Irrigation, Deep Tillage, and Nitrogen Management for a Corn–Soybean Rotation

C. R. Camp, E. J. Sadler

Abstract. *Of the numerous factors affecting crop yield, the major factor for corn and soybean in the southeastern Coastal Plain appears to be available soil water. Inadequate rainfall and soil compaction, which limits root exploration of stored soil water, exacerbate this problem. Potential solutions, though costly and energy intensive, include irrigation and annual deep tillage. Sometimes, doing both provides additive yield increases for corn. The objectives of this study were: (1) to prove a site–specific irrigation system, and (2) to test the separate and combined effects of irrigation, tillage, N–fertilizer, and crop rotation on corn and soybean yield. A center–pivot irrigation system that had been modified to allow variable–rate water and nutrient applications to 100–m² plots within the system was used to manage an experiment with corn–soybean rotation, irrigation, deep tillage, and N–fertilizer treatments during 1995–1998. The modified center–pivot system satisfactorily applied water and N fertilizer to the treatment areas, and reliability of the control system improved during this experiment. Irrigation increased corn yield all years (8% to 135%) and soybean yield three of four years (26% to 31%). Deep tillage increased yield in only two years, for corn (4% to 6%). For these soil and weather conditions, irrigation increased corn and soybean yields more consistently than deep tillage. The site–specific irrigation facility performed as expected and should provide the research infrastructure to answer many long–standing questions about irrigated cropping systems in the southeastern Coastal Plain.*

Keywords. *Precision agriculture, Site–specific irrigation, Soil water storage, Soil compaction, Center pivot.*

Crop yield is determined by numerous interacting factors. For corn and soybean in the southeastern Coastal Plain, the factor most limiting yield appears to be available soil water. Soil water may be limited by periods without rainfall, by low soil water storage capacity, or by both. Rainfall during the growing season normally exceeds crop evapotranspiration but is poorly distributed, both in time and space. Furthermore, many soils in the southeastern Coastal Plain have compacted soil horizons that severely restrict root development and, thus, extraction of water and nutrients from deeper soil layers. These two problems have been addressed by both tillage and irrigation. The tillage approach, in–row subsoiling during planting each year, is a common cultural practice for many agronomic crops, especially corn and soybean. Busscher et al. (2000, 2001) reported that corn and soybean yields decreased with time after performing deep tillage (increasing soil strength) and were closely related to rainfall for selected time periods during the growing season on a coastal plain soil. Corn grain yield increases due to irrigation have been reported for the southeastern Coastal Plain (Camp et al., 1985, 1988; Cassel et al., 1985; Hook et al., 1984). In some cases, the combination of deep tillage and irrigation on these soils has produced additive yield increases (Camp et al., 1988; Cassel et al., 1985). However, both practices are energy intensive and costly, and in some cases, the benefit may not justify the cost.

Within these tillage and irrigation questions lies the issue of nitrogen fertilizer management. To reduce the potential for nitrate loss in rainfall–induced leaching and to improve N use efficiency, one could use incremental topdress N applications on corn. Incremental N applications are not used in many cases because of the additional operational expense of using ground equipment; however, it can be accomplished easily and at little additional cost using a center–pivot irrigation system. For two sands with irrigation in Georgia, Gascho and Hook (1991) developed a fertilizer management program that consisted of about 25% pre–plant, about 22% at each fertigation application at V6, V12, and V16–18 growth stages, and the remainder at R1. This fertigation program yielded more than 56 kg/kg N and resulted in corn grain yield increases of 1.1 to 1.4 Mg/ha when compared to the conventional program of 25% at planting and 75% at V6 to V8. Others have emphasized the importance of proper management of irrigation and N fertilizer applications (timing and amounts) to reduce the potential for nitrate leaching, to optimally allocate limited resources and improve water and N–fertilizer efficiencies, and to consider N credits from water and antecedent crops in a rotation (Ferguson et al., 1991; Lamm et al., 1993; Oberle and Keeney, 1990). Most

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cropping systems involve two or three crops grown in rotation; one of the most common rotations is corn and soybean. For soybean, there has been success, including higher yields and easier weed management, using narrow ($\leq$0.25 m) rows. For this new system, however, a question remains regarding irrigation water requirements for soybean in these configurations, especially during periods without rainfall.

The above considerations hold for traditional whole–field, uniform irrigation management. However, within–field variability of the coarse–textured soils of the southeastern Coastal Plain is high, even for small fields or small center–pivot irrigation systems. Based on observations of spatial patterns in crop growth, especially during periods of plant water stress, the major factor contributing to yield variability for soils in the Coastal Plain appears to be plant–available soil water (Sadler et al., 2000). Results from an ongoing study that investigated yield for 22 crops during a 16–year period found no useful correlation between yield and several patterns of variation, including soil map unit and other soil properties. The combined effects of climate and soil variability and the uniform application rates of most center–pivot irrigation systems make it almost impossible to optimally manage irrigation and nutrients using a conventional irrigation system (Camp et al., 1988).

