# Evaluation of No-tillage Crop Production with Subsurface Drip Irrigation on Soils with Compacted Layers

C. R. Camp, P. J. Bauer, W. J. Busscher

**Abstract.** *Subsurface drip irrigation offers many advantages for management of water and nutrients, but its effectiveness may be limited by weather or soil conditions. Solving soil problems, such as compaction, in subsurface drip irrigation systems is understandably difficult using deep tillage. We hypothesized that the need for deep tillage in conservation tillage systems may be reduced if the compacted soil layers are kept moist enough for root growth. A two-year experiment that included wheat, soybean, and cotton under no-tillage culture was conducted with subsurface drip irrigation. The irrigation system had been used for five years before this experiment and provided two irrigation drip line spacings (1 m and 2 m) and three irrigation amounts (6, 9, and 12 mm/application). Irrigated soybean yields were greater than rainfed in one of the two years. No differences in yield occurred among irrigation drip line spacing or irrigation amounts. Also, neither cotton nor wheat yields were increased by irrigation. Observations during the growing seasons, cotton root observations after harvest, and soil strength measurements during the spring indicate that considerable soil compaction occurred at very shallow soil depths (< 5 cm) and restricted root growth. This compaction probably limited the efficacy of subsurface drip irrigation, which was located at the 30-cm depth. Based on these results, it appears that strategies must be developed to reduce soil strength to obtain optimum no-tillage crop production with subsurface drip irrigation on these soils.*
***Keywords.*** *Soil strength, Root growth, Cotton, Soybean, Wheat, Trickle irrigation.*

Subsurface drip irrigation has been used extensively for cotton production in arid and semi-arid areas; e.g., Arizona and western Texas (Tollefson, 1985a,b; Henggeler, 1995). In a review of subsurface drip irrigation, Camp (1998) found more reports on cotton than on any other agronomic crop. Because of longer system life and wider drip line spacings, these systems may be profitable for lower-valued crops, but good marginal return with irrigation is required for any crop to be profitable. Interest in subsurface drip irrigation for humid areas such as the southeastern U.S. has increased recently, especially for cotton on the coarse-textured soils of the southeastern Coastal Plain. Many farmers in this region have installed subsurface drip systems for on-site evaluation.

Annual rainfall normally exceeds evapotranspiration in the southeastern U.S., but it is often poorly distributed, especially during the summer growing season. The soils of the southeastern Coastal Plain have a coarse-textured Ap horizon, and many have a compacted E horizon that restricts root growth and development to a shallow soil layer, often 0.30 m or less. The coarse soil texture and limited rooting depth combine to provide low water storage. Consequently, drought periods are often long enough to reduce yields. Annual deep tillage is generally recommended for these soils to increase rooting depth and to increase plant available water, especially when irrigation is not used. Both rainfall amount and distribution are generally better during the winter wheat growing season; hence, this crop is seldom irrigated. However, increases in early spring N fertilization can increase the severity of plant water stress in winter wheat and can reduce individual kernel weight (Frederick and Camberato, 1994). If irrigation is not used in a double cropping system, the first crop (wheat) can deplete stored soil water, which causes seedbed water deficits for the second crop (soybean), especially if a drought period occurs early in the spring (Frederick and Camberato, 1994, 1995).

As with many other agronomic crops, irrigation can substantially increase yields of soybean and cotton in some years, depending upon rainfall amount and distribution. Camp et al. (1995) reported soybean yield increases of 17% and 105% with drip irrigation in a two-year experiment. Irrigation with a center pivot system increased mean soybean yield 51% for a three-year experiment. In a particularly dry year in that study, yield was increased 105% (Camp et al., 1984). Likewise, surface drip irrigation increased cotton lint yields in two of three years in an experiment that included cultivar and subsurface drainage treatments (Camp et al., 1993) and in all three years for one of seven irrigation treatments in an experiment that

Article was submitted for publication in August 1998; reviewed and approved for publication by the Soil & Water Division of ASAE in April 1999. Presented as ASAE Paper No. 98-2173.

Contribution of the U.S. Department of Agriculture, Agricultural Research Service, Coastal Plains Soil, Water, and Plant Research Center, Florence, S.C., in cooperation with the South Carolina Agricultural Experiment Station, Clemson, S.C. Mention of a trade name, proprietary product, or specific equipment does not constitute a guarantee or warranty by the USDA and does not imply approval of a product to the exclusion of others that may be suitable.

The authors are **Carl R. Camp**, ***ASAE Member Engineer***, Agricultural Engineer, **Philip J. Bauer**, Research Agronomist, and **Warren J. Busscher**, Soil Scientist, USDA-ARS, Coastal Plains Soil, Water, and Plant Research Center, Florence, S.C. **Corresponding author:** Carl R. Camp, USDA-ARS, Coastal Plains Soil, Water, and Plant Research Center, 2611 W. Lucas St., Florence, SC 29501-1242; voice: (843) 669-5203, ext. 107; fax: (843) 669-6970; e-mail: camp@florence.ars.usda. gov.

included drip line spacing and irrigation scheduling treatments (Camp et al., 1994). Camp et al. (1997) reported cotton lint yield increases in two of four years with subsurface drip irrigation in a study that included two drip line spacings and three nitrogen fertilizer rates.

