CORN YIELD RESPONSE TO NITROGEN FERTILIZER AND IRRIGATION IN THE SOUTHEASTERN COASTAL PLAIN

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ABSTRACT. *Availability of spatially-indexed data and crop yield maps has caused increased interest in site-specific management of crop inputs, especially water and fertilizer. As commercial equipment to implement site-specific applications of water and nutrients becomes available, crop response to variable inputs and decision support systems will be required to ensure profitable crop production while conserving natural resources and protecting the environment. The objective of this research was to determine corn yield response to a range of nitrogen fertilizer and irrigation amounts on a relatively uniform southeastern Coastal Plain soil under conservation tillage. Corn was grown in a field experiment using a center pivot irrigation system that had been modified to make site-specific applications of water and fertilizer during the period 1999-2001 on a site near Florence, South Carolina. Treatments included three antecedent crop rotations (prior four years), three irrigation regimes (0, 75%, and 150% of a base rate, IBR), and four nitrogen fertilizer amounts (50%, 75%, 100%, and 125% of a base rate, NBR), and with four replications. As expected, corn grain yields increased with irrigation and N fertilizer. Mean corn grain yields for the three-year study ranged from 6.3 to 8.9 Mg/ha for the 0% IBR treatment, 9.4 to 10.5 Mg/ha for the 75% IBR treatment, and 10.0 to 10.6 Mg/ha for the 150% IBR treatment. The mean corn grain yields in response to N applications ranged from 6.4 to 8.0 Mg/ha for the 50% NBR treatment, 8.6 to 9.4 Mg/ha for the 75% NBR treatment, 9.1 to 10.9 Mg/ha for the 100% NBR treatment, and 8.8 to 11.7 for the 125% NBR treatment. However, the nature of the response varied among the three years, mainly because of differences in rainfall and rainfall distribution during the growing season. Also, during the first year, there was less response to N fertilizer (7.9 to 9.1 Mg/ha) possibly because of residual soil N from antecedent soybean crop. A regression analysis indicated that the slopes of the corn yield response to increased N fertilizer application were low for both irrigated and rainfed treatments in 1999. In both 2000 and 2001, the slopes were greater for the corn yield response to increased N fertilizer. In 2000, the irrigated treatments had a greater slope of the yield response for additional N fertilizer than did the rainfed treatments. Using an orthogonal contrast analysis, the overall yield response for the combined irrigation treatments to N fertilizer was quadratic in 1999 and 2000, and linear in 2001. These quadratic yield responses indicated that, for these conditions, a potential upper limit on production for the applied N-fertilizer and water (rainfall and irrigation) was approached. For the rainfed treatment, yield response to N fertilizer was linear in all three years. These results provide useful information that should be helpful in developing management strategies and decision support systems for profitable management of both water and N fertilizer on spatially-variable soils in the southeastern Coastal Plain while conserving natural resources and protecting the environment.*

Keywords. *Site specific, Precision farming, Center pivot, Water conservation, Variable rate irrigation, Maize, Production function.*

Availability of position determination technology, yield measurement sensors, and software to produce spatially-indexed yield maps from these data has allowed detection and visualization of spatial yield patterns within fields. Observation of these spatial yield patterns has prompted an increased interest in site-specific management of crop inputs, either to reduce yield variation or to optimize resource management and/or profit. There is general agreement that water and fertilizer are the most important inputs in determining crop yield and profit. While site-specific application of fertilizer via ground equipment has been widely practiced for several years, most current irrigation applications remain nominally uniform within a field. When irrigation is used, most post-emergence fertilizers, especially N, are applied via fertigation (Gascho and Hook, 1991; Ferguson et al., 1991; Lamm et al., 2004; Bausch and Delgado, 2005). Consequently, fertigation applications generally also remain nominally uniform within a field. However, moving irrigation systems offer great potential for site-specific application of nutrients and water, if variable-rate applications to small management areas within these systems can be accomplished.

Several commercial moving irrigation systems have been modified to provide site-specific water and nutrient management, mostly for research purposes but some for

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commercial application (Buchleiter, et al., 2000; Sadler et al., 2000; Dogan et al., 2006). Once commercial site-specific systems become more widely available, knowledge about crop response to variable water and nutrient inputs will be required for optimum crop production and maximum profit. These crop responses, often called production functions (e.g., Hexem and Heady, 1978; Howell et al., 1990; Nielson et al., 2009), will be required for a range of crops and of soils that represent most agricultural operations. While existing water and nutrient recommendations may be useful in areas where there is little spatial variation or helpful in establishing general guidelines for other areas, more specific information must be developed for areas with considerable spatial variation (Or and Hanks, 1992; Hergert et al., 1997; Pan et al., 1997). Furthermore, economical and environmental impacts of site-specific water and N fertilizer applications must be extended from simulated data (Watkins et al., 1999; DeJonge et al., 2007; Shani et al., 2009) to measured data (Lu et al., 2004).

Most current N fertilizer application rates are based on mean plot responses rather than on individual plot responses, thus removing variation. Also, most N fertilizer recommendations apply to either an entire state or a region within that state (Ferguson et al., 1991; Hergert et al., 1997; Pan et al., 1997). In some areas, N fertilizer recommendations are now being based on crop yield potential of specific soils (e.g., CUCES, 2002; Hodges, 2000). Unfortunately, there is often as much yield variation within a soil map unit as between soil map units (Karlen et al., 1990). While this procedure could improve N fertilizer efficiency, increase profit, and reduce environmental damage caused by nitrate leaching, there are several factors that affect the N concentration in the soil profile at a given time. Because the process is dynamic in nature, available N in the soil profile is variable and difficult to predict. Consequently, site-specific N fertilizer management must consider all N sources, including mineralization, residual from previous crops, water source (rainfall, irrigation, or ground water), and fertilizer (Hergert et al., 1997; Pan et al., 1997). More recently, remotely sensing the nitrogen status of crops offers a more site-specific approach to spatial nitrogen fertilization recommendations (Scharf et al., 2002). Dellinger et al. (2008) reported the use of active sensors for developing corn nitrogen fertilization recommendations. They found a strong relationship between economically optimum rates and relative green normalized difference vegetative index measurements (GNDVI), suggesting that relative GNDVI could be used to successfully develop spatial sidedress N recommendations.