Beginning in 1991, a center–pivot irrigation system was developed by USDA–ARS at Florence, South Carolina, to provide variable–rate applications of water and nutrients to discrete elements within the total system. A commercial center–pivot system was modified by adding a variable–rate water delivery system (Omary et al., 1997) with a computer–based control system that provided spatial control of irrigation and nutrient applications to individual elements of the total system (Camp and Sadler, 1994; Camp et al., 1998). This modified system was used to apply water and nitrogen fertilizer to fixed–boundary plots of a replicated experiment to determine the effects of irrigation, crop rotation, N fertilizer, and deep tillage for corn and soybean grown in rotation under conservation tillage.

The objectives of this study were (1) to demonstrate the capabilities of a modified center–pivot irrigation system for site–specific applications of water and fertilizer, and using this system, (2) to determine the effects of irrigation, deep tillage, crop rotation, and N fertilizer on corn and soybean grain yield under conservation tillage culture.

Materials and Methods

The study was conducted from 1995 through 1998 on a relatively uniform, 6–ha site of Norfolk loamy sand (Typic Kandiudult) near Florence, South Carolina. The control system for a modified center–pivot irrigation system was also being developed and evaluated at this site. In the two–year period preceding this experiment, successive crops of corn, wheat, and soybean were grown on this site, but with no irrigation. In this experiment, there were three crop rotations (corn–corn, corn–soybean, and soybean–corn), two tillage practices (subsoiled and not subsoiled), and two water management treatments (rainfed and tensiometer–controlled irrigation). There were two nitrogen fertilizer regimes for corn (single fertigation application and multiple incremental fertigation applications) and four replications. The original experimental design included three water management treatments (total of 144 plots) but only two of these treatments were implemented (total of 96 plots) and included in these results. In 1998, the subsoiled treatment on soybean was split to include deep tillage by two different implements, either a subsoil shank or a paratill shank. All treatments remained in the same location each year, and no surface tillage was performed during the experiment. Because N fertilizer was not applied to soybean and there were no significant residual effects from the antecedent corn crop, soybean yield data for N–fertilizer treatments were combined.

The center–pivot irrigation system had been modified to provide 13 segments along its length, each 9.1 m long. The variable–rate water delivery system consisted of three manifolds to deliver 1×, 2×, or 4× of a base application depth at that specific location along the truss. All combinations of the three manifolds provided 0×, 1×, 2×, ..., 7× of the base depth. The 7× depth was 12.7 mm when the outer tower was operated at 50% duty cycle. The variable–rate delivery system was under the overall control of an 80386 PC computer (Horner Electric, Indianapolis, Ind.) with a hard drive, floppy drive, serial ports, and peripheral connectors, which was mounted on the programmable logic controller (PLC) backplane (model 90–30, GE Fanuc, Charlottesville, Va.) and connected via the system buss. The PC and PLC were mounted on the mobile portion of the system, from which they controlled solenoids attached to each manifold. Angular location of the truss was determined from the C:A:M:S management system (Valmont Industries, Inc., Valley, Neb.) via a communication link between the mobile PC and the stationary management system.

Software written in Visual Basic for DOS (Microsoft Corp., Redmond, Wash.) converted a set of control values to on–off settings in the directly addressable control registers of the PLC. The on–board computer retrieved and corrected angular position of the truss by repeated interrogation of the stationary computer. The fixed radius of each segment along the truss and the angular position of the truss determined the location of that segment at that time, which was expressed in polar coordinates. Appropriate manifold solenoids were switched on or off according to the current angular position and based upon user–supplied data. A more detailed description of the water delivery system may be found in Omary et al. (1997) and of the control system in Camp et al. (1998).

The nutrient injection system installed on the modified center–pivot system was based on the principle of maintaining a constant nutrient concentration in the water supply line. Variable nutrient amounts were applied to each segment by varying water application depth. Because the water flow rate varied frequently depending upon the number of solenoids switched on at any time, the nutrient injection rate also had to vary in proportion to water flow rate at that time. This was achieved with a 4–head, 24 VDC, variable–rate injection pump (model 40320, Ozawa R&D, Inc., Ontario, Ore.). The pump injected nutrient solution (UAN 24S in this case) into the water supply pipe at the center pivot. The pump injection rate was varied by the number of heads used and the pump speed, which was controlled by adjusting the 0–5 VDC signal to the pump controller. To keep the nutrient injection rate proportional to the water flow rate, the on–board computer calculated the water flow rate, the required nutrient injection rate, and the appropriate control voltage setting, and then set the appropriate control voltage for the pump controller via the PLC control system. All fertigation N fertilizer for corn (UAN 24S) was applied via the nutrient injection system using the 2× manifold, which delivered 3.6 mm of water at 50% duty cycle and 1.8 mm at 100%.

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's flow rate was 100 to 3,000 L/min at 275 kPa pressure using a 4–pump staged pumping plant. Additional details are included in Camp et al. (1998).

All experimental plots were located on the outer six 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 pattern, which made the minimum plot length 10 m in segment 8 and 17 m in segment 13. All rows were planted, and all subsequent operations were performed in the circular pattern that coincided with the travel pattern of the center–pivot system. Each of the four replicates was located in angular sectors of the circle (fig. 1). The experimental design was a split–split randomized complete block with crop rotation and deep tillage as splits, and irrigation and N–application treatment combinations in completely randomized blocks. Yield data were analyzed using analysis of variance (ANOVA), and means were separated by calculating the least significant difference (LSD) (SAS, 1990).