Double cropping wheat and soybean as a rotation with cotton are economically competitive alternatives to monocropping cotton in the southeastern Coastal Plain. Conservation tillage has been used extensively for soybean in the region, but its use for wheat and cotton has been limited. Conservation tillage should complement subsurface drip irrigation for all three of these crops because tillage is problematic, with possible damage to drip lines, especially when they are installed at depths of 0.30 m or less.

Currently, research on rainfed production of these crops on Coastal Plain soils indicates some form of deep tillage is needed for roots to explore subsoil moisture. Soybean yields with 19-cm rows were significantly greater with deep tillage than without, and the yield was greater when no surface tillage was used (Frederick and Bauer, 1998). Bauer and Busscher (1996) found that rye increased cotton lint yield for conservation tillage conditions while other winter cover crops reduced yield relative to a fallow treatment. For cotton production using conservation tillage, others have reported effects of equipment and cultural practices (Burmester et al., 1995; Naderman, 1993; Patterson and Burmester, 1993), effects of soil strength (Busscher and Bauer, 1995), and effects of irrigation and tillage (McConnell et al., 1995). Although winter wheat is seldom grown under conservation tillage conditions, recent results indicate that this may be feasible. With deep tillage, Frederick and Bauer (1996) reported 25% greater winter wheat yield with no surface tillage in a dry year and no effect in another year, and concluded that the probability of a yield increase from deep tillage should be greater without surface tillage than with disking.

Subsurface drip irrigation offers several advantages, including installation below the tillage zone, system life and amortization of system cost over 10 to 15 years, frequent fertilization via the irrigation system, potential for less leaching of nutrients and ground water contamination, and water applications more closely matched to crop use. The use of wider drip line spacing (2 m) without yield reduction (Camp et al., 1994, 1997) significantly reduces system cost and makes the technology more affordable. However, the limited deep tillage permitted with subsurface drip irrigation may allow soil strength to increase in some soils and reduce crop yield. Subsurface drip irrigation has not been evaluated for wheat followed by high population, narrow-row soybean under conservation tillage in the southeastern U.S. Consequently, research was initiated in 1996 with the objective of evaluating subsurface drip irrigation for a two-year wheat- soybean-cotton rotation under a no-tillage production system.

## Materials and Methods

Experimental treatments included all combinations of two drip line spacings, two crop rotation phases, and three irrigation amounts, plus rainfall only (RAIN). Drip irrigation lines were spaced either 1 m or 2 m apart and 0.30 m deep (fig. 1), which placed them either directly

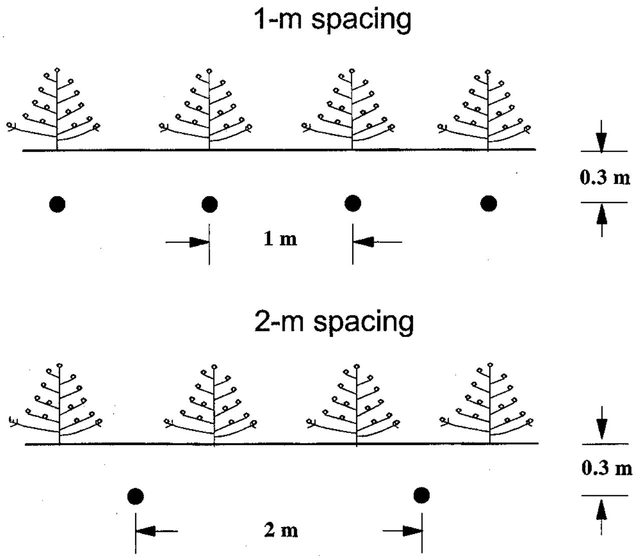


**Figure 1–Schematic diagram of the subsurface drip irrigation system with laterals spaced 1 m and 2 m apart, which places them either under the row or under the alternate mid-row area for cotton planted in rows spaced 1 m apart.**

under each cotton row (1 m) or under alternate mid-row areas (2 m). The three irrigation amounts were 6, 9, and 12 mm/application. Both phases of a winter wheat-soybean-cotton rotation in a no-tillage culture were included in each of two years (1996-1997). Soybean followed winter wheat in one phase and cotton followed winter fallow in the other phase. The experimental design was a randomized complete block with four replications.

The study was conducted on a 1.2-ha site of Eunola loamy sand (fine-loamy, siliceous, thermic, *Aquic Hapludults*) near Florence, South Carolina. The site had been subsoiled in two directions prior to installation of irrigation drip lines in 1991, and it then had been disked to a depth of about 0.20 m to prepare the seedbed each year until 1995. Thereafter, no tillage was performed except that the RAIN treatment was subsoiled annually to a depth of 0.35 m at a spacing of 1 m. Deep tillage was accomplished using forward-angled (45°), straight subsoiler shanks (2.5-cm tip and shoe) mounted on a tool bar.