Various methods have been used to manage irrigation water applications but no single method has been accepted as best for all conditions, and all methods have their respective strong and weak points for a specific location or system. Generally, irrigation management is less complex in areas with little or no rainfall because irrigation is generally applied to replace crop evapotranspiration (ET), which can be estimated by several methods. In more humid areas, where significant rainfall occurs, soil water replenishment and storage by rainfall must be considered along with an estimate of that portion of ET supplied via rainfall. In both cases, spatial variability of soils and of soil water storage complicates irrigation management, especially when applications are uniform for the entire irrigation system. While most irrigation managers strive for maximum application uniformity, in many cases it is normal to have areas of both excess and deficit soil water within the same field because of spatial variation in soil properties despite uniform application. In some cases, non-uniform irrigation application may allow determination of crop response to variable soil water storage (Or and Hanks, 1992). While evaluating several water and N-fertilizer combinations, including deficit irrigation, for corn production in the Central Great Plains, Lamm et al. (1993) found that management-induced yield variations caused a much greater shift in net income than did resource costs. Several researchers have concluded that the quantity of water available to the crop is more important than fertility level in determining crop yield. Even with uniform N-fertilizer application, Sadler et al. (1995) found large corn yield variations during drought years and attributed it to difference in soil water availability. However, because the water supply for irrigation is finite and increasingly more costly, knowledge of crop response to irrigation amount is necessary for profitable management of irrigation applications and conservation of the water resource.

The objective of this research was to determine corn yield response to a range of N-fertilizer and irrigation amounts on a relatively uniform southeastern Coastal Plain soil under conservation tillage.

Materials and Methods

Corn was grown under conservation tillage from 1999 through 2001 on a 6-ha site of uniform Norfolk loamy sand (fine-loamy, siliceous, thermic Typic Paleudult) near Florence, South Carolina (34° 14' 36.98" N, -79° 48' 34.13" W). In the four-year period preceding this experiment, corn and soybean were grown in three rotations (corn-corn, corn-soybean, soybean-corn) with two tillage practices (subsoiled and not subsoiled), two water managements (irrigated and rainfall only), and two nitrogen fertilizer regimes for corn (single and multiple incremental fertigation applications) on the same plot locations as the current experiment (Camp and Sadler, 2002). In this experiment, there were three irrigation treatments (0, 75%, and 150% of a base rate), four N-fertilizer regimes (50%, 75%, 100%, and 125% of a base rate), three antecedent crops (corn-corn, corn-soybean, soybean-corn during the preceding four years), and four replicates. The irrigation base rate (IBR) and irrigation criteria will be defined and discussed later. There were two N-fertilizer base rates, one for rainfed (135 kg/ha) and another for irrigated treatments (225 kg/ha), as recommended by the Clemson University Cooperative Extension Service. All treatments remained in the same location each year.

The center pivot irrigation system had been modified to permit variable applications to individual areas 9.1 × 9.1 m in size (Omary et al., 1997; Camp et al., 1998). The center pivot length was divided into 13 segments, each 9.1 m in length. Variable-rate water applications were accomplished by using three manifolds in each segment, each with nozzles sized to deliver 1x, 2x, or 4x of a base application depth at that location along the center pivot length. All combinations of the three manifolds provided application depths of 0 through 7x of the base rate, and the 7x depth was 12.7 mm when the outer tower was operated at 50% duty cycle. The variable-rate water delivery system solenoid valves were controlled by a computer and programmable logic controller (PLC) (model 90-30, GE Fanuc, Charlottesville, Va.) that obtained positional (angular) data from the C:A:M:S management system (Valmont Industries, Inc., Valley, Nebr.). A software control program written in Visual Basic for DOS (Microsoft, Redmond, Wash.) controlled the PLC using fixed positional data and user-supplied data stored in the computer, and angular positional data from the center pivot management system. A more detailed description of the water delivery system may be found in Omary et al. (1997) and for the control system in Camp et al. (1998).

All nitrogen fertilizer, except pre-plant granular applications, was applied via fertigation. Variable fertigation rates were obtained by varying the application depth of water with a constant nutrient concentration. Because the instantaneous water flow rate of the irrigation system varied frequently, the nutrient injection rate had to vary in proportion to the instantaneous water flow rate. This was achieved with a four-head, 24 VDC, variable-rate injection pump (model 40320, Ozawa R&D, Inc., Ontario, Ore.). The pump injected urea ammonium nitrate with sulfur (UAN 24S) into the water supply line at the center pivot. The pump injection rate was determined by the number of heads used and the pump speed, which was controlled by adjusting the 0-5 VDC signal to the pump controller. The onboard computer calculated the desired injection rate and the proper control voltage setting, and then it set the appropriate control voltage for the pump controller via the PLC system. All fertigation was applied via the nutrient injection system. The N concentration was maintained constant in the irrigation system, and using a combination of the three manifolds on multiple passes of the pivot, water and N were applied to each plot to obtain the desired N rate. The water depths required to apply the 50%, 75%, 100%, and 125% N base fertigation treatments were 4, 7, 5, and 11 mm for the rainfed treatment and 6, 11, 16, 19 mm for the irrigated treatments, respectively. These small water depths were not included in the irrigation totals.

