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Double-Cropped Soybean and Wheat with Subsurface Drip Irrigation Supplemented by Treated Swine Wastewater

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Double-Cropped Soybean and Wheat with Subsurface Drip Irrigation Supplemented by Treated Swine Wastewater

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*The wastewater from swine production facilities has been typically managed by treatment in anaerobic lagoons followed by land application. However, there have been considerable advances in superior treatment technologies. Wastewater from one of these technologies was effective for subsurface drip irrigation of bermudagrass. The objectives of this experiment were to assess accumulation of soil nitrogen and carbon along with grain yield, dry-matter accumulation, and plant nitrogen accumulation of soybean [*Glycine max *(L) Merr., cv.] and wheat [*Triticum aestivum *(L), cv.] when supplementally irrigated with treated swine effluent via subsurface drip irrigation (SDI). The soil series was Autryville loamy sand (loamy, siliceous, subactive, thermic Arenic Paleudults). Its low unsaturated hydraulic conductivity of 0.0017 ± 0.0023 mm* h^{-1} *caused problems with water movement to either the soil surface or laterally to adjoining soybean and wheat roots. This condition contributed to complete crop failure in soybean in 2 years and generally poor yields of wheat. In a good rainfall year, the soybean yield was somewhat satisfactory and benefited from the supplemental irrigation. In that year, nonirrigated and irrigated soybean mean yields were 1.55 versus 1.98 Mg* ha^{-1}*, respectively. The mean yield of wheat was only 1.06 Mg* ha^{-1}*, and it was not affected by irrigation. The means for soil nitrogen and carbon in the 0- to 15-cm depth were 414 and 5,679 mg* kg^{-1}*, respectively, and they were not affected by the water treatments. Thus, neither soil conditions nor soybean/wheat production were greatly enhanced by the SDI system.*

Keywords carbon, drought, nitrogen, sandy soil

Introduction

Swine production in North Carolina grew rapidly during the latter part of the twentieth century (Stone et al. 1995). The waste from these swine production facilities has been managed almost entirely by treatment in anaerobic lagoons followed by land application of the lagoon wastewater (Burns, King, and Westerman 1990: King, Burns, and Westerman 1990; Westerman, King, and Burns 1987). The fact that there were large numbers of these lagoons brought about significant known and perceived natural resources and socioeconomic problems (Stone et al. 1995; Williams 2002). This resulted in the establishment of

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an agreement between the swine producers and the North Carolina attorney general to find better and more sustainable methods of swine waste management (Williams 2002). In this search, one system was developed and put into full-scale use that met all of the technical required criteria (Vanotti et al. 2007; Vanotti and Szogi 2008). Whereas it dramatically reduced the nutrient load of the swine wastewater effluent, it was more amenable to swine wastewater effluent application in accordance with crop production. Stone, Hunt, et al. (2008) reported on the use of this treated effluent to irrigate bermudagrass via a subsurface drip irrigation system (SDI). It provided both nutrients and water to the bermudagrass so as to produce good forage quality and yields (Burns, King, and Westerman 2009; Stone, Hunt, et al. 2008). The forage also proved suitable for use as a source of bioenergy (Cantrell et al. 2010, 2009).

Even though application of the swine effluent to forage crops has been where the great majority of the wastewater has been applied, grain crops are important to the economy of the region. A common grain production cropping system is double-cropped wheat and soybean (Hunt et al. 2004). Moreover, this cropping system is commonly grown in conservation tillage, which is compatible with the permanent placement of subsurface drip irrigation (Hunt et al. 2004). One of the additional factors to be considered in subsurface irrigation is the spacing of irrigation tubing (Camp 1998). Stone, Hunt, et al. (2008) found that spacing of 1.9 m for the tubing was acceptable for the bermudagrass. It was also found to be satisfactory for the production of cotton and peanuts on an Enola loamy sand (Hunt et al. 1998). Thus, there was interest to learn how subsurface irrigation with the treated swine effluent would function on an Autryville sandy soil similar to the soil that Stone used for subsurface irrigation of bermudagrass. The objectives of this experiment were to assess the following: (1) grain yield, dry-matter accumulation, and plant nitrogen (N) accumulation and (2) soil carbon (C) and N contents for a wheat/soybean cropping rotation that was supplementally irrigated with treated swine effluent via subsurface drip irrigation.