The subsurface drip irrigation system had been used for five years when this study was initiated. The irrigation system included two polyvinyl chloride (PVC) pipe manifolds for each subplot (one at each end of the drip lines, supply and discharge), and each discharge manifold had removable end caps for flushing. Irrigation drip lines (GEOFLOW ROOTGUARD®) had in-line, labyrinth emitters spaced 0.6 m apart, each delivering 1.9 L/h at 140-kPa pressure. Pressure was regulated at about 140 kPa using in-line pressure regulators in the supply manifold for individual plots. Water was supplied from a well and filtered via a 100-mesh cartridge filter; see Camp et al. (1997) for additional details regarding the irrigation system. All irrigation applications were monitored and controlled by a programmable microprocessor-based irrigation controller or computer.

Timing of irrigation applications was determined by soil matric potential at the 0.30-m depth in the 6-mm treatment. The set point for initiation of irrigation was –35 kPa for cotton, –30 kPa for soybean, and –30 kPa for wheat. To achieve equal irrigation applications (equivalent rainfall depth) on the two drip-line-spacing treatments (1 m and 2 m), the 2-m system operated twice as long as the 1-m system. In the 6-mm treatment, each irrigation event was continuous. In the 9-mm and 12-mm treatments, each irrigation event was split into two equal applications, separated by an equal time without irrigation, e.g., 2 h on, 2 h off, 2 h on.

Each year the cotton rows were precisely placed relative to the subsurface drip lines (e.g, directly over buried drip line in the 1-m spacing). Each plot was 15 m long (irrigation drip line length) and 8 m wide, which provided eight cotton rows spaced 1 m apart. Soybean and wheat were planted with a conservation tillage grain drill in rows spaced 0.19 m apart and perpendicular to the irrigation drip lines. Wheat cultivars 'Coker 9134' and 'Coker 9835' were planted at 345 seeds/$m^2$ on 28 November 1995 and 25 November 1996. The soybean cultivar 'NK-7555' was planted on 10 June 1996 and 13 June 1997 at 50 seeds/$m^2$. The cotton cultivar 'Delta Pine and Land 90' (DPL 90) was planted on 2 May 1996 and 7 May 1997 at 14 seeds/$m^2$.

In both years, P, K, lime, and Mn were applied based on soil test results. Sulphur and boron were applied to the cotton each year. Total N fertilizer applied to the cotton was 92 kg/ha each year, and the wheat received 102 kg/ha. Because wheat was grown in 1996 only as a cover crop, no N fertilizer was applied at planting and the spring application was about one month later than in 1997. Weeds were controlled with a combination of herbicides and hand weeding. An in-furrow insecticide application was made to cotton at planting, and foliar insecticides were applied throughout the season as warranted.

In 1996, gauge-type tensiometers were installed in the 6-mm soybean treatment at depths of 0.3 m and 0.6 m and at either two or three distances from the irrigation drip line. In 1997, tensiometers were installed at depths of 0.3 m and 0.6 m in all irrigated soybean treatments and at two distances from the drip line, and at one location in the RAIN treatment. For cotton, tensiometers were also installed in the row at depths of 0.3 m and 0.6 m in the 6-mm treatments in 1996 and in all irrigated treatments in 1997. For wheat in 1997, tensiometers were installed in the 6-mm irrigated treatments at depths of 0.3 m and 0.6 m and at either two or three distances from the drip line. Tensiometers were serviced as required, and readings were recorded three times each week. Meteorological parameters were measured at a weather station located adjacent to the experimental area. Seasonal rainfall for each crop was computed for the period between planting and two weeks prior to first harvest.

Soybean yield in 1996 and wheat yield in 1997 were determined by harvesting 14 $m^2$ in the center of each plot on 14 November 1996 and 12 June 1997, respectively. Soybean yield in 1997 was determined by harvesting 88 $m^2$ on 25 November 1997. Cotton yield was determined by harvesting two interior rows of each plot with a spindle picker on 27 September 1996 and 29 October 1997. Subsamples of seed cotton were collected from each plot at harvest, and cotton lint yield was calculated from lint percentages determined after ginning the samples on a laboratory saw gin.

Soil strength was measured after wheat harvest in June of each year with a 12.5-mm diameter, 30° solid angle cone tip, hand-operated, recording penetrometer (Carter, 1967). Strength measurements (cone index values) were recorded to a depth of 0.60 m at seven positions along a 1-m transect between a former cotton non-wheel-tracked mid-row and a wheel-tracked mid-row. Means of measurements made at three locations were reported for each plot. Analog data were digitized and recorded in a computer file using the method described by Busscher et al. (1985). Data were log transformed for normalization before analysis (Cassel and Nelson, 1979). When required, cone index values were corrected for soil water content using the method described by Busscher and Sojka (1987). Soil pits were dug in selected cotton treatments following cotton harvest in 1997 to observe and photograph cotton root depth and distribution.