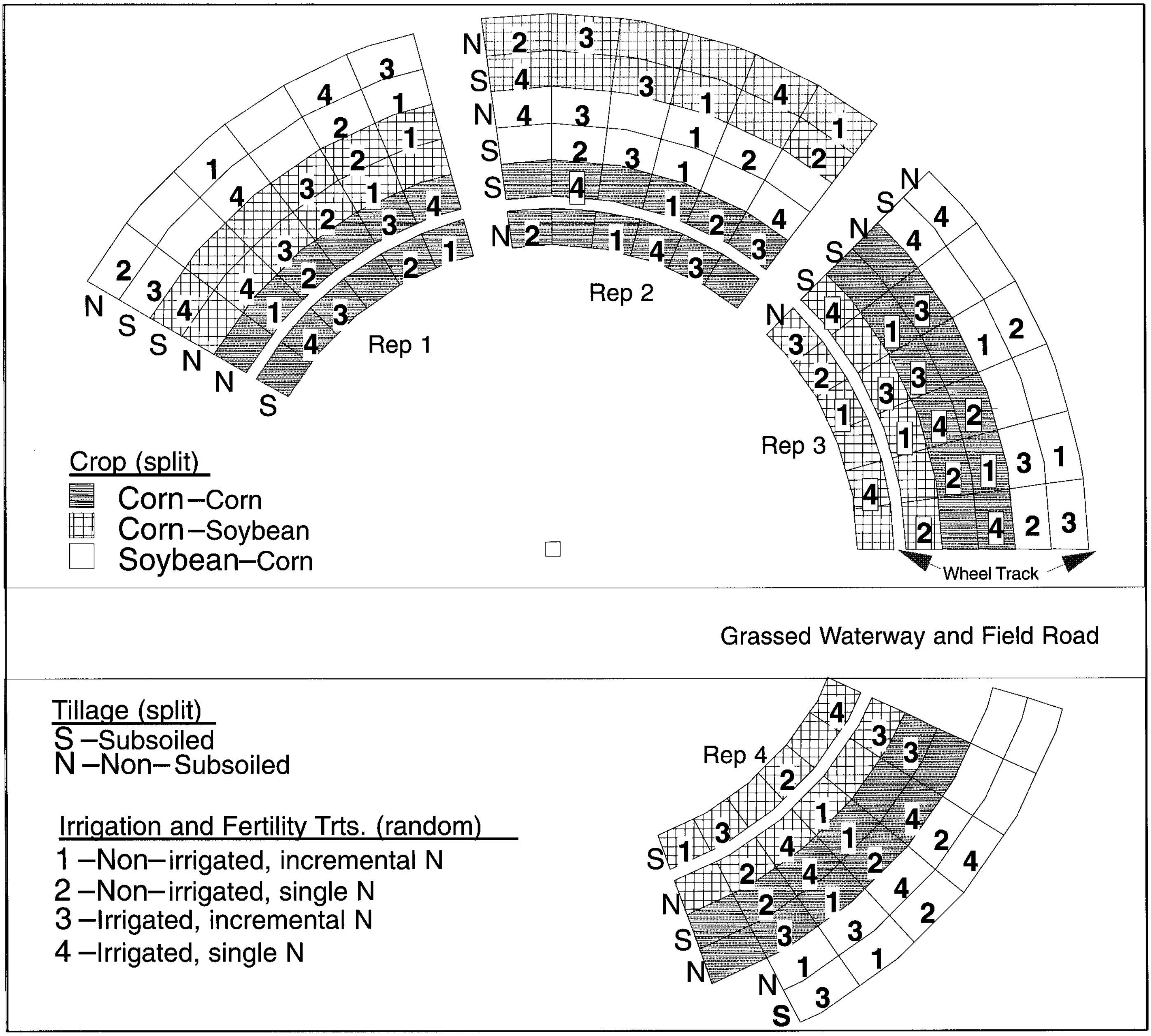


Figure 1. Schematic diagram of treatments in a corn–soybean rotation experiment under a site–specific center–pivot irrigation system with irrigation, tillage, and N–fertilizer treatments, all with conservation tillage, in the southeastern Coastal Plain.

Deep tillage in appropriate plots was done in both corn and soybean with subsoiler shanks spaced 0.76 m apart, which coincided with the row in corn. For soybean in 1998, an additional deep tillage treatment (paratill) was added, which was done with paratill shanks (Mukhtar et al., 1985; Unger, 1993) (Tye Co., Lockney, Texas) spaced 0.76 m apart. In both deep tillage methods, the soil was disturbed to a depth of about 0.40 m, but the paratill shank disturbed a wider band than the subsoil shank. In all years, soybean was planted with a grain drill in rows spaced 0.19 m apart and parallel to the deep tillage path. Except for N, fertilizer applications for both corn and soybean were based on soil test results. N fertilizer and pesticides were applied as recommended by the Clemson University Cooperative Extension Service for the soil texture and either rainfed or irrigation culture (Clemson, 1982). Annual fertilizer applications for corn ranged from 39 to 43 kg/ha for N, 9 to 21 kg/ha for P, and 61 to 112 kg/ha for K as broadcast pre-plant fertilizer with micronutrients. Fertigation N (134 kg/ha) was applied either in one or two applications within a one-week period or in six equal increments (approximately weekly), both starting at the same time. Soybean received 0 to 24 kg/ha P and 0 to 61 kg/ha K preplant broadcast fertilizer.