Materials and Methods

Site Description

This field study was conducted from 2003 to 2005 on a 4400-head swine finishing farm in Duplin County, North Carolina. Prior to initiation of the study, the plot site was a coastal bermudagrass (*Cynodon dactylon* L.) pasture/forage field that periodically received overhead irrigation from the adjacent swine wastewater lagoon. A contiguous experiment was conducted with bermudagrass forage by Stone, Hunt, et al. (2008). For the current study, the cropping system was a 3-year rotation of soybean [*Glycine max* (L) Merr., cv.] and wheat [*Triticum aestivum* (L), cv.]. The soil series was Autryville loamy sand (loamy, siliceous, subactive, thermic Arenic Paleudults). The experimental plots were 12.8 m × 12.8 m. They were arrayed in four randomized complete blocks for subsurface drip irrigations line spacing and nonirrigated water treatments. Each water treatment plot was split for cultivars of soybean and wheat. Irrigation water was supplied by an adjacent swine wastewater treatment facility and a local well (Vanotti et al. 2007). Selected, treated wastewater characteristics in mg L^{-1} (means and standard deviations) are as follows: total solids, 3339 (586); total suspended solids, 264 (154); chemical oxygen demand, 445 (178); total Kjeldahl N, 23 (24); nitrate + nitrite N, 224 (105); total phosphorus (P), 29 (16); copper (Cu), 0.36 (0.26); zinc (Zn), 0.25 (0.30); and alkalinity, 735 (263). These are dramatically lower than typically found in the swine wastewater of the region's anaerobic lagoons (Bicudo, Safley, and Westerman 1999; Chen et al. 2003; Hunt et al. 2010).

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Conversely, the electrical conductivity was 4.86 (0.87) mS cm^{-1}, only somewhat lower than typical lagoon's wastewater.

Irrigation

There were three water treatments. They consisted of SDI with well water supplemented by treated wastewater on two, line spacings and a nonirrigated control. The irrigation water was applied to meet evapotranspiration (ET). All SDI plots were fertilized with treated swine wastewater (Vanotti et al. 2007). The nonirrigated plots were fertilized according to standard practice with surface application of commercial fertilizer and lime. The SDI tubing was WasteflowPC (Geoflow, Inc., Corte Madera, Calif.). It was installed 0.3 m below the soil surface using two poly-hose injection shanks mounted on a tractor tool bar. The irrigation lines were spaced on centers of either 0.97 or 1.93 m. The main line from which the irrigation tubing emanated consisted of 1.9-cm-diameter polyvinylchloride (PVC) pipe manifolds. Irrigation lines had inline, pressure-compensating labyrinth emitters spaced 0.6 m apart with each delivering 1.9 L h^{-1}. The SDI irrigation system was controlled by a computer with a custom Visual Basic (VB) program. It operated a digital output peripheral component interconnect (PCI) board, an analog to digital (A/D) input board, and a counter/timer board. The digital output board operated supply pumps and solenoid valves. The A/D input board read supply-line pressures. All treatments could receive either well water or wastewater. Screen filters were used for both well water and wastewater. A media filter with sand and gravel was used to filter the treated effluent before it reached the screen filter.

A tripod-mounted weather station was installed at the irrigation site with a Campbell Scientific, Inc. (CSI) data logger to measure relative humidity, air temperature, solar radiation, wind speed, wind direction, and rainfall. The data logger tabulated data at 5-min intervals and downloaded it daily to the irrigation control PC. Potential evapotranspiration (ET) was calculated using daily data from the weather station. Potential ET was multiplied by a crop coefficient to obtain daily ET values for the crop. The ET and daily rainfall were accumulated for the previous 7 days. When the cumulative ET exceeded cumulative rainfall by greater than 6 mm, an irrigation event was initiated (Figures 1–3). The accumulated rain, irrigated well water, and irrigated wastewater are presented in Table 1.

Soybean/Wheat

At the initiation of this study, the existing coastal bermudagrass was sprayed with herbicides via standard agronomic practices to prepare the site for planting of soybeans. Four soybean cultivars were planted: Deltapine 7220RR, Southern States RT6202NRR, Pioneer 97B52RR, and Northrup King 573Z5RR. They were planted at the rate of 112 kg ha^{-1} with a John Deere model 750 no-till grain drill on 25 June 2003, 30 June 2004, and 29 June 2005. In 2004, soybean failed to germinate because of drought. There were abundant ungerminated seed present in the drill rows of dry surface soil. This was despite irrigation via the drip lines. Even the 0.93-m spacing was insufficient to provide enough water to wet the seed bed. Although a stand was established in 2005, the subsequent yield was a complete failure. Seed yields were less than 0.2 Mg ha^{-1}. Thus, only soybean data from 2003 are presented.