Crop yield data were analyzed by crop and by year using analysis of variance (ANOVA). Treatment sums of squares were partitioned with single degree of freedom contrasts (SAS, 1990). With these contrasts, we compared (1) 1-m and 2-m drip line spacings, averaged over all irrigation treatments; (2) rainfed (RAIN) and irrigated, averaged over drip line spacing and irrigation amount; (3) irrigation amount, averaged over drip line spacing, for linear relationship; (4) irrigation amount, averaged over drip line spacing, for deviation from linear relationship; (5) interaction between drip line placement and linear irrigation (amount) relationship; and (6) interaction between drip line placement and deviation from linear irrigation (amount) relationship.

## Results and Discussion

Seasonal irrigation amounts for the three irrigation treatments were not closely related to seasonal rainfall amounts and varied considerably both among crops and growing seasons. For soybean, more than twice as much irrigation was required in 1997 than in 1996 (86 vs 34 mm for 6-mm treatment) although seasonal rainfall was similar (493-494 mm). For cotton, two to three times more irrigation was required in 1997 than in 1996 (112 vs 42 mm for 6-mm treatment) although seasonal rainfall was slightly greater in 1996 (542 mm vs 470 mm). Five irrigation applications (27 mm for 6-mm treatment) were required for wheat in 1997 although significant rainfall (361 mm) occurred.

In 1996, high rainfall (494 mm) that was almost uniformly distributed kept the soil very wet throughout the growing season for soybean and there were no differences in soil matric potential (SMP) among drip line spacings and position relative to the irrigation drip line. SMP values for cotton reflected similar but slightly drier conditions, with values of –50 MPa on two dates (data not shown). In 1997, SMP values reflected slightly drier soil conditions in the irrigated treatments for both soybean and cotton, but all values were greater than –40 MPa (figs. 2-3). SMP values were similar for both drip line spacings in both soybean and cotton in 1997 except that soil in the cotton 2-m spacing was slightly drier. This probably occurred because tensiometers in that treatment were located in the cotton row (19 cm away from the drip line), which is normally drier than the soil adjacent to the drip line. In 1997, soil in the RAIN treatment with soybean was much drier than in

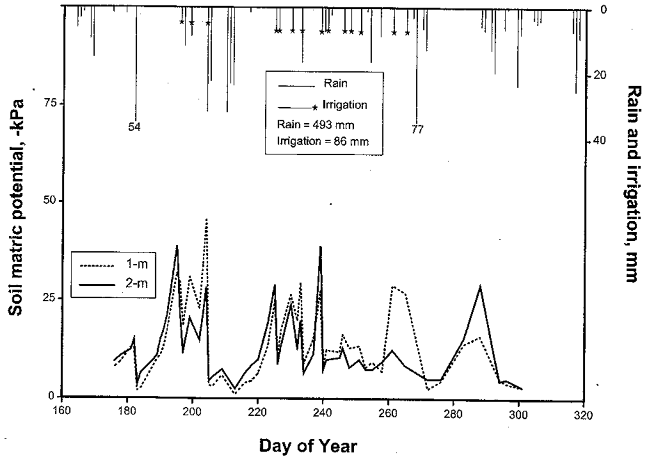


**Figure 2–Mean soil matric potential at the 30-cm depth (adjacent to drip line) for two drip line spacings on soybean in 1997. Each data point is the mean of two values. Daily rainfall and irrigation (stars) amounts are shown at top of the graph. Numerals indicate rainfall amounts greater than the plot range.**

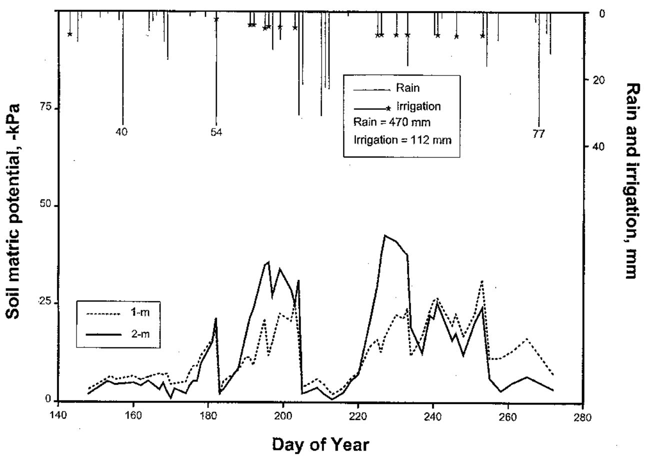


**Figure 3–Mean soil matric potential in the cotton row at the 30-cm depth for two drip line spacings in 1997 (measurement point is adjacent to drip line in the 1-m spacing and 19 cm from the drip line in the 2-m spacing). Each data point is the mean of four values. Daily rainfall and irrigation (stars) amounts are shown at top of the graph. Numerals indicate rainfall amounts greater than the plot range.**

the irrigated treatments, especially from day of the year (DOY) 230 to DOY 265 (data not shown).

