Spatial variation in crop response: I. Overview for variable irrigation of corn.

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Abstract

During the 1990's, independent research at four sites created methods to apply irrigation water in a site-specific manner, both along the direction of travel and along the boom of moving irrigation systems. At one of these, ARS - Florence, SC, research in this area produced more than 25 publications dealing with specific aspects of the system and research results, and these need to be integrated into a comprehensive summary. This paper provides an overview of the project, sets it in the context of the preceding Florence research, and provides the foundation for a companion paper that examines site-specific irrigation and nitrogen production functions for representative soils of the southeast US Coastal Plain. In these two papers, data are discussed from two experiments that were conducted during 1999-2001 using the two site-specific center pivots in the irrigation facility. Both used corn as the first test crop. One was a 144-plot irrigation x nitrogen experiment on the predominant soil map unit for the area, and the other was a 396-plot irrigation x nitrogen x soil experiment on a field with 12 soil map units. This paper shows the spatial variation in crop response that was obtained; the companion paper discusses implications for irrigation management.

Introduction

For more than two decades, two series of research projects conducted at the USDA-ARS Coastal Plains Soil, Water, and Plant Research Center in Florence, SC, have converged toward the site-specific application of irrigation water and nutrients to address the problems of managing crop production on fields with extreme soil variation. During this time, research reports have documented individual studies, but no comprehensive summary has been done. This paper and the companion paper in this proceedings (Camp et al., 2002) comprise an overview of the suite of studies and discuss the implications of the collective findings. Space constraints necessarily prevent an extensive treatment of literature in this paper. For a discussion of the state of the art of site-specific irrigation, the reader is referred to Sadler et al. (2000), Evans et al. (2000b), and Buchleiter et al. (2000). For general issues relating to irrigation in humid regions, see Camp et al. (1990) and Sadler et al. (2002d)

In 1979, a 5-state southeast regional irrigation scheduling project was initiated for the coastal plain from Florida through Virginia (Camp and Campbell, 1988). The experiences at the Florence location (Camp et al., 1988) highlighted the difficulty in fine-tuning the management of irrigation for center pivots sited on typically variable Coastal Plains soils. Despite the relatively small size of this irrigation system (4 towers), it encompassed one soil with substantially more sand and another with substantially more clay than the prevalent soil, which was a loamy sand. No matter which set of physical parameters were used in the computer-based irrigation scheduling program, the result was inevitably not optimized for nearly two-thirds of the system. However, equipment to

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independently manage these soils was not available from any source.

In a separate study, inherent productivity of various soil types in a typical Coastal Plain field was examined to build a basis for soil productivity ratings (Karlen et al. 1990). In this and subsequent examinations (Sadler et al. 1995, 1998), it became apparent that site-specific management of soil fertility, by itself, could not address the variation observed in grain yields for several field crops. By this time, commercial equipment for variable-rate fertilizer application was available, but only in other regions of the country.

Consequently, a site-specific center pivot irrigation machine was designed (Camp and Sadler, 1994), and two 3-tower, 140-m commercial systems were modified to meet these specifications (Camp and Sadler, 1997;Omary et al., 1997; Camp et al., 1998). The design called for the capability to apply irrigation independently to 9-m square cells, and by varying application depth while injecting nutrients for a constant concentration, to apply nutrients independently to these same 9-m square cells. The small size of these areas necessitated locating nozzles with very small (<3 m) wetted radii (Omary et al., 1997). The control of this system also required a separate PC/PLC (programmable logic controller) unit that communicated with the commercial system's controller. The modifications also included 3 separate manifolds that applied geometrically larger flow rates for each of the 13 section along the center pivot main boom. These were chosen to be 1x, 2x, and 4x, so that all three, or 7x, applied 12.7 mm when the center pivot was moving at 50% of full speed. System performance was evaluated and documented in Camp and Sadler (1997), Omary et al. (1997), and Camp et al. (1998).

These machines were used in two experiments, the first from 1995-1998 to prove the function of the design on center pivot #1 (CP1) on a reasonably uniform soil (Camp and Sadler, 2002), and the second from 1999-2001 to evaluate irrigation (Sadler et al. 2002b) and nitrogen (Camp et al., 2002) production functions on both center pivots. The varied irrigation applications on center pivot #2 (CP2), on a typically variable field, had correspondingly varied water stress, which provided an opportunity to examine capabilities of infrared thermometers to detect stress with suitable precision under Southeastern climatic conditions (Evans et al., 2000a; Sadler et al., 2002a).