As a result of the soybean stand failure in 2004, a check experiment was planted on an Eunola loamy sand in Florence, South Caroline, in 2005. This site had been used in SDI experiments with row crop for several experiments over a 10-year period (Bauer,

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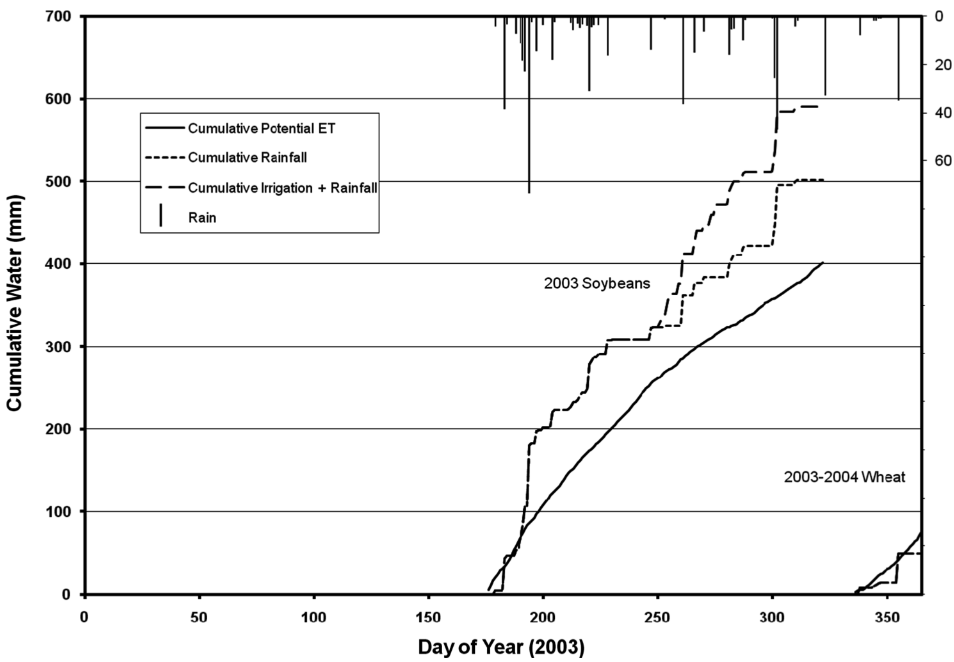

Figure 1. Water management in 2003.

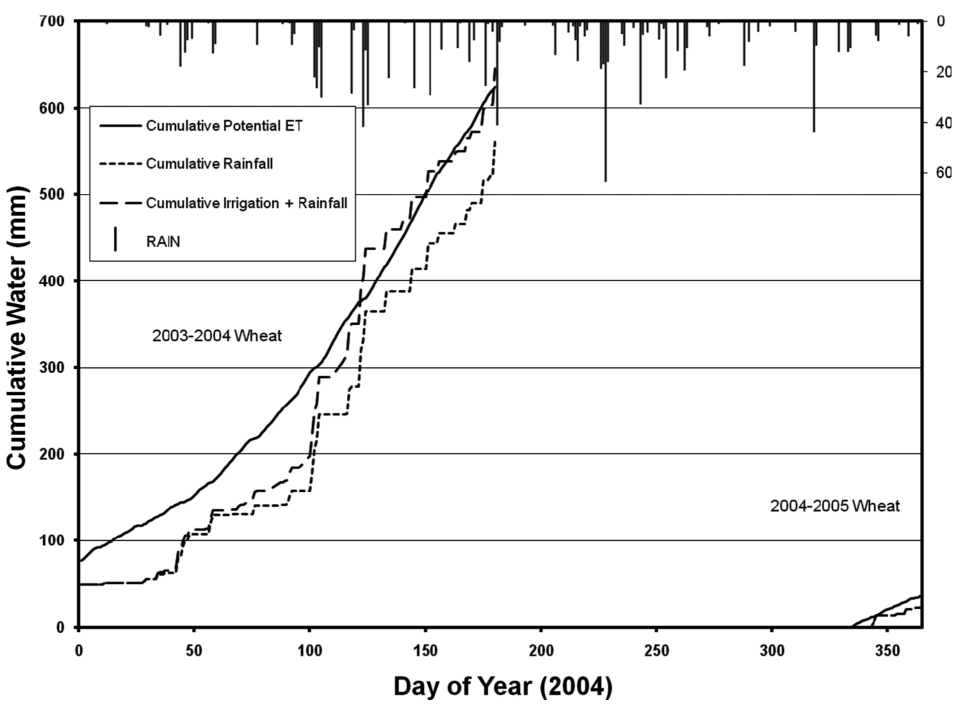

Figure 2. Water management in 2004.