**Table 1. Soybean, cotton, and wheat yields for irrigated and rainfed treatments in a conservation tillage, wheat-soybean-cotton rotation experiment on a southeastern Coastal Plain soil during 1996-1997**

| Year | Crop | Irrigated* | RAIN |
|---|---|---|---|
| | | ----------------kg/ha---------------- | |
| 1996 | Soybean | 2745 | 2790 |
| | Cotton | 1330 | 1345 |
| 1997 | Wheat | 2360 | 2000 |
| | Soybean | 2765† | 2105 |
| | Cotton | 1130 | 1110 |

* Means of two drip line spacings and three irrigation amounts.
† Indicates yield for the irrigated and RAIN treatments differed at $P \leq 0.05$.

Crop yields for the three irrigation amounts and the two drip line spacings were not different for any crop in either year. Therefore, mean soybean, wheat, and cotton lint yields for all irrigation treatments are reported in table 1. Yields for the irrigated treatments were greater than for the RAIN treatment for soybean in 1997 but not for other crops, or for any crop in 1996. Except for cotton in 1996, crop yields were less than expected. For a similar soil and culture but without irrigation, Frederick and Bauer (1996, 1998) reported yields of 5800 to 6550 kg/ha for soybean and 4150 to 4500 kg/ha for wheat. Previously, at the site of this experiment, cotton lint yields ranged from 1145 to 1815 kg/ha for three years (1991, 1993, 1994), but ranged from 535 to 770 kg/ha in a fourth year (1992). Cool temperatures probably reduced yields in 1992. Yields decreased linearly with an increase in the number of days that had minimum temperatures ≤ 15.6°C during the first 20 days after planting and with a decrease in accumulated heat units for 50 days after planting (Camp et al., 1997). In a similar manner, cool temperatures during the early growing season in 1997 may have reduced cotton lint yield in this experiment. Also, inadequate rainfall probably caused sufficient water deficits to limit cotton yield in the RAIN treatment although it was subsoiled.

Differences in soil strength measurements, as reflected by cone index values, for three irrigation treatments (two drip line spacings and the RAIN treatment) can be seen in figures 4-5 and are indicated by interactions ($P < 0.05$). The irrigation-soil depth, soil depth-position, and irrigation-position interactions were significantly different for both years (position is indicated along a 1-m transect between a former cotton non-wheel-tracked mid-row and a wheel-tracked mid-row). The soil depth-position interaction is caused by deep tillage in the RAIN treatment and the greater soil strength values below the wheel tracks (seen especially in the two irrigation treatments). The irrigation-position interaction is caused by deep tillage in the RAIN treatment and other spatial variability throughout the soil profile. The irrigation-depth interaction reflects high soil strength values at different soil depths for different treatments. Soil water contents were not different among treatments either year but were different with soil depth in 1997 (table 2). This allows direct comparison of cone index values among treatments without corrections for soil water content.

In the RAIN treatment, which was subsoiled each year, cone index values were < 2 MPa from the soil surface to a depth of 20 cm in the former cotton row area (position = 48 ± 6 cm). In both irrigated treatments (two drip line spacings), cone index values were < 2 MPa only in a thin soil layer from the surface to a depth of 3 to 5 cm. At all other positions, cone index values were > 2 MPa, generally increasing with soil depth to a depth of about 30 cm, then decreasing with depth. Cone index values were greatest (4 MPa) in areas 15 to 25 cm deep and under the wheel-traffic mid-rows. Plant roots generally cannot penetrate soils with cone index values > 2 MPa (Taylor and Gardner, 1963; Blanchar et al., 1978). Correcting the cone index values in 1996 for different soil water contents increased the cone index values for the 0- to 10-cm and 30- to 40-cm depths. However, these corrections did not affect the overall pattern of soil strength values. Consequently, it is likely, depending upon soil water content, that crop roots