Irrigation production functions were reported by Sadler et al. (2002b) for map unit means and field means for the three years. While the production functions for the different soil map units were significantly different by classical analysis of variance, it was clear that there were also different functions for the different experimental blocks within most of the soil map units. Therefore, a re-analysis on a strictly spatial basis was conducted that ignored the soil map unit delineations (Sadler et al., 2002c). In this analysis, spatial patterns were evident in both irrigation response and the irrigation amount that produced the maximum yield.

The studies above for the period 1999-2001 under center pivot #1 and #2 provide the data used in this and the companion paper. Results will be briefly summarized here, to illustrate the salient findings and provide the data basis for the companion paper, which reports irrigation and nitrogen production functions and discusses the implications of these findings (Camp et al., 2002).

Materials and Methods

Under CP1, a 144-plot replicated factorial experimental design (Fig. 1) was used to specifically examine nitrogen production functions for the most-prevalent soil, which was a Norfolk loamy sand. Plots were 9 m by 7.5 degrees of travel, which was 9 m for the innermost ring and 14 m for the outer one. There were 4 levels of nitrogen fertilization (50%, 75%, 100%, and 125% of recommendations), 3 levels of irrigation (0%, 75%, and 125% of the hypothetical normal amount to replace ET), 3 antecedent cropping conditions at the initiation of the experiment (corn in a corn-soybean rotation, soybean in a corn-soybean rotation, and continuous corn), and 4 replications. The recommended nitrogen fertilizer amount depended on irrigation because the value for rainfed was 135 kg/ha, corresponding to 6 Mg/ha target yield, and the value for the two irrigated treatments was 225 kg/ha, corresponding to 10 Mg/ha target yield. Application of the variable fertilizer, which was UAN 24S (24% urea ammonium nitrate with sulphur), was achieved through variable irrigation with a small irrigation amount. The cultivation was a conservation tillage system that retained surface residue, but tilled the subsoil under the row to a depth of 40 cm. Corn was planted in 76-cm rows around the circle. Cultural operations followed regional extension guidelines. Corn was harvested using a plot combine in 2-row swaths 6 m in length from the center 6x6-m control area of the plots. Yields were stated at 15.5% moisture.

Under CP2, which was on quite variable soils, the focus of the experimental design was to examine whether irrigation production functions for corn were different among soil map units (Fig. 2). The soil map units were determined on a 1:1200 scale by USDA-SCS in 1984 (Karlen et al., 1990). The Norfolk loamy sand mentioned above is designated NkA and can be seen to be the prevalent soil under CP2. In the orientation shown in the figures, 'up' is almost directly northeast. Center pivot 2 is sited directly NE of CP1.

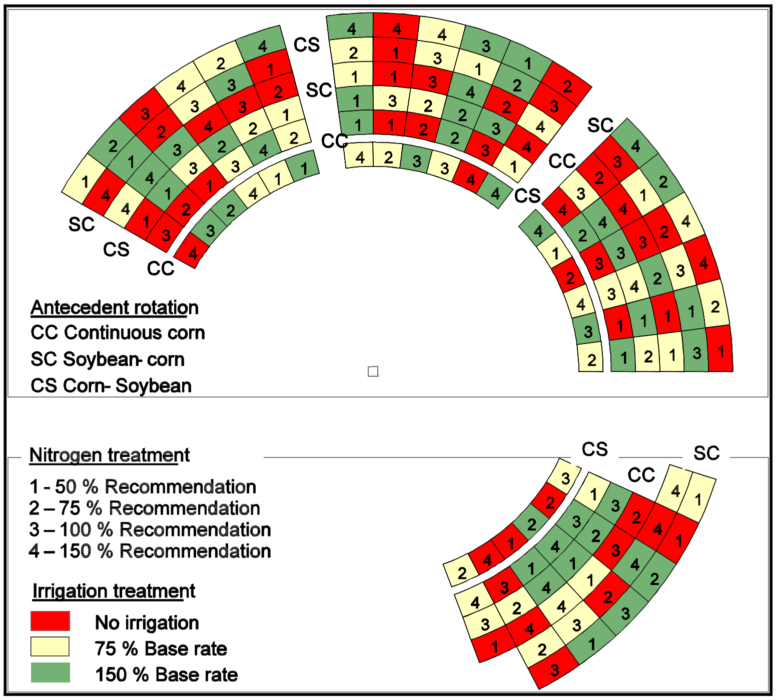

Figure 1. Experimental design for CP1 experiment on corn during 1999-2001.