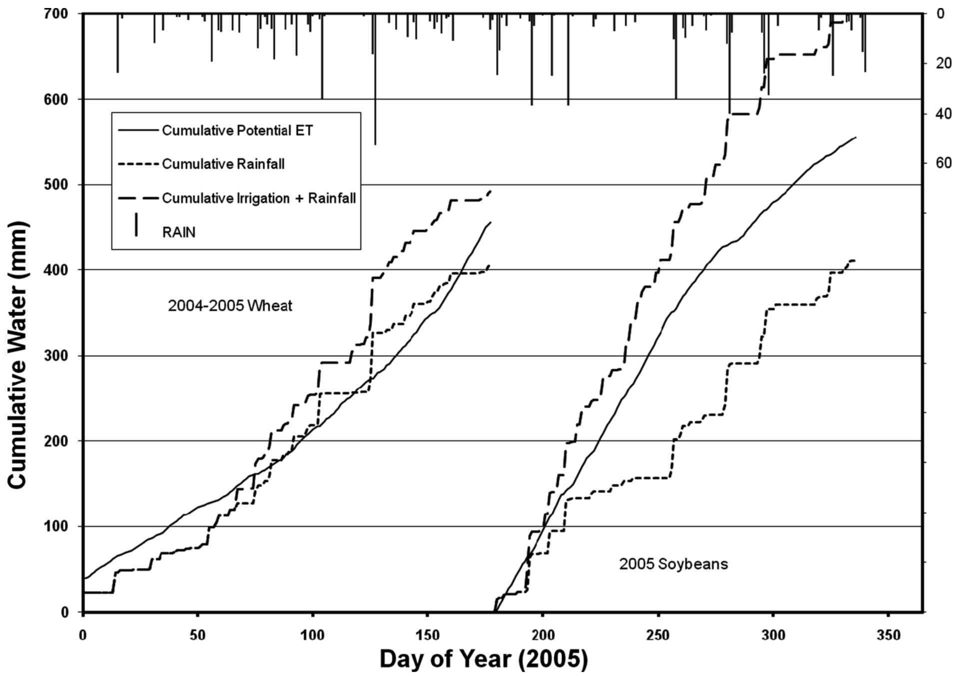

Figure 3. Water management in 2005.

Table 1
Accumulations of rain, irrigated well water, and irrigated wastewater (mm) for soybean and wheat grown on a sandy Coastal Plain soil

	Soybeans				Wheat			
Year	Rain	Total irrigation	Well water	Waste water	Rain	Total irrigation	Well water	Waste water
2003	502.0	88.9	0.0	88.9		—	—	—
2004	338.8	106.4	106.4	0.0	562.3	82.9	60.5	22.4
2005	411.2	292.1	292.1	0.0	406.7	85.6	54.1	31.5

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Camp, and Busscher 2002; Camp, Bauer, and Busscher 1999; Camp, Bauer, and Hunt 1997; Hunt et al. 1998). The SDI lines were 30 cm deep. They were spaced at both 1 and 2 m between lines. The soybean on the SDI plots and nonirrigated plots were planted on 10 July. This was 10 days after planting the experiment in Duplin County experiment. The cultivars were Delta Pineland 7220RR, Northrop King 573Z5RR, Southern States RT6202N, Pioneer 97B52RR, and Prichard RR. The soybean was irrigated with SDI using well water.

In the Duplin County experiment, four cultivars of wheat were planted: Vigoro Tribute, Pioneer 26R61, UniSouth Genetics 3209, and Southern States FFR566. The plantings were at a rate 134 kg ha^{-1} on 2 December 2003 and 30 November 2004.