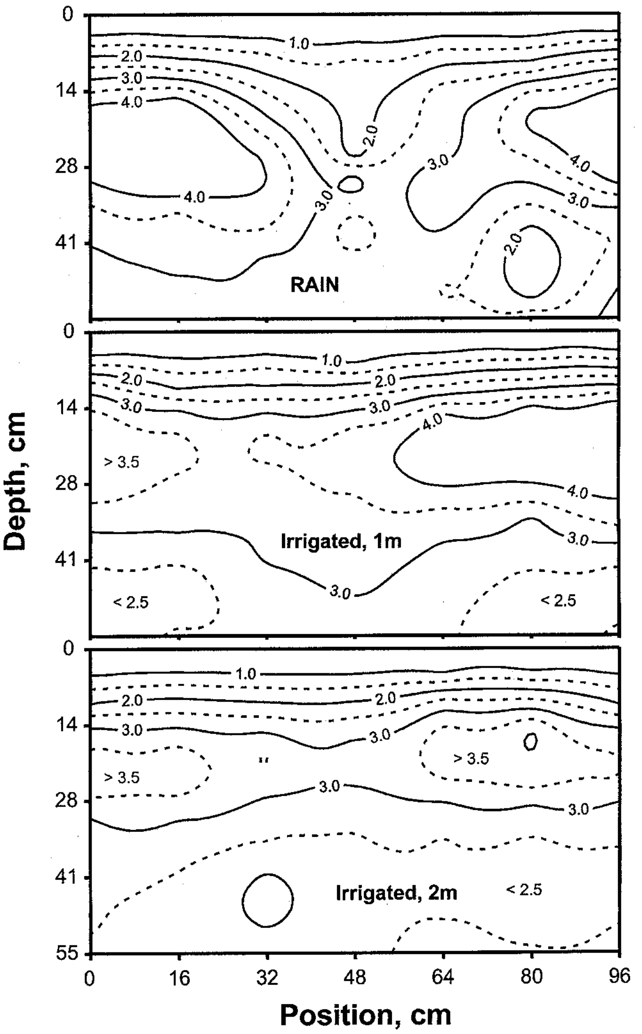


Figure 4–Cone index values for RAIN (non-irrigated) and two irrigation drip line spacing treatments in a wheat-soybean-cotton rotation with subsurface drip irrigation and conservation tillage in 1996. Cone index contours (MPa) were constructed from measurements at seven positions along a 1-m transect between a prior, non-wheel-tracked cotton mid-row (position = 0) and a prior, wheel-tracked cotton mid-row (position = 96 cm).

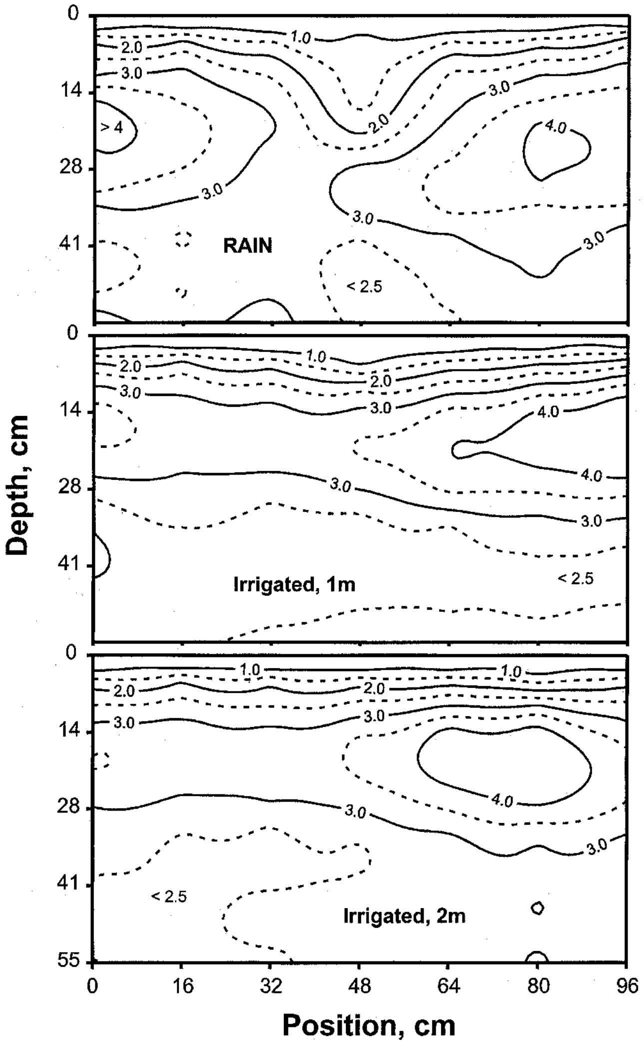


Figure 5–Cone index values for RAIN (non-irrigated) and two irrigation drip line spacing treatments in a wheat-soybean-cotton rotation with subsurface drip irrigation and conservation tillage in 1997. Cone index contours (MPa) were constructed from measurements at seven positions along a 1-m transect between a prior, non-wheel-tracked cotton mid-row (position = 0) and a prior, wheel-tracked cotton mid-row (position = 0.96 m).

(cotton, soybean, or wheat) were limited to soil depths of 15 cm or less in the irrigated plots and were unable to develop in the soil zone near the irrigation drip lines. Soil compaction at this shallow depth was probably caused by equipment traffic (combines, cotton pickers, etc.) and absence of shallow (< 15 cm) tillage for the last two years. Equipment traffic and conventional tillage (disking) during the previous five years as well as the lack of deep tillage for seven years could also contribute to total soil profile compaction.

