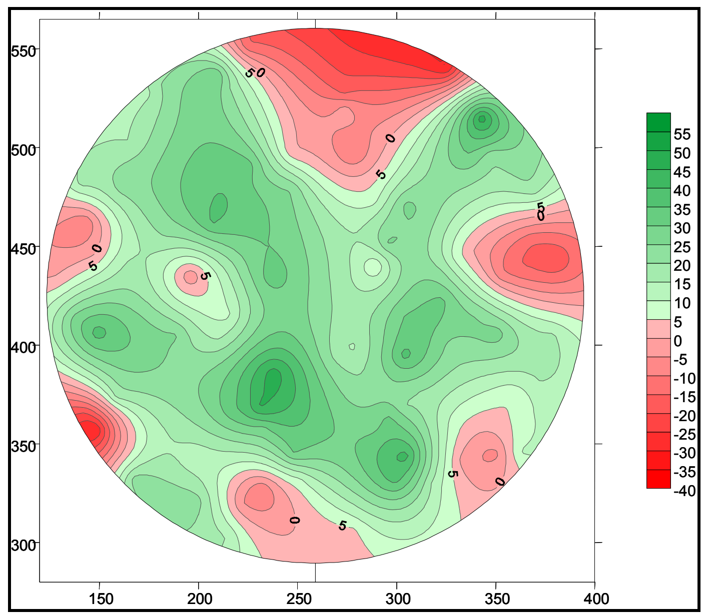

Figure 8. Marginal corn yield benefit to N fertilizer with 150% irrigation on CP2 during 2001 (kg corn/kg N).

Implications for System Design and Management. From the results presented in this and the companion paper, it is obvious that there is considerable spatial variation in corn yield as a result of variable water and N-fertilizer applications as well as other factors. Unfortunately, crop response to these inputs is not constant from year to year, suggesting interactions among the environment, crop, soil, and other factors not yet known. While these results are representative of the southeastern Coastal Plain, spatial variability exists, to a greater or lesser extent, in most all locations. Consequently, site-specific irrigation machines must be designed to accommodate expected conditions.

The first issue to be addressed is determining the management unit size, which is the smallest area within the system to receive independent applications. This depends upon both existing spatial variability and producer preferences. Obviously, the degree and type of spatial variability depend upon the location and region of the

U. S. For example, soil variation may be the greatest source of variation in one location while groundwater recharge zones or obstructions may be the source in other areas. Also, the consequence of improper management can vary from unprofitable management to violation of regulations or statues. Generally, larger areas of similar characteristics can be managed by combining multiple smaller management units.

The range of application rates required within each management unit will also vary considerably with location and region of the country, especially with soil water storage capacity and evaporative demand, e.g. humid vs. arid areas. While current commercial moving irrigation systems have an extensive range of available application rates for water, other considerations such as timeliness of application (total cycle time vs. crop water need) and application efficiency may present constraints. Generally, the range of application rates needed can be addressed by using different sprinkler/nozzle sizes, as it is in current irrigation systems. However, as the management zone size decreases, the selection of acceptable sprinklers/nozzles becomes very limited because of very small wetter diameters, which places a severe constraint on system design. Because variable-rate sprinklers are not yet commercially available, other methods must be used to obtain a range of application rates. To date, three different approaches have been used, including (1) multiple manifolds, each with a different rate and used in various combinations, (2) pulsed water supply to standard sprinkler, with rate depending upon on/off periods, and (3) pulsed variable-orifice sprinkler (rod moving in/out of orifice) to provide application rate of 40 to 100%. For further information on available variable-rate irrigation application see Buchleiter et al. (2000).

Variable-rate applications of chemicals can be accomplished in two different ways. Traditionally, the chemical has been injected into the water supply so that a constant chemical concentration is maintained, and the application rate is determined by the water application. This method is generally acceptable for nutrients such as N fertilizer but is becoming less acceptable for pesticides because of label restrictions and safety concerns. For these chemicals, new commercial application systems are becoming available that have a completely separate supply and delivery system and use the moving irrigation system as a transport device, much like a self-propelled crop sprayer. These systems require less water and can deliver low rates of active ingredient, if needed.

While the design objective in most uniform-rate irrigation systems has been to apply irrigation in the most uniform manner possible, the objective of site-specific irrigation is quite different. Application uniformity is still desired within management units (areas of similar need) but application rates among management units may be quite variable. However, the variable application rates must be predictable and controllable, not random or periodic, and the range must satisfy the crop need for a wide range of conditions.

Once a properly designed site-specific irrigation system is available, it must be managed so that it meets enterprise objectives. Traditional methods for determining the need for irrigation are useful in site-specific management, but the database required will be larger and more complex, and the information must be interpreted differently. The first step is to adopt a management strategy for the enterprise and/or irrigation system. Several options are available, including maximum profit, maximum yield, minimum risk, conserved resources, or limited resource (e.g. water supply, capital). A part of this decision is selection of the crop with considerable attention devoted to the response of the crop to input management. For example, will this crop provide the greatest yield, quality, and/or income increase with the increased water or nutrient input levels for the specific soil, climate, and location? Once these decisions have been made, specific guidelines can be developed for managing these inputs to achieve the management goal. This may require very accurate mechanistic models to augment spatial soil and plant measurements.

The water supply for a variable-rate irrigation system has unique requirements that are often overlooked. The nature of a site-specific irrigation system is such that the water supply flow rate changes continuously, the frequency depending primarily on the severity of spatial variability at the location, unless very sophisticated control algorithms are employed. Generally, the pressurized water supply must be provided by either a variable-flow-rate pump or a group of fixed-flow-rate pumps operated to deliver a range of flow rates. In some cases, water supply volume, flow rate, or quality may be restricted, either temporally or spatially, by either natural, physical, or regulatory means. In all cases, the water supply must be capable of providing the water flow rate during the growing season required to accomplish management objectives and system requirements. Otherwise, alternative or contingency plans must be available.

Summary and Conclusions

Corn crop response functions for variable irrigation and N-fertilizer inputs on southeastern Coastal Plain soils were presented, along with preliminary economic interpretations for the water input. The developed crop response functions varied among the three years making it difficult to select a single function for the crop-location combination. Furthermore, even with 150% normal irrigation in two years, large areas of the irrigation system did not receive adequate water to achieve maximum corn grain yield. These results provide the basis for examination of system design and management considerations for corn in this region. It appears that site-specific irrigation systems must be capable of applying a wide range of irrigation rates, and that the previous irrigation initiation criteria used for these crops and soils probably need to be revised. For maximum economic return, the crop to be grown must be responsive to increased water and nutrient inputs and the enterprise must be managed according to a suitable and sustainable management strategy.

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