Soybean plant population was determined by counting the number of plants in 1 m^2 of each subplot. Soybean plant dry matter was determined by collecting whole-plant samples

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from 1 m^2 of each subplot on 15 October 2003 (Hunt, Burnham, and Matheny 1987). Wheat plant dry matter was determined similarly on 11 May 2004 and 17 May 2005. Soybean and wheat plant samples were dried at 43 °C for 72 h, weighed, and ground for N analysis. Soybean and wheat seed yields were determined by harvesting 17.2 m^2 from the center of each subplot with an Almaco plot combine. Seed moisture was determined on a Steinlite model SS250 moisture meter. The weight of 100 seeds was determined by manually selecting 100 seeds, drying them at 60 °C for 48 h, and weighing them. Dried soybean and wheat seeds were ground for N analysis. Plant and seed N was determined on a Leco C/N 2000 analyzer.

Soil Carbon and Nitrogen

Soil samples were collected from each main plot on 13 June 2002, 9 September 2003, 19 October 2004, and 24 January 2006. Fifteen soil cores (15 cm long × 2 cm in diameter) were taken to a depth of 60 cm. The core samples were composited for each main plot, placed in storage bags, transported to the laboratory, and air-dried for 1 week. The air-dried samples were ground to pass a 2-mm sieve. Soil N and C were determined with a Leco C/N 2000 analyzer.

Soil Water Analysis

Soil hydraulic conductivity samples were taken at 30-cm and 60-cm depths from the middle of replicates to determine general soil water flow characteristics. Samples were 245 cm^{-3}, 7.25-cm-diameter cores that were analyzed for unsaturated hydraulic conductivity using an unsaturated hydraulic conductivity K(u)-pF apparatus. Unsaturated hydraulic conductivity curves were used to determine conductivity values for soil water tensions of 10 kPa and 33 kPa.

Data were analyzed by Proc GLIMIX and LSM (least squares means) conducted with version 6.12 of Statistical Analysis System (SAS).

Results and Discussion

The irrigation water filtration and delivery system worked effectively. As with the bermudagrass experiment of Stone, Hunt, et al. (2008), the swine wastewater from the treatment plant caused no problems within the subsurface irrigation system.

Soybean

Seed germination and stand establishment are major factors for any cropping system. In 2003, the stand establishment and seed yields were generally good (Table 2). The mean stand was 70 plants m^{-1}. The stands were not significantly affected by irrigation ($P = 0.65$). However, they were significantly affected by cultivar [probability value (P) = 0.01]. The cultivars Deltapine (DP) and Southern States (SS) had the most dense and least dense stands with 95.9 and 58.0 plants m^{-2}, respectively. In 2004, there was a short but extreme drought period (Figure 2). Under these low rainfall conditions, this Autryville loamy sand provided such a dry matrix for soybean seed that a stand failed to establish despite irrigation. Even with the narrower 0.93-m subsurface drip irrigation line spacing, there was insufficient water in the seed bed to promote germination. This result was consistent with the low unsaturated hydraulic conductivity of Autryville soil. Though

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Table 2
Soybean 2003 stands (plants ha^{-1} × 10,000) as influenced by water management with treated swine wastewater

	Cultivar[b]				
Water treatment[a]	DP	NK	SS	PI	Mean[c]
A	87.8ab	62.0dc	57.7d	73.1bc	70.2a
B	103.3a	49.9d	50.8d	72.8bc	69.2a
C	96.4a	63.3dc	65.4dc	65.4dc	72.6a
Mean[c]	95.9a	58.4c	58.0c	70.5b	

[a]Water treatment: A, ET irrigation and 0.97 m spacing; B, ET irrigation and 1.93 m spacing; and C, nonirrigated.
[b]Cultivar: DP, Delta Pineland 7220RR; NK, Northrop King 573Z5RR; SS, Southern States RT6202NRR; and PI, Pioneer 97B52RR.
[c]Means with similar letters are not different by least significant means at 0.05%.

Table 3
Unsaturated hydraulic conductivity (mm h^{-1}) at 10 kPa and 33 kPA (field capacity) for the Autryville soil

	10 kPA		33 kPA	
Depth (cm)	Mean	Std	Mean	Std
30	0.0106	0.0077	0.0017	0.0023
60	0.0068	0.0042	0.0010	0.0000

the Autryville soil has moderately rapid saturated hydraulic conductivity (51 to 152 mm h^{-1}), it dries out quickly because of its high sand content (∼80%), and much of this sand is coarse. As a result, it has low unsaturated hydraulic conductivity (Table 3). At soil water field capacity (33 kPa), the unsaturated hydraulic conductivity was 0.0017 ± 0.0023 mm h^{-1}. Low unsaturated conductivity made it difficult for water to move either upward into the dry soil of the seedbed or laterally to rows between the laterals. This stand failure occurred in the nonirrigated plots as well as the irrigated plots. Moreover, the irrigation water that was applied was well water (Table 1). Thus, there was no involvement of the wastewater in this stand failure.