Observations during both years indicated limited rooting depth for all crops. Vastly different cotton root growth occurred between the irrigated and RAIN treatments (fig. 6). In the irrigated treatment, tap root growth was limited to a depth of about 10 cm with limited horizontal distribution. In the RAIN treatment, which had annual deep tillage, taproot growth extended to a depth of at least 20 cm and had extensive horizontal growth (fig. 7). The limited root development suggests that the high soil strength prevented optimal benefit from the subsurface drip irrigation system. Annual disking during the previous experiment probably provided sufficient tillage for crop roots to utilize irrigation water. With conversion to a no-tillage system, soil strength may limit rooting depth and development. It appears that strategies to reduce soil

**Table 2. Soil water contents at several depths corresponding to cone index measurements in cotton on a subsurface drip irrigation experiment near Florence, S.C., during 1996-1997**

| Depth (cm) | Water Content (%) | |
|---|---|---|
| | 1996 | 1997 |
| 0-10 | 13.5 b* | 11.7 b |
| 10-20 | 10.9 d | 10.9 b |
| 20-30 | 10.5 d | 11.3 b |
| 30-40 | 11.5 c | 11.7 b |
| 40-50 | 13.4 b | 13.2 a |
| 50-60 | 14.4 a | 14.2 a |

* Means followed by the same letter are not different by the LSD test at P ≤ 0.05.

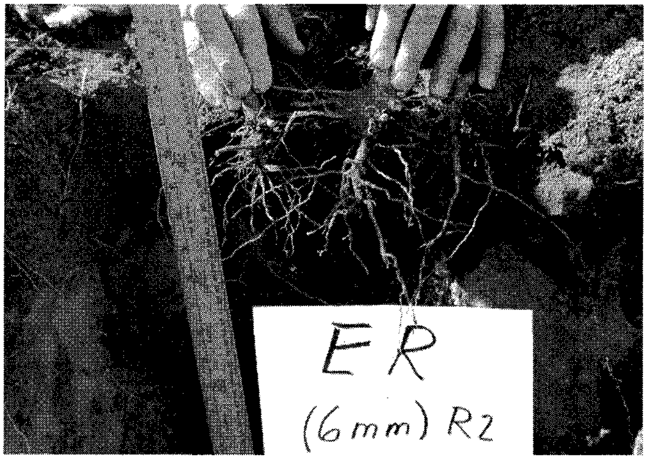


**Figure 6–Photograph of cotton roots in a subsurface drip-irrigated treatment (drip line spacing of 1 m) following harvest in 1997.**

**Figure 7–Photograph of cotton roots in RAIN treatment (non-irrigated, deep tilled) following harvest in 1997.**

strength at relatively shallow soil depths are needed for conservation tillage culture in these soils before the full benefits of subsurface drip irrigation can be realized.

## Summary and Conclusions

After five years of use, a site with drip irrigation lines at a depth of 0.30 m was converted from conventional tillage to conservation tillage. Both phases of a wheat-soybean-cotton rotation were grown in each of two years under no-tillage culture. The site (irrigated areas) had not been deep tilled since 1991 when the irrigation system was installed. There were no differences in yield of wheat, soybean, or cotton for two irrigation drip line spacings (1 m and 2 m) or for the three irrigation depths (6, 9, or 12 mm/application). Yield was greater for irrigated treatments than for the RAIN treatment (deep tilled) only for soybean in 1997. Observations and soil strength measurements indicate that a shallow compacted soil zone (< 5 cm from the soil surface) limited root growth and reduced the effect of irrigation on these crops. Based on these results, it appears that strategies to reduce soil strength in the surface 15 cm of these soils are required for conservation tillage systems to realize the benefits of subsurface drip irrigation. Alternatively, drip irrigation laterals could be installed 10 to 15 cm deep in no-tillage culture, but controlled traffic would probably be required.

## References


Bauer, P. J., and W. J. Busscher. 1996. Winter cover and tillage influences on Coastal Plain cotton production. *J. Prod. Agric.* 9(1): 50-54.

Blanchar, R. W., C. R. Edmonds, and J. M. Bradford. 1978. Root growth in cores formed from fragipan and B2 horizons of Hobson soil. *Soil Sci. Soc. Am. J* 42: 437-440.

Burmester, C. H., M. G. Patterson, and D. W. Reeves. 1995. Challenges of no-till cotton production on silty clay soils in Alabama. In *Conservation-Tillage Systems for Cotton*, eds. M. R. McClelland, T. D. Valco, and R. E. Frans, 5-7. Special Report 169. Fayetteville, Ark.: Arkansas Agric. Exper. Sta., University of Arkansas.

Busscher, W. J., and P. J. Bauer. 1995. Soil strength of conventional- and conservation-tillage cotton grown with a cover crop. In *Conservation-Tillage Systems for Cotton*, eds. M. R. McClelland, T. D. Valco, and R. E. Frans, 18-20. Special Report 169. Fayetteville, Ark.: Arkansas Agric. Exper. Sta., University of Arkansas.