Corn (cv. Pioneer 3163) was planted at the rate of 74,000 seeds/ha in 1995 and 81,500 seeds/ha in other years. Corn was planted on 12 April 1995 (DOY 102), 26 March 1996 (DOY 86), 25 March 1997 (DOY 84), and 2 April 1998 (DOY 92) using a Case/IH model 800 planter (Case Corp., Racine, Wisc.). In 1995, 37–m^2 areas of the center eight rows of each corn plot were harvested 5 to 20 September (DOY 248–263) using an Almaco plot combine with corn header (Almaco, Nevada, Iowa). Because of lodging caused by Hurricane Fran in 1996, 9–m^2 areas of the center four rows of each corn plot were hand harvested 10 to 19 September (DOY 254–263). In 1997 and 1998, 37–m^2 and 28–m^2 areas of the center eight rows of each corn plot were harvested using the Almaco plot combine on 5 to 24 September (DOY 248–267) and 2 to 10 September (DOY 245–253), respectively. All corn yields were corrected to 15.5% grain moisture.

Soybean (cv. Hagood) was planted at the rate of 95 kg/ha on 22 May 1995 (DOY 142), 22 May 1996 (DOY 143), 13 May 1997 (DOY 133), and 13 May 1998 (DOY 133) using a Deere model 750 drill (Deere and Co., Moline, Ill.). Areas of varying size were harvested from the center of each soybean plot using an Almaco plot combine with a small grain header: 14 to 20 m^2 on 28 November 1995 (DOY 332), 18 to 39 m^2 on 10 December 1996 (DOY 345), 13 to 21 m^2 on 18 to 19 December 1997 (DOY 352–353), and 8 to 18 m^2 on 5 November 1998 (DOY 309). All soybean yields were corrected to 12.5% moisture content.

Tensiometers were installed at depths of 0.30 m and 0.60 m in both tillage treatments of the irrigated treatment in all four replicates. Tensiometers were usually read and recorded three times each week and were serviced as required. Irrigation was applied when the mean soil water potential (SWP) values at the 0.30–m depth were less than –25 kPa for corn and –35 kPa for soybean. Daily irrigation application depths were equal for all irrigated treatments, either 12 or 25 mm/application depending upon soil water depletion and crop growth stage.

Results and Discussion

Cumulative rainfall, rainfall plus irrigation, and calculated evapotranspiration (ET) (Walter et al., 2000) for both corn and soybean growing seasons during 1995–1998 are shown in figures 2 through 5. Seasonal rainfall, irrigation, and solar radiation values are shown in table 1 for the same periods. Seasonal rainfall was least in 1998 for both corn and soybean (356 mm and 354 mm). Seasonal rainfall was greatest for corn in 1996 (599 mm) and for soybean in 1995 (922 mm). Rainfall distribution varied among the four years, with little rainfall during the spring of 1995 and the late fall of both 1996 and 1998. Rainfall during these years included several large events (>30 mm). Rainfall was distributed more uniformly in 1997 but also included three large events. The large seasonal rainfall for soybean in 1995 resulted from several rainfall events, some very large, during the early summer and fall. Seasonal solar radiation was least in 1995 and greatest in 1997 for both corn and soybean (2638 to 3022

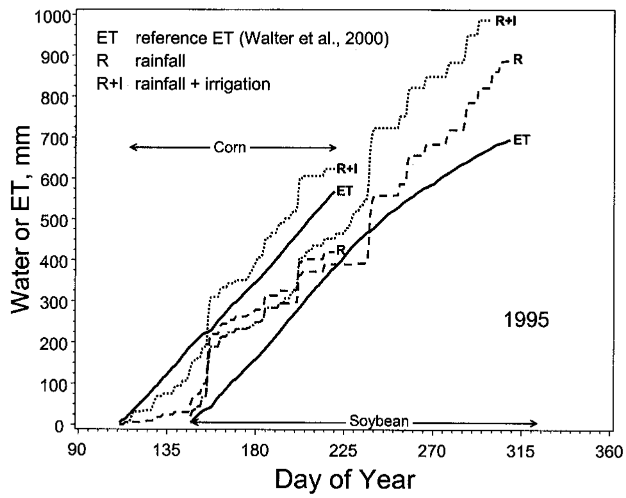
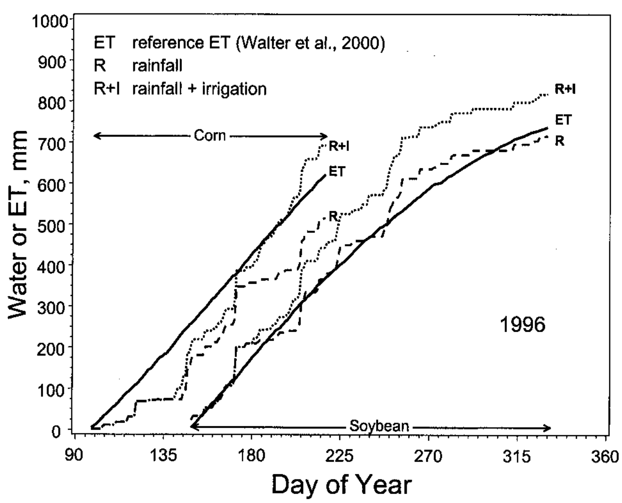