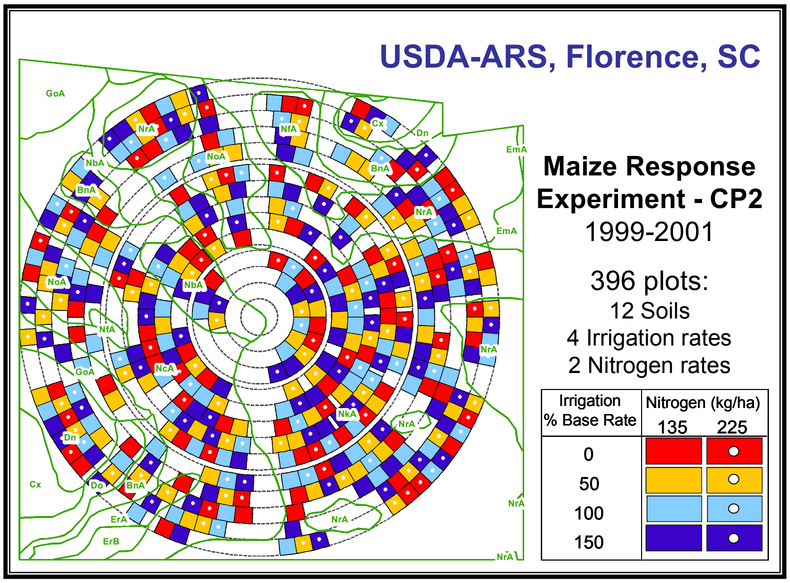

Figure 2. Experimental design for CP2 experiment on corn during 1999-2001.

An innovative 396-plot design combined 2x4 factorial randomized complete blocks where there was sufficient area within a soil map unit and randomized incomplete blocks where there was not. The factors were irrigation amount (0%, 50%, 100%, and 150% of normal, which replaced ET according to tensiometers in selected 100% plots) and nitrogen fertilizer (135 kg/ha and 225 kg/ha, which are the recommendations for rainfed and irrigated corn and correspond to target yields of 6 and 10 Mg/ha). Conventional surface tillage was used, including disking of the surface. Corn was planted in 76-cm rows around the circle with in-row subsoiling to 40 cm to break up a dense eluviated horizon. Cultural operations followed regional extension guidelines. Corn was harvested using a plot combine in 2-row swaths 6 m in length from the center 6x6-m control area of the plots. Yields were stated at 15.5% moisture.

Results and Discussion

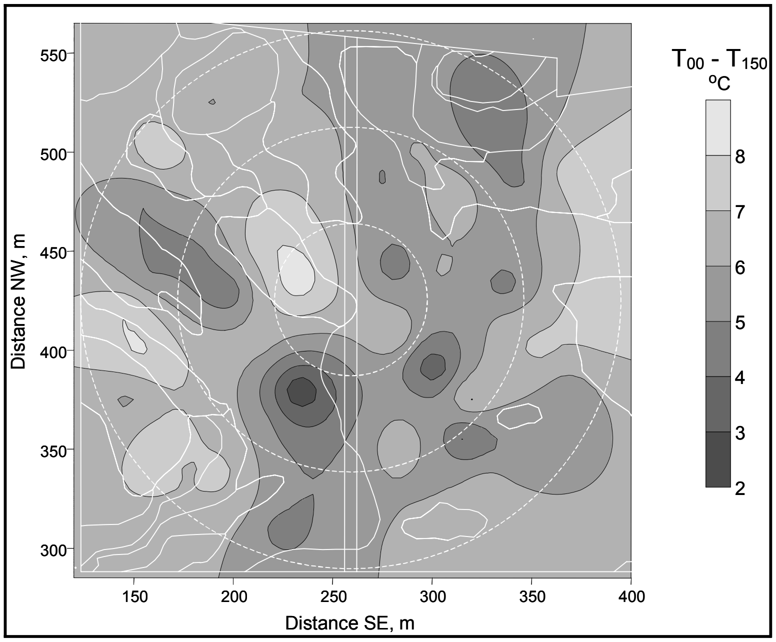

Figure 3. Canopy temperature of water stressed plots minus canopy temperature of well-watered plots of corn on July 23, 1999 for CP2.