Somewhat similarly in 2005, there were the multiple effects of low unsaturated conductivity and significant drought. A good stand was established. The plant populations ranged from 49 to 74 plant m^{-2}. However, less than 30 days after soybean plant emergence and initiation of soybean vegetative growth, there was a significant drought along with insect and wildlife damage. These biotic and abiotic factors resulted in low dry-matter growth and accumulation. The shoot dry matter ranged from 1.8 to 2.9 Mg ha^{-1}. This was less than half of the shoot dry-matter accumulation in 2003. Those factors were also likely contributors to that year's soybean grain yield failure (<0.2 Mg ha^{-1}).

The low impact of the irrigation treatment is not an altogether surprising result. For instance, the SDI lateral distance was found to significantly affect corn grain yield (Stone, Bauer, et al. 2008), even in soils where unsaturated hydraulic conductivities were an order of magnitude greater. Camp (1998) reported that SDI systems installed for multiple-year

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use and tillage were generally installed at depths from 0.2 to 0.7 m, optimized for site-specific conditions, but not optimized for seed germination. Separate sprinkler or surface irrigation systems were needed to ensure adequate seed germination. Schwankl, Grattan, and Miyao (1990) suggested that SDI laterals be placed as shallow as tillage practices allow for coarse-textured soils and at the appropriate depth to prevent undesired surface wetting. The current experiment, with SDI laterals installed 0.3 m deep, was shallow relative to the 0.2- to 0.7-m depth range described by Camp (1998). Yet, in the Autryville loamy sand, it was not hydraulically adequate to provide moisture movement upward for seed germination and stand establishment. Collectively, these facts established a clear warning that SDI does not remove drought vulnerability from grain crops grown on this kind of sandy soil. Even if much closer lateral spacings might improve the irrigation effectiveness, they would dramatically increase the installation cost.

Fortunately, these results with grain crops are in contrast to that found for SDI of bermudagrass plots in a contiguous experiment (Stone, Hunt, et al. 2008). In the bermudagrass plots, stand establishment was never a factor because the SDI was installed in an established pasture/field. Moreover, the existing root web allowed the bermudagrass to benefit rapidly from receiving SDI. The wastewater-irrigated treatments were equal or better in hay yield and quality than those receiving well water and commercial fertilizer (Burns, King, and Westerman 2009; Cantrell et al. 2010, 2009; Stone, Hunt, et al. 2008). Thus, SDI in an established forage crop would not have nearly as much drought vulnerability as grain crops.

In 2003, when stand establishment and yield were generally good, rainfall was adequate for acceptable nonirrigated soybean yields (Figure 1 and Table 3). Even so, soybean seed yields were enhanced by irrigation with the treated wastewater (Table 4). When nonirrigated soybean was contrasted against irrigated, the means were 1.55 versus 1.98 Mg ha^{-1}; the significance level was $P = 0.04$. However, there was no significant difference between the lateral spacings. The Delta Pineland cultivar had a significantly greater soybean seed yield, 2.30 Mg ha^{-1}, than any other cultivar. Its yield was also most enhanced by irrigation, 1.85 versus 2.53 Mg ha^{-1}. The seed yields of other cultivars were neither significantly different with irrigation nor significantly different from each other. Their seed yields were 1.78 Mg ha^{-1}. The overall mean yield for the Northrup King (NK) soybean

Table 4
The 2003 soybean seed yield (Mg ha^{-1}) as influenced by water management with treated swine wastewater

	Cultivar[b]				
Water treatment[a]	DP	NK	SS	PI	Mean[c]
A	2.48b	1.73cd	1.65cd	1.70cd	1.89a
B	2.58a	2.01abc	1.90abc	1.79bcd	2.07a
C	1.85cd	1.36cd	1.81bcd	1.91d	1.55a
Mean[c]	2.30a	1.70b	1.78b	1.56b	

[a]Water treatment: A, ET irrigation and 0.97 m spacing; B, ET irrigation and 1.93 m spacing; and C, nonirrigated.