Figure 2. Cumulative rainfall, rainfall plus irrigation, and calculated reference evapotranspiration (ET) during the 1995 corn and soybean growing seasons at Florence, South Carolina.



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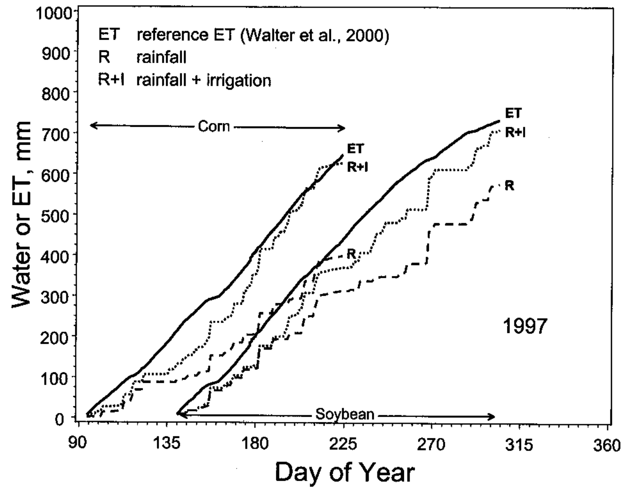

Figure 4. Cumulative rainfall, rainfall plus irrigation, and calculated reference evapotranspiration (ET) during the 1997 corn and soybean growing seasons at Florence, South Carolina.

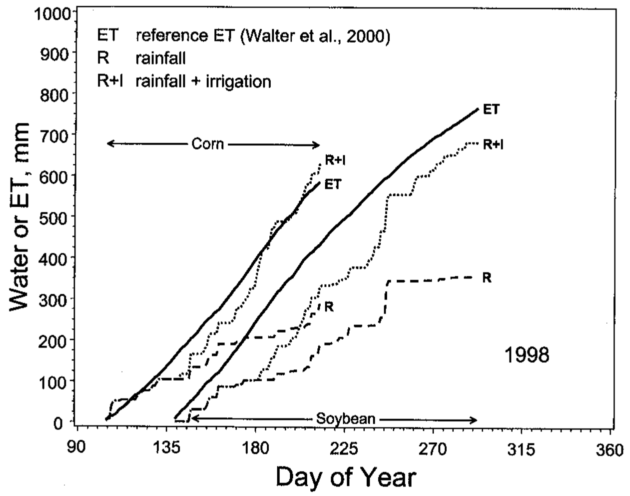

Figure 5. Cumulative rainfall, rainfall plus irrigation, and calculated reference evapotranspiration (ET) during the 1998 corn and soybean growing seasons at Florence, South Carolina.

Table 1. Seasonal rainfall, irrigation, and solar radiation for corn and soybean under a site–specific center–pivot irrigation system on a southeastern Coastal Plain soil near Florence, South Carolina, during 1995–1998.

	Corn[a]			Soybean[b]		
Year	Irrigation (mm)	Rainfall (mm)	Solar Radiation (MJ/m^2)	Irrigation (mm)	Rainfall (mm)	Solar Radiation (MJ/m^2)
1995	221 (18)[c]	420	2638	178 (14)	922	3120
1996	178 (16)	599	2936	114 (11)	793	3432
1997	216 (20)	402	3022	140 (11)	666	3670
1998	341 (24)	356	2802	390 (29)	354	3397

[a] Season length was defined as planting date to day that cumulative growing degree units (GDU base 10°C) reached 1640°C–days.
[b] Season length was planting date to two weeks prior to harvest.
[c] Numbers in parentheses indicate number of irrigation events during the season.

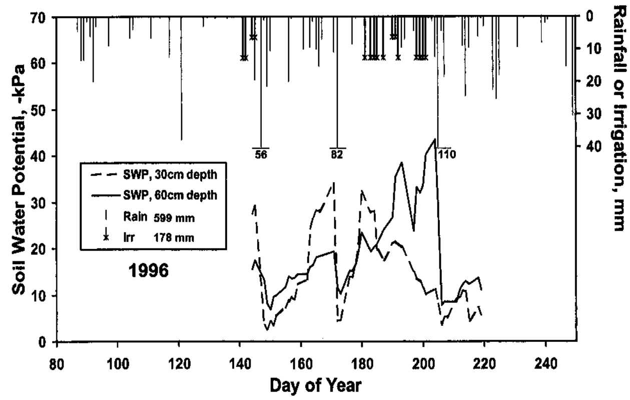

Figure 6. Daily rainfall, irrigation, and soil water potential at two depths for corn irrigated with a site–specific center–pivot irrigation system in 1996. Soil water potential values are the mean of two tillage treatments and two N–fertilizer treatments. Numbers adjacent to truncated rainfall lines are daily rainfall amounts in mm. Seasonal rainfall and irrigation totals are shown in the legend.