Canopy temperature appears to be the most-sensitive indicator to illustrate the varied response of corn to the physical characteristics of the soil as they varied across the field. Sadler et al. (2002a) presented a map of the canopy temperature of rainfed (stressed) plots minus the canopy temperature of irrigated (well-watered) plots under center pivot 2 (Fig. 3). These temperatures were measured with an array of infrared thermometers mounted on the boom as it moved around the field during the period ~1130-1500 hrs LST. The range of this difference extends from about 2 to about 8 °C, which comprises radically different conditions for a corn plant. This shows the extreme variation in crop water stress caused by the typically varied soils within this representative Coastal Plain field.

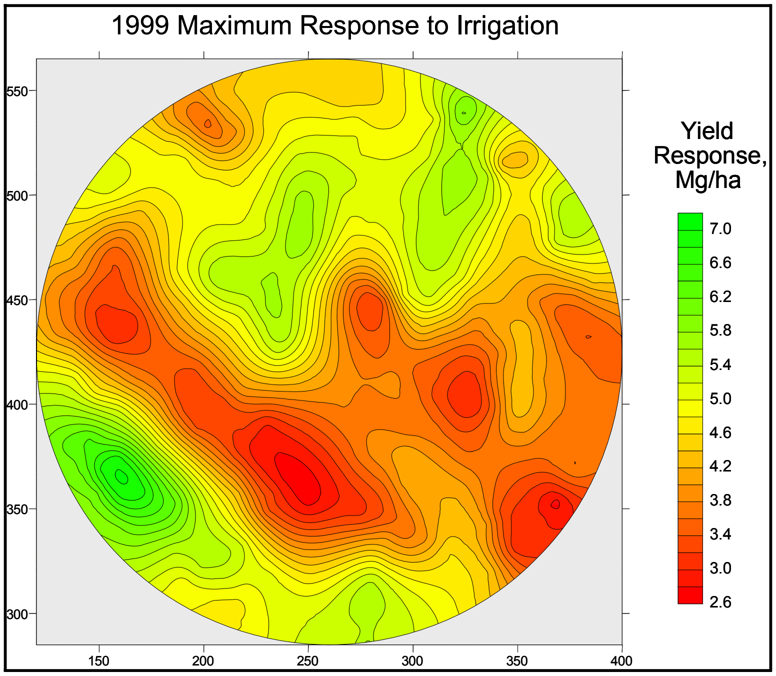

Figure 4. Maximum irrigation response for corn in 1999 for CP2.

The maximum corn yield response to irrigation was examined by Sadler et al. (2002b) and is shown in Fig. 4 for 1999. In this dry year (seasonal rainfall was 288 mm, compared to 410 normally during April-July), the spatial patterns of irrigation response were quite marked. This resulted from distinct spatial patterns in both rainfed yield and also in maximum irrigated yield (neither shown here). Furthermore, these patterns were neither similar nor complementary, resulting in the third spatial pattern of irrigation response, which is shown in Fig. 4. The diagonal low-response area across the lower-left corresponds to the highest yielding area in the field for unirrigated corn, but other patterns in this field are different from either the rainfed yield or the maximum irrigated yield. The maximum response to irrigation ranged from about 2.5 to 7.0 Mg/ha, corresponding to a range from $243.50 to $681.80/ha at local corn prices ($97.4/Mg on 8/28/02).