Water was supplied to the center pivot by a pressure-regulated pipe distribution system from a lined reservoir. The reservoir was filled by a float-controlled pump delivering 1,500 L/min open discharge from a well. The pipe distribution system flow rate was 100 to 3,000 L/min at 275-kPa pressure using a four-stage pumping plant. Additional details are included in Camp et al. (1998).

All experimental plots were located on the outer 6 of the 13 segments of the center pivot system on the most uniform soil areas. Individual plots were established in a regular 7.5° by 9.1-m (12 rows) pattern, which made the minimum plot length 10 m in segment 8 and 17 m in segment 13. All rows were circularly planted, and all subsequent operations were performed in a circular pattern that coincided with the travel pattern of the center pivot system. The experimental design was a split randomized complete block with antecedent crop as the split, and irrigation and N-application treatment combinations as the randomized complete blocks. Each of the four replicates was located in angular sectors of the circle (fig. 1). In 2001, the continuous corn antecedent crop treatment was removed from the experiment, and those plots were used for another study.

The schedules of cultural operations are given in table 1, and common activities are reported here. Conservation tillage culture was used. This included subsoiling annually to a depth of 0.40 m within the row at planting, broadcast granular fertilizer prior to planting, and herbicide and banded insecticide applications as recommended by Clemson University Cooperative Extension Service at rates given in table 1. Corn (c.v. Pioneer 3163) was planted around the circle using a six-row Case/IH (Case Corp., Racine, Wis.) planter at a seeding rate of 71,500 seeds/ha. Row spacing was 0.76 m, and the final plant population was about 64,000 plants/ha. This plant population was chosen to be an intermediate population between regional recommended populations for both rainfed and irrigated corn in order to

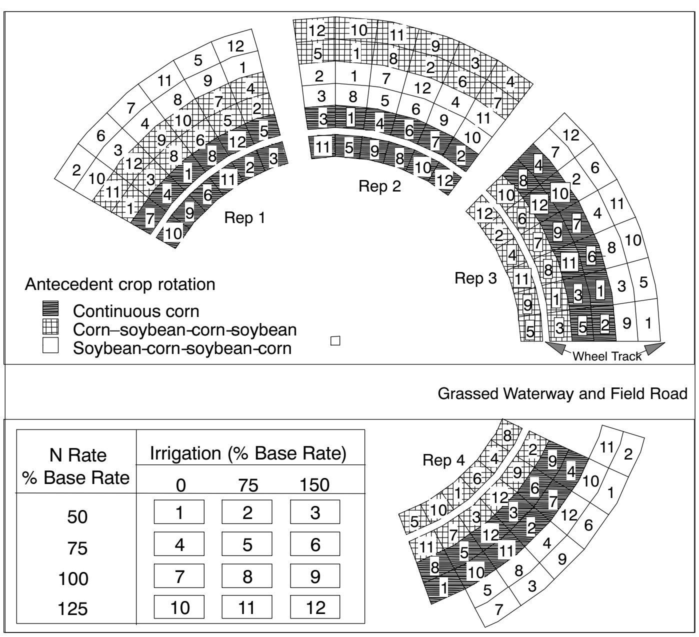


Figure 1. Diagram of experimental design for corn response experiment during 1999-2001. Numbers within plots identify the irrigation-N-fertilizer treatment combination for the plot.

Table 1. Cultural operations for three corn growing seasons, 1999-2001.

Event, Operation, or Cropping Season Characteristic	Year		
Material applied	1999	2000	2001
Herbicide application date	3/17	3/15	3/24
Glyphosate (kg a.i./ha)	1.4	1.3	
Paraquot dichloride (kg a.i./ha)			0.7
Lime application date (2.2Mg/ha)			3/19
Granular fertilizer application date	3/22	3/28	3/27
Granular fertilizer amounts, N-P-K (kg/ha)	31-23-44	45-31-121	68-43-138
Planting date (Pioneer 3163)	4/02	3/30	4/11
Terbufos (kg a.i./ha) (banded in row)	0.9	1.3	1.3
Pre-emergence herbicide application date	4/05	4/03	4/11
Glyphosate (kg a.i./ha)	1.1	1.1	1.1
Metolachlor (kg a.i./ha)	1.7	1.1	1.2
Atrazine (kg a.i./ha)	1.9	0.9	1.0
Emergence date	4/09	4/08	4/19
Post-emergence herbicide date		5/04	5/11
Atrazine (kg a.i./ha)		1.4	1.4
Crop oil (kg /ha)			2.2
UAN 24S[a] application date	5/28 - 5/30	5/19 - 5/21	5/23 - 5/25
Tasseling date	6/13	6/11	6/16
Physiological maturity date (by GDU[b])	8/07	8/03	8/10
Seasonal solar radiation ($MJ/m^2/day$)	2666	2802	2729
Harvest date	9/08 - 9/10	9/29 - 10/02	9/20

[a] UAN 24S is urea ammonium nitrate with sulfur.
[b] GDU = 1580 C-days computed using limits of 10°C and 30°C.

compare results across treatments. Fertigation N (UAN 24S) was applied according to the treatment plan shown in tables 1 and 2.

Soil samples were collected prior to planting each year for determining fertilizer requirements and residual N. In each year, samples from the Ap horizon were collected and combined for each antecedent crop treatment by replication. These samples were analyzed for nitrate-N by Clemson University Agricultural Services Laboratory (CUASL, Clemson, S.C.).