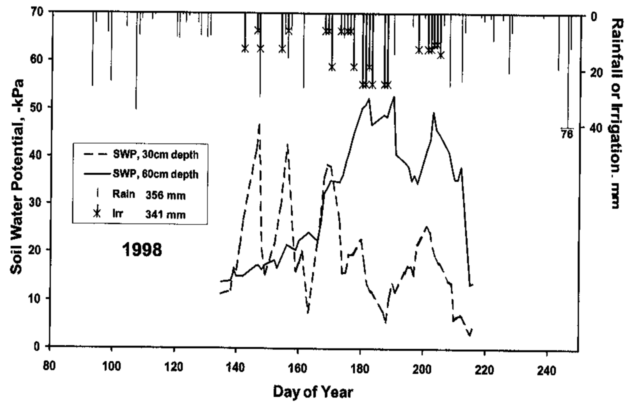

Figure 7. Daily rainfall, irrigation, and soil water potential at two depths for corn irrigated with a site–specific center–pivot irrigation system in 1998. Soil water potential values are the mean of two tillage treatments and two N–fertilizer treatments. Numbers adjacent to truncated rainfall lines are daily rainfall amounts in mm. Seasonal rainfall and irrigation totals are shown in the legend.

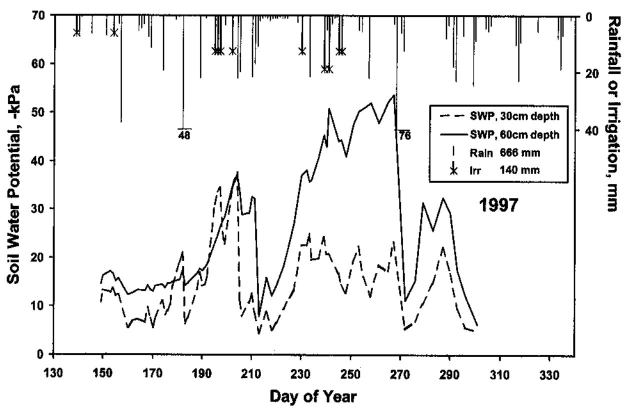

Figure 8. Daily rainfall, irrigation, and soil water potential at two depths for soybean irrigated with a site–specific center–pivot irrigation system in 1997. Soil water potential values are the mean of two tillage treatments and two N–fertilizer treatments. Numbers adjacent to truncated rainfall lines are daily rainfall amounts in mm. Seasonal rainfall and irrigation totals are shown in the legend.

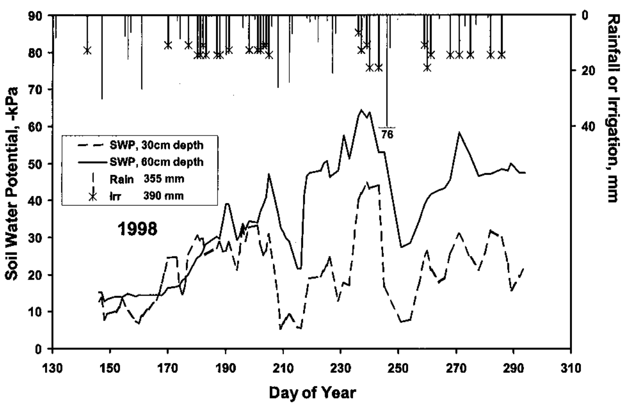

Figure 9. Daily rainfall, irrigation, and soil water potential at two depths for soybean irrigated with a site–specific center–pivot irrigation system in 1998. Soil water potential values are the mean of two tillage treatments and two N–fertilizer treatments. Numbers adjacent to truncated rainfall lines are daily rainfall amounts in mm. Seasonal rainfall and irrigation totals are shown in the legend.

MJ/m^2 for corn and 3120 to 3670 MJ/m^2 for soybean). Mean air temperature values and the diurnal variation of daily air temperatures were similar for the four years, but maximum temperatures were slightly greater in 1995 and 1998 (data not shown).

Seasonal irrigation amounts were greatest in 1998 for both corn and soybean (341 and 390 mm) and least in 1996 for both crops (178 and 114 mm) but were not consistently related to seasonal rainfall amount, primarily because of rainfall distribution and a lower fraction of rainfall that infiltrated during large rainfall events. Daily irrigation and rainfall amounts and SWP values at two soil depths are shown in figures 6 through 9 for selected years with each crop. SWP values at the 0.30–m depth during the corn growing season were maintained greater than –30 kPa except in 1998, which will be discussed later. SWP values at the 0.60–m depth were slightly lower (<–40 kPa), especially in the latter part of the growing season, which indicates that irrigation amounts were not sufficient to replace water extracted from the subsoil during the growing season. Past observations indicate that large rainfall amounts are required to replace subsoil water during the latter part of the growing season for corn. This was evident by the SWP values for corn at about DOY 208 in 1996 (fig. 6) when daily rainfall was 110 mm. In the case of soybean, SWP values at the 0.30–m depth were greater than –40 kPa for most of the season in all years. SWP values at the 0.60–m depth were less than for the 0.30–m depth for most of the time in all years, especially during the middle and latter portions of the seasons, and often reached values of –50 kPa in 1998.