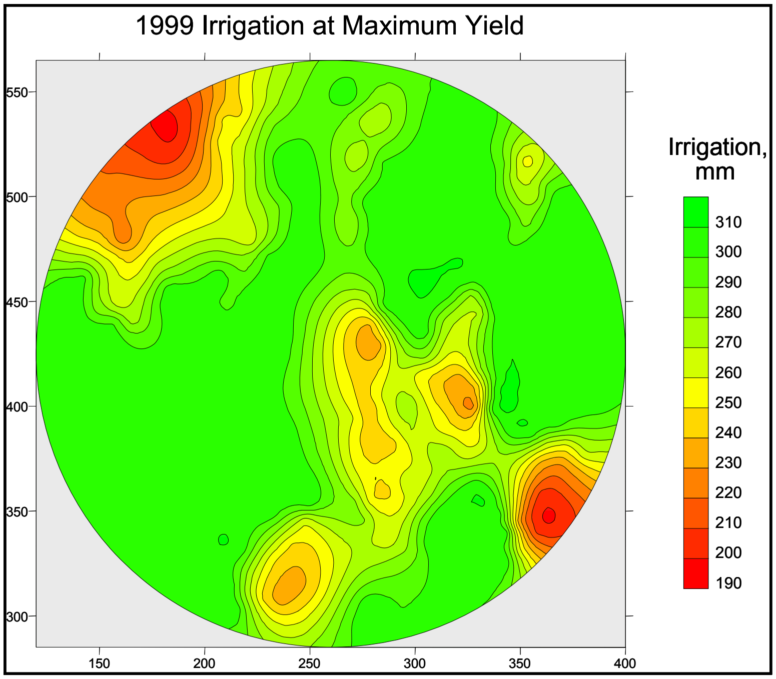

Figure 5. The irrigation amount that produced the maximum corn yield in 1999 for CP2.

The amount of irrigation that produced the maximum yield is of considerable interest to irrigation system designers and managers. The greatest amount must be considered in designing the total irrigation capacity of a system, and the spatial variation in the amount needed must be considered in both the design and management. The value obtained in the same 1999 season for which we have seen the maximum irrigation response is shown in Fig. 5. There are two patterns seen. One is spatially variable and covers about half the center pivot. The other is exactly the maximum irrigation amount applied during 1999, which means that approximately half the center pivot's area did not receive enough irrigation to reach a plateau - the production function was still climbing at the maximum irrigation amount. This occurred despite the irrigation management to achieve constant soil water content as measured by tensiometers in selected plots. Clearly, the tensiometer placement did not represent some of these sub-optimal areas. It is also surprising for a second reason, in that these tensiometers were placed in the 100% irrigated plots. One would think that the plots in the experiment that were irrigated at 150% of normal would have made up for the spatial variability, but apparently not. The implications of these findings will be discussed by Camp et al. (2002) in the companion paper.

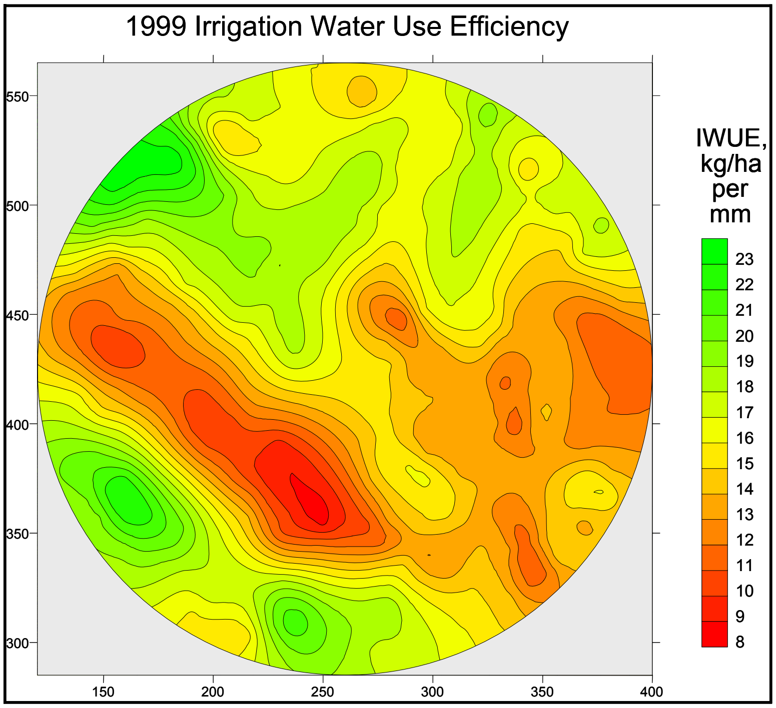

Figure 6. Irrigation water use efficiency at the point of maximum yield for corn in 1999 for CP2.