Soil water potential (SWP) was measured using tensiometers at two depths (0.30 and 0.60 m) and at multiple locations within the experimental site. Measurements were recorded at least three times each week, and data were used both to determine irrigation initiation and to monitor SWP. The irrigation base rate (IBR) was estimated by interpolating between SWP values for the 75% and 150% IBR treatments

Table 2. Total seasonal N fertilizer applied to corn in each of three years (1999-2001) for two irrigation treatments and four N-fertilizer treatments on a coastal plain soil near Florence, S.C.

Irrigation Treatment	Total N Fertilizer Applied			
	50% BR[a] (kg/ha)	75% BR (kg/ha)	100% BR (kg/ha)	125% BR (kg/ha)
Rainfed	68	101	135	169
Irrigated	112	169	225	281

[a] BR = N-fertilizer base rate: 135 kg/ha for rainfed and 225 kg/ha for irrigated.

as measured with tensiometers at a soil depth of 0.30 m. Irrigation was initiated when mean estimated SWP value at 0.30-m depth reached -25 kPa.

All treatments were irrigated simultaneously with a maximum irrigation depth of 13 mm. The irrigation depths for the 75% and 150% IBR treatments were 6.5 and 13 mm, respectively. To evaluate how well our SWP based irrigation scheduling performed, we compared it with calculated daily reference evapotranspiration using the ASCE standard for grass (Walter et al., 2000) and the dual-crop-coefficient method of Allen et al. (1998). For this calculation, the Kc value was 0.15 until plant emergence, increased linearly from 0.15 to 1.15 until tasseling, and then remained constant until physiological maturity, which was defined as Growing Degree Unit (GDU) of 1580 C-days using limits of 10°C and 30°C. Physiological maturity was confirmed with observations of black layer formation in 1999 and 2001. The Kc value after physiological maturity decreased from 1.15 to 0.15. All irrigations were halted at physiological maturity. Weather data used in these calculations were obtained from an on-site weather station, supplemented in 1999 with air temperature and dew point data from the Florence Regional Airport (FLO), Florence, South Carolina (approximately 10 km from research site). Comparisons between the on-site weather air temperature and dew point data and the Florence Regional Airport data for 2000-2001 indicated that the two sites were highly correlated, which confirmed the use of the airport data in 1999.

Corn grain yields were determined by weighing the grain harvested from a 6.1-m length of two rows near the center of each plot using an Almaco plot combine with corn header (Almaco, Nevada, Iowa) at the dates shown in table 1. Grain yields were corrected to 15.5% moisture. Yield data were statistically analyzed using analysis of variance (ANOVA), orthogonal contrasts, and regression analysis, and means were separated by calculating the least significant difference (LSD) (Statistical Analysis System, SAS Institute, Cary, N.C.).

RESULTS AND DISCUSSION

Cumulative rainfall, irrigation, and evapotranspiration values for all irrigation treatments during the 1999, 2000, and 2001 corn growing seasons are given in figures 2, 3, and 4. The rainfall totals from planting to maturity were 10% to 30% less than the 30-year normal seasonal rainfall of 410 mm (table 3) (http://lwf.ncdc.noaa.gov/oa/nc three years. Although seasonal rainfall totals were different each year, conditions during 1999 and 2000 were similar and were generally considered to be drought years. Seasonal rainfall in 2000 was 29% greater than in 1999, and the rainfall distribution was different. During these two years, more than 100 mm of rainfall came during short time periods, early in 1999 (DOY 118-120) and later in 2000 (DOY 145-157). Also, rainfall during the grain fill period was less in 1999 than in 2000 (~120 mm vs. ~160 mm). In 2001, seasonal rainfall was only 16% greater than in 1999 but it was much better distributed through the growing season, especially during grain fill, with over 100 mm occurring during several days in the last half of that period. Although rainfall in 2001 was 18% less than the long-term normal, crops were less water stressed than in 1999 and 2000 because of the better rainfall

Table 3. Seasonal rainfall and irrigation for a corn experiment on a coastal plain soil near Florence, S.C., during the period 1999-2001.[a]

Year	Water Source	Seasonal Rainfall and Irrigation (mm)		
		Rainfed	75% IBR[b]	150% IBR
1999	Irrigation	0	214	428
	Rainfall	286	286	286
	Rain + irrigation	286	500	714
2000	Irrigation	11[c]	155	299
	Rainfall	375	375	375
	Rain + irrigation	386	530	674
2001	Irrigation	16[c]	134	252
	Rainfall	334	334	334
	Rain + irrigation	350	468	586
1999-2001	N applications[d]	4-11	6-19	6-19

[a] For comparison, climatic normals (1971-2000) indicate 410 mm during April through July.
[b] IBR = Irrigation base rate.
[c] A small amount of irrigation water was applied to all plots for germination in 2000 and 2001.
[d] A range of irrigation depths was required to apply the various N base rates for both irrigated and rainfed corn. These depths were not included in the irrigation totals.

distribution and fewer high-intensity events. Evidence of these 2001 favorable conditions is record high corn yields (rainfall only) in South Carolina (>6.5 Mg/ha). Average statewide corn yields (irrigated and non-irrigated) from 1999 to 2001 were 4.4, 4.1, and 6.8 Mg/ha, respectively (USDA-NASS, 2009).