Mean corn grain yields are reported in table 2 across all crop rotation, deep tillage, and N–fertilizer treatments for all years. Results of the analysis of variance are reported in table 3. There was no difference in corn yield between the two N–fertilizer treatments in any year. Corn grain yields were increased by irrigation in all years, ranging from 8% greater in 1996 to 135% greater in 1998. Yields were greatest in 1996 and much less in 1998. Possible reasons for the low yields in 1998 will be discussed later. Corn grain yields in subsoiled treatments were greater than in non–subsoiled treatments only in 1997. Yield increases with subsoiling and irrigation in this year may have been caused by extraction of leached nutrients from the lower soil profile, but the yield differences were relatively small (8%). Mean corn grain yields in the soybean/corn rotation were greater than for continuous corn only in 1997, but again, the yield increase was small (<8%). Only three of the 24 two–way interactions were significant during the four years (table 3).

Table 2. Corn grain yields with and without irrigation under a center–pivot irrigation system on a southeastern Coastal Plain soil near Florence, South Carolina, during the four–year period 1995–1998. Each value is the mean of deep tillage, crop rotation, and N–fertilizer treatments.

Year	Irrigated (Mg/ha)	Rainfed (Mg/ha)
1995	11.03 a [a]	9.82 b
1996	12.06 a	11.18 b
1997	10.77 a	9.38 b
1998	7.73 a	3.29 b

[a] Means followed by the same letter within a year are not different at P≤ 0.01 by LSD.

Table 3. Analysis of variance results for corn yield by year in an experiment with irrigation, tillage, crop rotation, and N–fertilizer treatments.

		Mean Squares			
Source[a]	df	1995	1996	1997	1998
Crop	1	1.81	13.16	34.94** [b]	24.18
Error A	3	2.16	24.78	0.55	7.97
Tillage	1	0.03	12.19	21.86**	3.89
Crop*Tillage	1	0.44	1.88	0.73	0.11
Error B	6	5.31	2.17	0.45	3.73
UAN	1	2.88	3.66	0.40	0.41
Water	1	54.40**	50.14**	123.51**	939.30**
Crop*UAN	1	6.85	0.71	4.29	3.09
Crop*Water	1	0.88	0.01	6.15	19.26*
Tillage*UAN	1	0.24	5.67	3.44	0.68
Tillage*Water	1	9.73	25.65**	2.68	0.70
Water*UAN	1	4.36	3.35	0.31	15.98*
Crop*Tillage*UAN	1	7.97	1.17	0.58	1.53
Crop*Tillage*Water	1	0.05	0.01	0.32	2.05
Crop*Water.*UAN	1	1.03	2.96	0.05	0.67
Tillage*Water*UAN	1	3.32	0.09	0.15	3.85
Crop*Tillage*Water*UAN	1	9.42	13.53*	2.18	2.12
Error C	36	4.15	2.80	4.20	2.72

[a] Crop = crop rotation phase, UAN = nitrogen fertilizer treatment, Tillage = deep tillage treatment, and Water = irrigation treatment.
[b] * and ** indicate significance at P≤ 0.05 and 0.01, respectively.

As mentioned above, even though the irrigated corn yield in 1998 (7.73 Mg/ha) was more than double the rainfed yield (3.29 Mg/ha), it was less than the irrigated yields for other years (mean of 11.29 Mg/ha) and was less than even the rainfed yields in those years (mean of 10.13 Mg/ha). There was little significant rainfall during the 20 days prior to the first tensiometer data (DOY 115–135) in 1998 (fig. 7) and solar radiation and temperatures were relatively high. Because of the sandy soils and clear skies during the spring season in this region, it has been speculated that, without rainfall in April and May, the microclimate for young corn plants may have been quite severe. In 1998, SWP values at the 0.30–m depth were –35 to –40 kPa on three occasions early in the growing season (DOY 145–170), while the values at the 0.60–m depth were slowly decreasing but were much greater, especially for the early part of the period. This indicates that the corn root system was very active at the shallow soil depths but much less active at the deeper depths until the latter part of the period. The general recommendation for this region is that little irrigation be applied during the early part of the growing season. However, there may have been significant crop stress prior to installation of tensiometers in 1998 (fig. 7). These conditions, in combination with the low SWP values (<–35 kPa) on three occasions early in that growing season (fig. 7), may have caused the much lower corn grain yield for this year. These results suggest that additional research is required to determine whether irrigation earlier in the growing season, starting irrigation at a wetter soil condition, or applying greater irrigation amounts later in the growing season will increase corn grain yield.

Soybean yields were 26% to 31% greater for irrigated than for rainfed conditions in all years except 1996 (table 4). Results of analysis of variance are reported in table 5. Soybean seed yields were not different among crop rotation, tillage (two deep tillage types in 1998), or antecedent (corn) N–fertilizer treatments in any year. Consequently, values reported in table 4 are means of these treatments. While irrigation increased soybean yields in three of four years, the yield was not as great as expected based on yields obtained using this cultural practice at other nearby locations. The reasons for the lower–than–expected yields are not known. There were no significant interactions during the four years.