Busscher, W. J., R. E. Sojka, E. J. Sadler, and C. W. Doty. 1985. Simplified data analysis for an inexpensive, manual analogue penetrometer. *Comput. Elect. Ag.* 1: 197-204.

Busscher, W. J., and R. E. Sojka. 1987. Enhancement of subsoiling effect on soil strength by conservation tillage. *Transactions of the ASAE* 30(4): 888-892.

Camp, C. R. 1998. Subsurface drip irrigation: A review. *Transactions of the ASAE* 41(5): 1353-1367.

Camp, C. R., P. J. Bauer, and P. G. Hunt. 1997. Subsurface drip irrigation lateral spacing and management for cotton in the southeastern Coastal Plain. *Transactions of the ASAE* 40(4): 993-999.

Camp, C. R., G. D. Christenbury, and C. W. Doty. 1984. Tillage effects on crop yield in Coastal Plain soils. *Transactions of the ASAE* 27(6): 1729-1733.

Camp, C. R., E. J. Sadler, W. J. Busscher, R. E. Sojka, and D. L. Karlen. 1995. Experiences with microirrigation for agronomic crops in the southeastern USA. In *Proc. 5th Microirrigation Congress*, ed. F. R. Lamm, 638-644, Orlando, Fla., 2-6 April. St. Joseph, Mich.: ASAE.

Camp, C. R., W. M. Thomas, and C. W. Doty. 1994. Drainage and irrigation effects on cotton production. *Transactions of the ASAE* 37(3): 823-830.

Camp, C. R., W. M. Thomas, and C. C. Green. 1993. Microirrigation scheduling and tube placement for cotton in the southeastern Coastal Plain. *Transactions of the ASAE* 36(4): 1073-1078.

Carter, L. M. 1967 Portable penetrometer measures soil strength profiles. *Agricultural Engineering* 48: 348-349.

Cassel, D. K., and L. A. Nelson. 1979. Variability of mechanical impedence in a tilled one hectare field of Norfolk sandy loam. *Soil Sci. Soc. Am. J.* 43: 450-455.

Frederick, J. R., and P. J. Bauer. 1996. Winter wheat responses to surface and deep tillage on the southeastern Coastal Plain. *Agon. J.* 88(5): 829-833.

Frederick, J. R., and P. J. Bauer. 1998. Tillage management for doublecropped soybean grown in narrow and wide row width culture. *Crop Sci.* 38: 755-762.

Frederick, J. R., and J. J. Camberato. 1994. Leaf net $CO_2$-exchange rate and associated leaf traits of winter wheat grown with various spring nitrogen fertilization rates. *Crop Sci.* 34: 432-439.

Frederick, J. R., and J. J. Camberato. 1995. Water and nitrogen effects on winter wheat in the southeastern Coastal Plain: I. Grain yield and kernel traits. *Agron. J.* 87: 521-526.

Henggeler, J. C. 1995. A history of drip-irrigated cotton in Texas. In *Proc. 5th Int. Microirrigation Congress*, ed. F. R. Lamm, 669-674, Orlando, Fla., 2-6 April. St. Joseph, Mich.: ASAE.

McConnell, J. S., W. H. Baker, C. S. Rothrock, and B. S. Frizzell. 1995. Cotton yield response to irrigation, reduced tillage and cover crops. In *Conservation-Tillage Systems for Cotton*, eds. M. R. McClelland, T. D. Valco, and R. E. Frans, 79-81. Special Report 169. Fayetteville, Ark.: Arkansas Agric. Exper. Sta., University of Arkansas.

Naderman, G. 1993. Equipment considerations for reduced-tillage cotton production in the Southeast. In *Conservation-Tillage Systems for Cotton*, eds. M. R. McClelland, T. D. Valco, and R. E. Frans, 13-17. Special Report 160. Fayetteville, Ark.: Arkansas Agric. Exper. Sta., University of Arkansas.

Patterson, M. G., and C. H. Burmester. 1993. General production practices for conservation tillage cotton in the Southeast. In *Conservation-Tillage Systems for Cotton*, eds. M. R. McClelland, T. D. Valco, and R. E. Frans, 10-12. Special Report 160. Fayetteville, Ark.: Arkansas Agric. Exper. Sta., University of Arkansas.

SAS Institute Inc. 1990. *SAS/STAT Users Guide*, Ver. 6. Cary, N.C.: SAS Institute Inc.

Taylor, H. M., and H. R. Gardner. 1963. Penetration of cotton seedling taproots as influenced by bulk density, moisture content, and strength of the soil. *Soil Sci.* 96: 153-156.

Tollefson, S. 1985a. The Arizona system: Drip irrigation design for cotton. In *Proc. 3rd Int. Drip/Trickle Irrigation Congress*, 1: 401-405. St. Joseph, Mich.: ASAE.

Tollefson, S. 1985b. Subsurface drip irrigation of cotton and small grains. In *Proc. 3rd Int. Drip/Trickle Irrigation Congress*, 2: 887-895. St. Joseph, Mich.: ASAE.