The ratio of the maximum irrigation response shown in Fig. 4 to the irrigation amount that produced it shown in Fig. 5 is the corresponding irrigation water use efficiency. It is shown in Fig. 6 stated in terms of kg/ha yield per mm applied water. This generally corresponds to the maximum response to irrigation (Fig. 4), except in locations needing less than the maximum irrigation amount (Fig. 5). The irrigation water use efficiency ranged from 8 to 23 kg/ha yield per mm applied water. This corresponded to $0.78 to $2.24 increase in return per mm of applied irrigation water. The irrigation water use efficiency was similar for 2000, when seasonal rainfall was 371 mm (not shown here.)

The maximum response to irrigation for 2001 was quite different, ranging from essentially zero to only 3 Mg/ha. The irrigation amount that produced the maximum yield ranged from near zero to about 280 mm. Therefore, the irrigation water use efficiency varied from near zero to about 16 kg/ha yield per mm applied water (Fig. 7). This upper limit represented a marginal benefit to irrigation of $1.56 per mm applied. The differences appear to be related to rainfall distribution. The seasonal rainfall of 334 mm was intermediate between 1999's 288 mm and 2000's 371 mm, and all were below the 410 mm normal rainfall for April-July. However, the in-season distribution for 2001 was much more favorable than 1999 and 2000, as reflected in county-average corn yields (4.4, 5.3, and 6.8 Mg/ha in the 3 years).

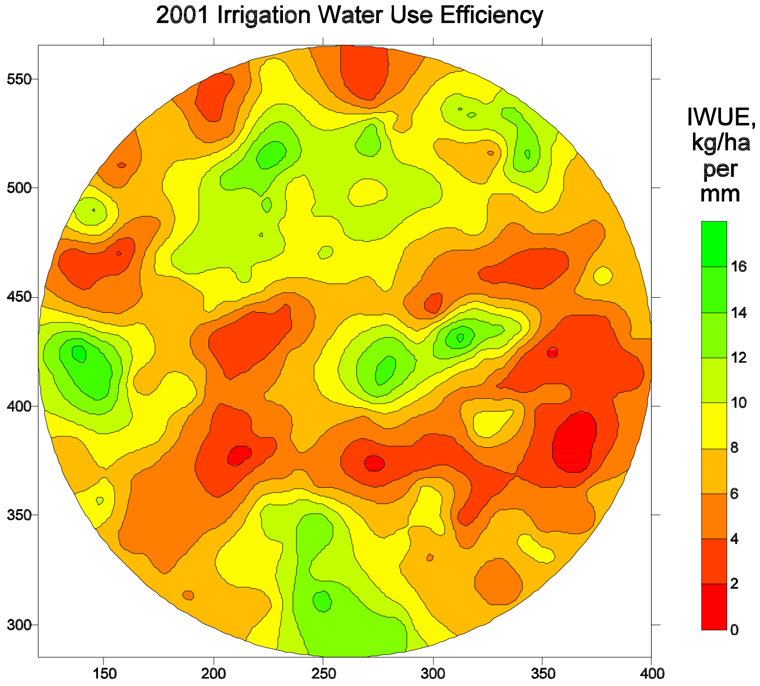

Figure 7. Irrigation water use efficiency during 2001 for CP2, expressed as kg/ha yield per mm irrigation water applied.

Summary and conclusions

The preceding discussion and selected results from the series of experiments conducted at the Florence USDA-ARS center were intended to provide the basis with which to examine the managerial implications of irrigation of corn in the humid southeastern coastal plain. This will be done in the companion paper, Camp et al. (2002), following this in the program and proceedings.

References

Buchleiter, G. W., C. R. Camp, R. G. Evans, and B. A. King. 2000. Technologies for variable water application with sprinklers. In Proc. 4th Decennial National Irrigation Symp., R. G. Evans, B. L. Benham, and T. P. Trooien (eds.). pp. 316-321. ASAE, St. Joseph, MI.