Table 4. Soybean yields with and without irrigation under a center–pivot irrigation system on a southeastern Coastal Plain soil near Florence, South Carolina, during the four–year period 1995–1998. Each value is the mean of deep tillage treatments and antecedent N–fertilizer treatments on corn.

Year	Irrigated (Mg/ha)	Rainfed (Mg/ha)
1995	1.85 a [a]	1.47 b
1996	2.26 a	2.22 a
1997	1.75 a	1.37 b
1998	2.18 a	1.66 b

[a] Means followed by the same letter within a year are not different at $P \leq 0.01$ ($P \leq 0.05$ in 1995).

Table 5. Analysis of variance results for soybean yield by year in an experiment with irrigation, tillage, and N–fertilizer treatments. MS is mean squares, UAN is nitrogen fertilizer treatment in previous corn crop, Tillage is deep tillage treatment, and Water is irrigation treatment.

Source	df	Mean Squares 1995	1996	1997	1998[a] df	MS
Rep	3	1.16**[b]	0.19	0.48	2	0.40**
UAN	1	0.57	0.19	0.28	1	0.00
Water	1	1.13*	0.03	2.35**	1	2.44**
Tillage*UAN	1	0.02	0.00	0.28	2	0.19
Tillage*Water	1	0.00	0.00	0.17	2	0.07
Water*UAN	1	0.04	0.27	0.12	1	0.00
Tillage*Water*UAN	1	0.01	0.00	0.41	2	0.01
Error A	18[c]	0.15	0.09	0.17	18	0.06
Tillage	1	0.07	0.00	0.05	2	0.03
Error B	3	0.03	0.31	0.71	4	0.12

[a] In 1998, the deep tillage treatment was split to include tillage by two different implements: a subsoil shank and a paratill shank.

[b] * and ** indicate significance at $P \leq 0.05$ and 0.01, respectively.

[c] Error A df = 50 for 1996 and 1997 when the number of treatment observations was different.

While the site–specific center–pivot irrigation system was not used to apply water and nutrients in a typical precision agriculture sense, it was successfully used to accurately apply a wide range of irrigation and N fertilizer amounts to a pre–defined array of fixed plots, which included some plots that received no water. As such, it applied variable rates according to a pre–defined map, which demonstrated its capability to do so for any such map, as required for site–specific agriculture. In particular, the spatial control portion of the site–specific center–pivot system was fully utilized and tested. The control system software for the system evolved during the 1995 growing season through experience and modification so that, by the end of season, the system operated unattended most of the time. Improvement in communication reliability between the fixed and movable components continued during 1996 and 1997 so that by 1998 the system was operating in a reliable manner with minimal operator attention. Acceptable irrigation distribution uniformity within control areas (center 6 m × 6 m area within a plot) and expected border effects between elements with different irrigation application depths were measured and reported previously (Omary et al., 1997). Observations during the 1995–1998 growing seasons presented no evidence that border effects were different than expected from previous measurements, and border effects were therefore considered acceptable. Water ponding and surface redistribution were not observed, even during nutrient application when nozzle discharge was collected in a 37–mm diameter flexible hose and discharged near the soil surface. This had been a concern during design because of relatively high instantaneous application rates and small wetted diameters by the nozzles. Satisfactory water distribution uniformity values were previously measured both along the radius and parallel to the travel path of the system (Camp and Sadler, 1997).

Summary and Conclusions

The site–specific center–pivot irrigation system applied water and N fertilizer to 144 individual fixed–boundary plots in an acceptable manner. Single and incremental fertigation applications were made by varying the application depth of a solution with a constant concentration of N fertilizer, which had been injected into the water supply. Reliability of the control system hardware and software improved during this experiment so that it could operate unattended much of the time. Observations during this experiment confirmed previously reported acceptable water distribution uniformity and border effects when two adjacent elements applied different water depths. Thus, the first objective, to demonstrate the system capability and acceptability, was accomplished.

In an experiment with irrigation, deep tillage, crop rotation, and N–fertilizer treatments for corn and soybean on conservation tillage, irrigated corn yields were greater than rainfed yields in all years. Corn grain yields were greater for deep tillage treatments in two years. In only one year were corn grain yields in the corn–soybean rotation greater than in continuous corn. There was no difference in corn grain yields for the N–fertilizer treatments in any year. Soybean seed yields were greater with irrigation in three of four years. Deep tillage and antecedent N–fertilizer (for previous corn crop) treatment had no effect on soybean yield in any year.

Although not used in a typical precision agriculture sense, the site–specific center–pivot system applied variable water and N fertilizer amounts to a pre–defined array of fixed plots and provided experimental treatments that would have been extremely costly to impose using conventional means. Thus, it demonstrated its acceptability to do so for any such map, as required for precision agriculture. The site–specific irrigation facility should provide the research infrastructure to answer many long–standing questions about irrigated cropping systems in the southeastern Coastal Plains.

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