The cumulative evapotranspiration (ET) curves for irrigation generally paralleled the calculated IBR curves throughout the season in all years (figs. 2-4) except for the latter portion of 2001, beginning just prior to corn maturity, when the calculated IBR fell below the cumulative ET curve. The 75% IBR and 150% IBR curves generally bounded the cumulative ET curves except for a brief period near harvest in 2000 when irrigation was not applied after crop maturity. Based on the measured ET and calculated IBR based on SWP measurements at 0.30 m, the surface soil layer appeared to have adequate plant available soil water. However, SWP values at greater depth indicated little irrigation water was

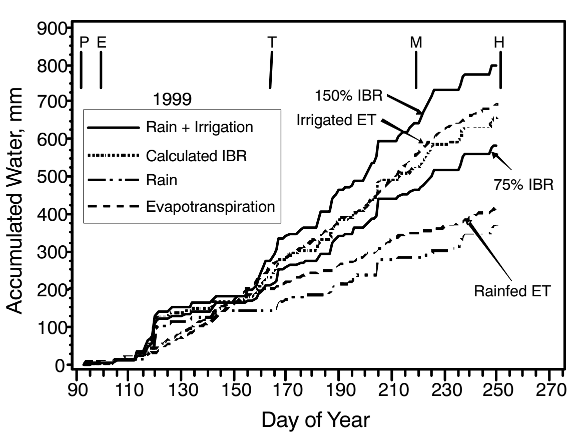
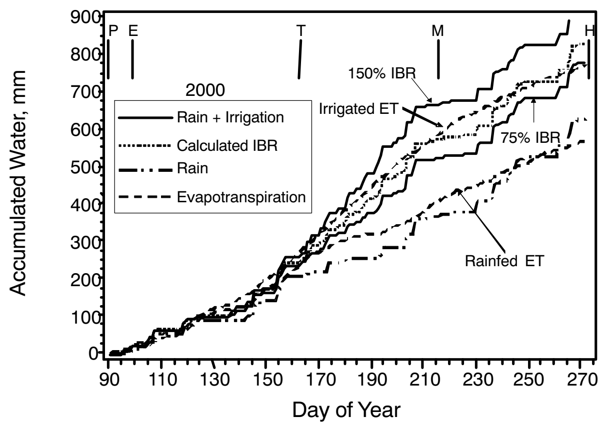


Figure 2. Cumulative rainfall, calculated rainfed and well-watered corn evapotranspiration, and rain plus irrigation for all irrigated treatments during the 1999 corn growing season. The annotations P, E, T, M, and H identify planting, emergence, tasseling, maturity, and harvest dates, respectively, and IBR is irrigation base rate.



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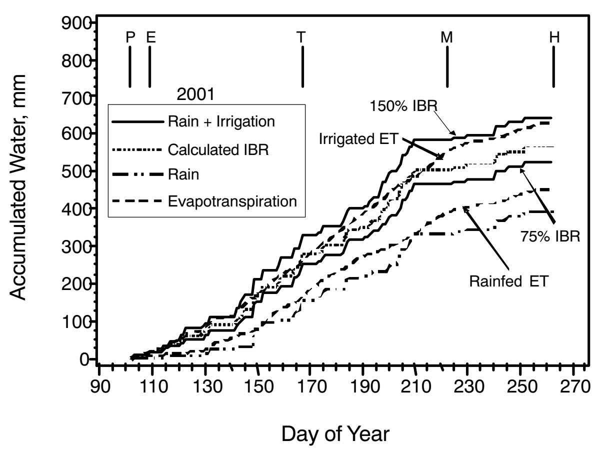

Figure 4. Cumulative rainfall, calculated rainfed and well-watered corn evapotranspiration, and rain plus irrigation for all irrigated treatments during the 2001 corn growing season. The annotations P, E, T, M, and H identify planting, emergence, tasseling, maturity, and harvest dates, respectively, and IBR is irrigation base rate.

moving into the subsoil (0.60-m depth). Even with adequate irrigation at the soil surface, previous observations had suggested that one could expect a depletion of soil water in the subsoil late in the corn growing season possibly caused by more active root growth at that depth. In both 1999 and 2000, total seasonal irrigation was generally inversely related to total seasonal rainfall. In 2001, seasonal rainfall was intermediate (between 1999 and 2000 rainfalls) but had less irrigation (table 3).

Mean grain yields and results of the analysis of variance for grain yield across all three years are given in tables 4 and 5. The dominant significant effects were irrigation, N-fertilizer, and year. The irrigation and N-fertilizer effects were expected; the year effect was probably caused by differences in weather conditions, including the 1999 and 2000 drought years and the more favorable rainfall distribution in 2001. There were significant irrigation-by-year and N-fertilizer-by-year interactions. In

1999, the all irrigation treatments were significantly different. In 2000 and 2001, yields for the two irrigated treatments were not statistically different from each other and both were significantly higher than the rainfed treatment. These results are consistent with those from an adjacent center pivot experiment with conventional tillage on extremely variable soils (Sadler et al., 2002). Halvorson et al. (2006) and Al-Kaisi and Yin (2003) found similar significant dominant effects and interactions in Nebraska and Colorado, respectively. Yield response to N fertilizer was less in 1999 than for other years. This low yield response may have been affected by residual soil N from antecedent soybean crops or from an antecedent low-yielding rainfed corn crop during a dry season. The antecedent crop effect was significant, where continuous corn yields were less than the two corn-soybean rotation yields. Boquet et al. (2009) likewise observed in a corn-cotton rotation that antecedent residual corn N influenced cotton lint yield. Over all years, grain yields for the 125% BR N treatments were higher than for the 100% BR N treatment, which was higher than the 75% BR, all at the 5% level. In the interpretation of corn yield response to N fertilizer, it is important to remember that the N base rate for rainfed and irrigated corn was different (135 vs. 225 kg/ha). Thus, the amount of N fertilizer applied to a given treatment (50%, 75%, 100%, and 125% of an N base rate) was different for the rainfed and irrigated cases. Consequently, corn yield response to N fertilizer is discussed with respect to N fertilizer amount instead of N-fertilizer treatment in some cases.