[b]Cultivar: DP, Delta Pineland 7220RR; NK, Northrop King 573Z5RR; SS, Southern States RT6202NRR; and PI, Pioneer 97B52RR.

[c]Means with similar letters are not different by least significant means at 0.05%.

Table 5
The 2003 soybean 100-seed weight (g 100-seed^{-1}) as influenced by water management with treated swine wastewater

Water treatment[a]	Cultivar[b] DP	NK	SS	PI	Mean[c]
A	14.2b	15.1b	16.6a	14.8b	15.2a
B	14.7b	15.1b	17.2a	15.2b	15.6a
C	15.2b	14.8b	16.7a	14.7b	15.4a
Mean[c]	14.7b	15.0b	16.8a	14.9b	

[a]Water treatment: A, ET irrigation and 0.97 m spacing; B, ET irrigation and 1.93 m spacing; and C, nonirrigated.
[b]Cultivar: DP, Delta Pineland 7220RR; NK, Northrop King 573Z5RR; SS, Southern States RT6202NRR; and PI, Pioneer 97B52RR.
[c]Means with similar letters are not different by least significant means at 0.05%.

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was 1.70 Mg ha^{-1}. This yield was comparable to an earlier study with double-cropped NK soybean and wheat. In that study with tillage on Eunola loamy sand, the NK soybean 4-year mean yield was 1.78 Mg ha^{-1} (Hunt et al. 2004). In that totally nonirrigated study, the yearly means ranged from 0.67 to 2.60 Mg ha^{-1}. Thus, the nonirrigated NK soybean yield of 1.36 Mg ha^{-1} in a good rainfall year was about the middle of the range of those found by Hunt et al. (2004).

Some insight into the growth and yield responses of the soybean cultivars can be obtained from the soybean seed size. It varied significantly with the cultivars but not irrigation treatments (Table 5). The SS soybean was significantly larger than any of the other cultivars ($P = 0.05$). Whereas the SS soybean seed had a greater 100-seed weight of 16.8 g than the NK soybean, their equal yield was a result of more seed production in the NK soybean. Similarly, the greater yield of the DP soybean was related to more seeds. This is also consistent with the greater plant population, 96 plants m^{-2}, of the DP soybean.

Soybean shoot dry matter was significantly increased by SDI [single degree of freedom contrast ($P = 0.01$)]. The nonirrigated versus irrigated means were 4.97 versus 6.90 Mg ha^{-1}, respectively (Table 6). There was no significant difference for subsurface drip line spacing. At variance to seed yield, the DP soybean was only significantly greater in dry-matter accumulation from the SS soybean; their means were 6.80 and 5.93 Mg ha^{-1}, respectively. These values are slightly greater than the 4.00 Mg ha^{-1} 4-year mean shoot dry matter found by Hunt et al. (2004) for double-cropped conservation tilled soybean. In that study, they had a mean grain/shoot ratio of 0.36. In the current study, the grain/shoot ratio for the nonirrigated soybean was 0.31. The grain/shoot ratio for the irrigated treatments was 0.25. Similar to dry-matter accumulation, the accumulated soybean plant N was significantly impacted by irrigation ($P = 0.05$). The nonirrigated versus irrigated means were 147 vs. 213 kg N ha^{-1}, respectively (Table 7). Cultivars did not accumulate significantly different amounts of N ($P = 0.05$).

In the check experiment on an Eunola loamy sand in Florence, South Carolina, in 2005, the soybean grown with SDI from well water were planted 10 days later (July 10). Nonetheless, the five tested soybean cultivars produced modest seed yields of 0.72 to 1.04 Mg ha^{-1} even under nonirrigated conditions (Table 8). They produced significantly ($P = 0.05$) better yields of 1.13 to 1.46 Mg ha^{-1} with subsurface irrigation. The SDI line spacing did not significantly impact the soybean seed yields. This irrigation site had also

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Table 6
The 2003 soybean dry matter (Mg ha^{-1}) as affected by irrigation rate and line spacing

	Cultivar[b]				
Water treatment[a]	DP	NK	SS	PI	Mean[c]
A	7.44ab	6.66abc	5.96bc	6.49abc	6.64a
B	7.76ab	8.28a	6.10abc	6.46abc	7.15a
C	5.21cd	5.34cd	5.71bc	3.60d	4.97b
Mean[c]	6.80a	6.76ab	5.93ab	5.52b	

[a]Water treatment: A, ET irrigation and 0.97 m spacing; B, ET irrigation and 1.93 m spacing; and C, nonirrigated.
[b]Cultivar: DP, Delta Pineland 7220RR; NK, Northrop King 573Z5RR; SS, Southern States RT6202NRR; and PI, Pioneer 97B52RR.
[c]Means with similar letters are not different by least significant means at 0.05%.