Camp, C. R., and R. B. Campbell, (eds.). 1988. Scheduling irrigation for corn in the Southeast. ARS-65, U.S. Dept. Agric., Agric. Res. Service. Washington, D.C.

Camp, C. R., G. D. Christenbury, and C. W. Doty. 1988. Scheduling irrigation for corn and soybean in the southeastern coastal plain. Trans. ASAE 31(2):513-518.

Camp, C. R., Y.-C. Lu, and E. J. Sadler. 2002. Spatial variation in crop response, Part 2: Implications for water and nitrogen management. Irrigation Association Technical Conference, New Orleans, LA. (This proceedings)

Camp, C. R., and E. J. Sadler. 1994. Center pivot irrigation system for site-specific water and nutrient management. ASAE Paper # 94-1586. 1994 Winter International Meeting, Atlanta, GA, Dec. 13-16, 9 pgs. ASAE, St. Joseph, MI.

Camp, C. R., and E. J. Sadler. 1997. Capabilities of a center pivot irrigation system for precision management of water and nutrients. In Proceedings of the Irrigation Association Technical Conference. pp. 235-242. The Irrigation Association, Falls Church, VA.

Camp, C. R., and E. J. Sadler. 2002. Irrigation, deep tillage, and nitrogen management for a corn-soybean rotation. Transactions ASAE 45 (3):601-608.

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

Camp, C. R., E. J. Sadler, R. E. Sneed, J. E. Hook, and F. Ligetvari. 1990. Chapter 15: Irrigation for Humid Areas. In Management of Farm Irrigation Systems. G. J. Hoffman, T. A. Howell, and K. H. Solomon (eds.) pp. 551-578. ASAE, St. Joseph, MI.

Evans, D. E., E. J. Sadler, C. R. Camp, and J. A. Millen. 2000a. Spatial canopy temperature measurements using center pivot mounted IRT's. In Precision Agriculture: Proceedings of the 5th International Conference. P. C. Robert, R. H. Rust, and W. E. Larson, (eds.) Madison, WI, ASA/CSSA/SSSA.

Evans, R. G., G. W. Buchleiter, E. J. Sadler, B. A. King, and G. B. Harting. 2000b. Controls for precision irrigation with self-propelled systems. In Proc. 4th Decennial National Irrigation Symp., R. G. Evans, B. L. Benham, and T. P. Trooien (eds.), pp. 322-331 ASAE, St. Joseph, MI.

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

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

Sadler, E. J., W. J. Busscher, P. J. Bauer, and D. L. Karlen. 1998. Spatial scale requirements for precision farming: A case study in the southeastern USA. Agron. J. 90 (2):191-197.

Sadler, E. J., W. J. Busscher, and D. L. Karlen. 1995. Site-specific yield histories on a SE Coastal Plain field. Ch 11. In Site-specific Management for Agricultural Systems. P. C. Robert, R. H. Rust, and W. E. Larson (eds.) pp. 153-166. ASA/CSSA/SSSA, Madison, WI.

Sadler, E. J., C. R. Camp, D. E. Evans, and J. A. Millen. 2002a. Corn canopy temperatures measured with a moving infrared thermometer array. Transactions ASAE. 45 (3):581-591.

Sadler, E. J., C. R. Camp, D. E. Evans, and J. A. Millen. 2002b. Spatial variation of corn response to irrigation. Trans. ASAE. (In press)

Sadler, E. J., C. R. Camp., D. E. Evans, and J. A. Millen. 2002c. Spatial analysis of corn response to irrigation. In Proc. 6th International Conference on Precision Agriculture, P. C. Robert, R. H. Rust, and W. E. Larsen (eds.) ASA/CSSA/SSSA, Madison, WI. (CDROM)

Sadler, E. J., C. R. Camp, and J. E. Hook. 2002d. Irrigation management in humid regions. In Encyclopedia of Water Sci. B. A. Stewart, and T. A. Howell (eds.) Marcel Dekker. (In press)

Sadler, E. J., R. G. Evans, G. W. Buchleiter, B. A. King, and C. R. Camp. 2000. Design considerations for site specific irrigation. In Proc. 4th Decennial National Irrigation Symp., R. G. Evans, B. L. Benham, and T. P. Trooien (eds.), pp. 304-315. ASAE, St. Joseph, MI.