These results are more easily visualized in a graphical format. Corn grain yield as a function of total water applied for four N-fertilizer rates in all three years is shown in figure 5. In 1999, grain yield increased linearly (yield range of about 3 Mg/ha) for all N-fertilizer treatments as total water increased from the rainfed regime to the 150% IBR irrigation treatment. The yield response curves for the four N-fertilizer rates were essentially parallel, with yields increasing as both total water and N fertilizer ranged from low to high. In 2000, yields also increased with total water but the slope of the response curve increased as N-fertilizer rate increased. Hence, the yield increase with total water (irrigation) ranged from about 1.8 to about 5 Mg/ha with increasing N fertilizer. These higher 2000 yield increases were probably due in part to the higher grain fill period rainfall (~160 mm) and higher overall growing season rainfall. In 2001, yields also increased with total water but the slopes of the response curves were less than in 2000, especially for the lower N rates. Again, the yield response curves for individual N-fertilizer rates were generally parallel and were ordered the same as the N rate. Corn yield increases with irrigation ranged from about 1 to 2 Mg/ha for the four N-fertilizer rates. Our results were in general agreement with other irrigation

Table 4. Mean corn grain yield for an experiment with irrigation and N-fertilizer treatments on a coastal plain soil near Florence, S.C., during the period 1999-2001.

		Corn Grain Yield (Mg/ha)							
Irrigation Treatment	N Treatment (% base rate)	1999		2000		2001		1999-2001	
Rainfed	50	5.9	± 1.3	5.0	± 1.4	7.0	± 2.1	5.9	± 1.7
	75	6.3	± 1.0	5.9	± 1.3	8.9	± 1.8	6.8	± 1.8
	100	6.8	± 1.6	7.2	± 2.1	9.6	± 1.3	7.7	± 2.0
	125	6.9	± 1.3	7.2	± 1.5	10.1	± 0.9	7.8	± 1.9
75% IBR	50	8.7	± 1.5	7.3	± 1.5	8.8	± 1.7	8.2	± 1.7
	75	9.2	± 1.5	10.3	± 1.5	9.3	± 1.1	9.6	± 1.5
	100	10.1	± 1.4	11.1	± 1.6	11.6	± 1.6	10.9	± 1.6
	125	9.4	± 1.3	12.0	± 1.1	12.5	± 0.7	11.1	± 1.8
150% IBR	50	9.3	± 2.0	6.9	± 1.9	8.2	± 1.0	8.2	± 2.0
	75	10.3	± 1.4	9.8	± 1.8	10.1	± 1.4	10.1	± 1.5
	100	10.4	± 1.5	11.9	± 2.5	11.4	± 1.7	11.2	± 2.0
	125	10.1	± 1.1	12.8	± 1.4	12.6	± 1.5	11.7	± 1.8

Summary Statistics

	1999	2000	2001
Irrigation Treatment			
Rainfed	6.5 a[a]	6.3 a	8.9 a
75% IBR	9.4 b	10.2 b	10.5 b
150% IBR	10.0 c	10.3 b	10.6 b
N Treatment (% base rate)			
50	7.9 a	6.4 a	8.0 a
75	8.6 b	8.7 b	9.4 b
100	9.1 b	10.1 c	10.9 c
125	8.8 b	10.7 c	11.7 d

[a] Column means followed by the same letter were not significantly difference at the P = 0.05 level.

Table 5. Analysis of variance results for corn grain yield in an experiment with irrigation and N-fertilizer treatments on a coastal plain soil near Florence, S.C., during the period 1999-2001.

Source	df	Mean Squares	Significance Level[a]
Replication (Rep)	3	13.406	
Antecedent crop (Crop)	2	29.290	*
Error A (Rep*Crop)	6	3.066	
Irrigation	2	347.909	**
UAN[b]	3	154.706	**
Crop*Irrigation	4	0.504	
Crop*UAN	6	1.855	
Irrigation*UAN	6	4.116	
Crop*Irrigation*UAN	12	2.287	
Error B (Rep*Crop*Irrigation*UAN)	99	2.348	
Year	2	29.243	**
Crop*Year	3	2.694	
Irrigation*Year	4	14.834	**
UAN*Year	6	21.953	**
Crop*Irrigation*Year	6	1.415	
Crop*UAN*Year	9	2.080	
Irrigation*UAN*Year	12	2.758	
Crop*Irrigation*UAN*Year	18	1.000	
Error C	168	2.017	

[a] * and ** indicate significant difference at $P \geq 0.05$ and 0.01, respectively.
[b] UAN is N fertilizer.

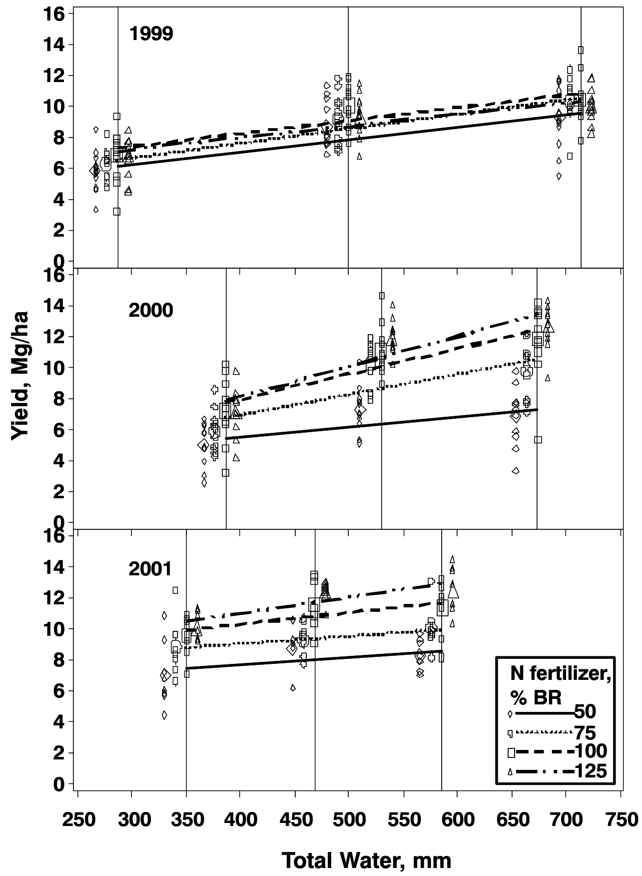

Figure 5. Corn grain yield response to irrigation by N-fertilizer treatment for 1999-2001. Large symbols indicate the mean value for that treatment. Some symbols are offset slightly in horizontal direction to make symbols visible. Vertical lines (from left to right) represent the rainfall, 75%, and 150% irrigation base rates (IBR).

studies. In a limited-irrigation study in Kansas, Norwood (2000) observed both linear and quadratic yield response curves to increasing irrigation water applied. Al-Kaisi and Yin (2003) observed similar increases in corn grain yield with greater irrigation water applications.

Corn grain yield responses to N-fertilizer amount for the three irrigation rates are shown in figure 6. In 1999, all yield response curves were linear and had low slopes (< 1 Mg/ha). This response was possibly influenced by residual soil N from the antecedent soybean crops in some treatments. Although residual pre-plant soil nitrate N in the Ap horizon was greater for the two corn-soybean rotations than for continuous corn (4.7 vs. 3.8 kg/ha), all values were very low. It is more likely that low, poorly distributed rainfall along with the low seasonal solar radiation (table 1) during that growing season limited yields. Yields for both irrigated treatments were greater than that for the rainfed condition. In 2000, yield response curves were linear and similar for irrigated and rainfed conditions, but the slopes were much greater than in 1999. Corn grain yields increased 4 to 5 Mg/ha with increased N fertilizer for irrigated conditions and about 2.5 Mg/ha for rainfed conditions. In 2000, residual soil pre-plant nitrate N in the Ap horizon was the same for all antecedent crop treatments (7.9 kg/ha). In 2001, yield increases resulting from increased N fertilizer were about 4 Mg/ha for irrigated conditions and about 3 Mg/ha for rainfed conditions.

Data for the two irrigated treatments were combined because there was no overall significance difference in mean grain yield. When results for the two irrigated treatments were combined, the pattern of corn yield response to N fertilizer was similar to that for individual years for both irrigated and rainfed conditions (fig. 7). A regression analysis was performed to determine whether the yield response to N fertilizer was linear or quadratic (table 6). The quadratic component of yield response to N fertilizer was significant in 1999 and 2000, but only the linear component was significant in 2001 for the irrigated treatments. The linear component was significant in all years for the rainfed treatment (table 6). The deviation from quadratic was not significant for any treatment in any year. As reflected in the response curves for individual years, yield response to N-fertilizer rate was much less for irrigated treatments in 1999 than in 2000 and 2001 (table 7). Yield responses in 2000 and 2001 were similar, except that the yield range was greater in 2000 with a quadratic relationship. Yield responses that had significant quadratic responses appeared to approach a potential upper limit on production for the applied N-fertilizer and water (rainfall and irrigation). The linear yield responses indicated the crop had not reached a potential upper yield limit for the applied N-fertilizer and water. For rainfed conditions, yield response to N-fertilizer was linear for all years. However, the response slopes were less in 1999 and 2000, and yields were greater in 2001 because of better rainfall distribution. Coefficients for these response curves are included in table 7. In similar studies, Al-Kaisi and Yin (2003) observed that grain yield response to N was impacted by both irrigation amount and year. Overall, they observed little to no significant differences in grain yield response to N application rates greater than 140 kg/ha indicating that an optimal yield-N response was probably obtained. In

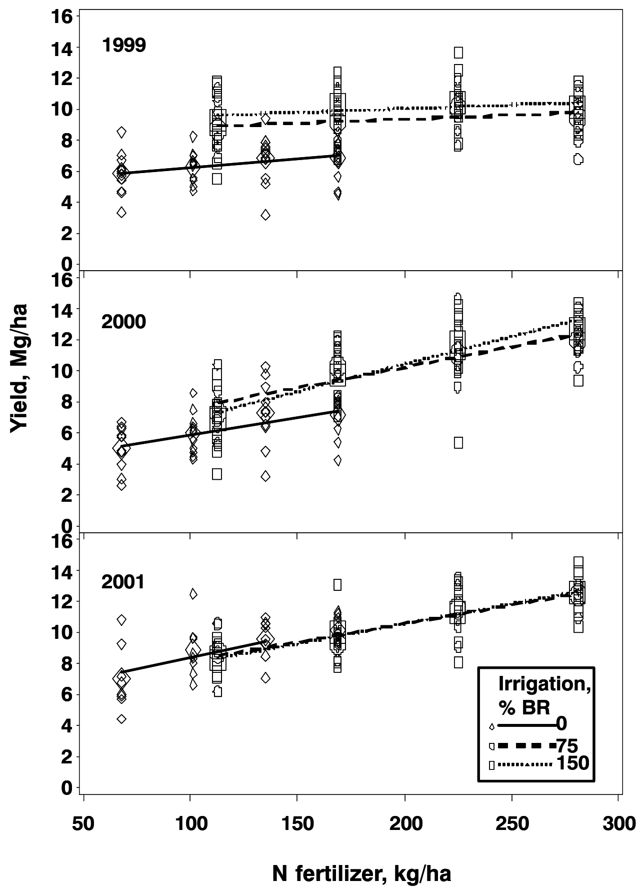

Figure 6. Corn grain yield response to N-fertilizer rate by irrigation treatment for 1999-2001. Large symbols indicate the mean value for that treatment.

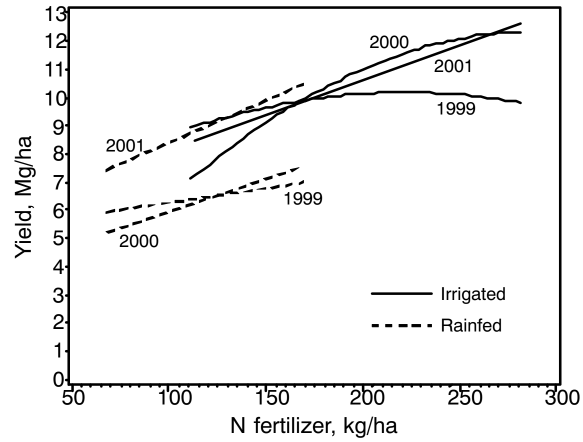

Figure 7. Mean corn grain yield response to N-fertilizer rate for irrigated and rainfed treatments during 1999-2001.

Nebraska, Sims et al. (1998) evaluated irrigated corn yield response to the nitrogen for both no-till and conventional-till. For both tillage systems evaluated, they observed both linear and quadratic yield responses to increased nitrogen applications. They noted that the linear yield responses indicated that higher N fertilizer rates could have been applied to reach an optimal yield-N response. In Northern Colorado, Archer et al. (2008) observed similar grain yield response curves for applied N. Their yield response curves also varied from year to year both in terms of the shape of the response curve and the maximum yield attained. Our results combined with those from similar studies could be used in future analyses for determining economic thresholds to optimize for both N-fertilizer and water applications.

SUMMARY AND CONCLUSIONS

Crop response functions for water and fertilizer will be needed to implement site-specific management of irrigation and fertilizer inputs using irrigation machines if commercial application equipment becomes available. These functions will enable the manager to optimize crop production for maximum profit while conserving natural resources and minimizing offsite environmental effects. A commercial center pivot irrigation system modified for site-specific water and fertilizer applications was used to develop

Table 6. Regression statistics for corn grain yield on N-fertilizer rate for irrigated and rainfed treatments during 1999-2001.

		Linear		Quadratic		Deviation from Quadratic	
Year	Irrigation Treatment	MS	Significance Level[a]	MS	Significance Level	MS	Significance Level
1999	Rainfed	7.556	**	0.534		0.272	
	Irrigated[b]	9.779	*	10.050	*	0.679	
2000	Rainfed	34.512	**	2.384		1.949	
	Irrigated	331.770	**	25.528	**	0.274	
2001	Rainfed	40.119	**	3.538		0.251	
	Irrigated	153.447	**	0.067		1.645	

[a] * and ** indicate significant difference at $P \geq 0.05$ and 0.01, respectively.
[b] 'Irrigated' is the combination of two irrigation treatments, 75% and 150% IBR.

Table 7. Regression coefficients, levels of significance, and equation coefficient values for corn grain yield response to N-fertilizer rate curves for irrigated ($Y = a + bx + cx^2$) and rainfed ($Y = a + bx$) conditions during 1999-2001.

	Irrigated												
	Quadratic					Linear				Rainfed			
Year	a	b	c	r^2	P	a	b	r^2	P	a	b	r^2	P
1999	5.136	0.045	-0.0001	0.09	0.0156	8.695	0.0051	0.04	0.0446	5.221	0.011	0.09	0.0381
2000	-1.491	0.095	-0.0002	0.59	<0.0001	4.19	0.031	0.55	<0.0001	3.580	0.023	0.24	0.0006
2001	5.34	0.029	-0.00001	0.57	<0.0001	5.696	0.025	0.57	<0.0001	5.410	0.030	0.35	0.0004

relationships between yield and water/nitrogen that can be useful to site-specific field applications. Corn grain yields for three irrigation rates and four N-fertilizer rates were measured during three years, 1999-2001. While growing season rainfall was 10% to 30% less than long-term normal seasonal rainfall in all years, the effect of deficit rainfall was more severe during 1999 and 2000 than in 2001 because of favorable rainfall distribution in the latter year. As expected, corn grain yields increased with irrigation and N fertilizer, but the nature of the response varied among the three years, probably because of differences in rainfall and rainfall distribution during the growing season. Also, there was less response to N fertilizer during the first year (1999), probably because of residual soil N from antecedent soybean crop. The increase in corn grain yield with increased N fertilizer was greater with irrigation than with only rainfall in 2000 and 2001 because of the greater N-fertilizer base rates applied for the irrigated treatment. The slope of the yield response curve with additional N fertilizer was greater for irrigated treatments than for rainfed treatments in 2000 but not in the other two years. When the two irrigation treatments were combined, the yield response to N fertilizer was quadratic in form in 1999 and 2000, and linear in 2001. For the rainfed treatment, yield response to N fertilizer was linear in all three years. The quadratic response indicated that a potential optimal rate of N was being approached. Increased N applications generally produced increasing corn yields over all irrigation and rainfed treatments. Additional experiments with higher N applications may be needed to determine optimal N and water applications. These findings should be helpful in developing management strategies and decision support systems for profitable management of water and N fertilizer on spatially-variable soils in the southeastern Coastal Plain while conserving natural resources and protecting the environment.

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