Table 7
The 2003 soybean nitrogen accumulation (kg ha^{-1}) as affected by irrigation rate and line spacing

	Cultivar[b]				
Water treatment[a]	DP	NK	SS	PI	Mean[c]
A	224abc	209bdc	184bdc	188bdc	201a
B	238ab	278a	179bdc	201bdc	224a
C	149ed	166dc	174bdc	96.7e	147b
Mean[c]	204ab	218a	179bc	162c	

[a]Water treatment: A, ET irrigation and 0.97 m spacing; B, ET irrigation and 1.93 m spacing; and C, nonirrigated.
[b]Cultivar: DP, Delta Pineland 7220RR; NK, Northrop King 573Z5RR; SS, Southern States RT6202NRR; and PI, Pioneer 97B52RR.
[c]Means with similar letters are not different by least significant means at 0.05%.

produced good cotton and peanut yields (Hunt et al. 1998). Even with 1.9-m lateral spacing, this Eunola soil was able to adequately transmit the irrigation water to the soil surface for cotton seedbed wetting and laterally for water to plants growing halfway between the irrigation lines for several experiments over a 10-year period (Bauer, Camp, and Busscher 2002; Camp, Bauer, and Busscher 1999; Camp, Bauer, and Hunt 1997; Hunt et al. 1998). For corn at this site, there were differences among SDI spacings in 1 of 2 years (Stone, Bauer, et al. 2008). However, even in the year with a lower yield for the 2-m lateral spacing; the corn yield was greater than 5 Mg ha^{-1}. The Autryville soil was not able to support a relatively similar yield for soybean/wheat with or without SDI. As discussed earlier, its apparent inability to move water either upward or laterally is consistent with its very low hydraulic conductivity.

Wheat

Wheat yield was not significantly affected by irrigation ($P = 0.45$). The mean yield was 1.06 Mg ha^{-1} (Table 9). This nonsignificant wheat yield increase from SDI is similar to

Table 8
Soybean seed yield (Mg ha^{-1}) on a Eunola loamy sand in Florence, S.C., in 2005

	Cultivar[b]					
Water treatment[a]	DP	SS	PI	NK	PR	Mean[c]
A	1.46a	1.24abcde	1.29abcd	1.15cdef	1.37ab	1.30a
B	1.32abc	1.24abcde	1.19cdef	1.13def	1.45a	1.27a
C	1.04ef	0.86gh	0.80h	0.72h	0.99fg	0.88b
Mean[c]	1.27a	1.11b	1.09bc	1.00c	1.27a	

[a]Water treatment: A, ET irrigation and 0.97 m spacing; B, ET irrigation and 1.93 m spacing; and C, nonirrigated.
[b]Cultivar: DP, Delta Pineland 7220RR; NK, Northrop King 573Z5RR; SS, Southern States RT6202NRR; PI, Pioneer 97B52RR; and PR, Prichard RR.
[c]Means with similar letters are not different by least significant means at 0.05%.

the findings of Camp, Bauer, and Busscher (1999). In their experiment on an Eunola loamy sand, they had a mean wheat yield of 2.18 Mg ha^{-1}. The wheat yields for both of these experiments were dramatically lower than the 6.34 Mg ha^{-1} subsurface-irrigated wheat yields in China with 0.75-m line spacing (Yu et al. 2010). In the current experiment with supplemental irrigation from treated swine wastewater, the wheat yield was greatly affected by cultivar (Table 9). The Pioneer (PI) cultivar seed yield of 1.42 Mg ha^{-1} was more than double the 0.60 Mg ha^{-1} of the Vigoro Tribute (VT) cultivar. Likewise, the SS wheat yield of 1.27 was greater than either the VT or UniSouth Genetics (USG) wheat cultivars. The PI yield advantage was in part associated with the greater seed weight (Table 10). Their 3.60 g 100 seed^{-1} was significantly greater than any other cultivar ($P = 0.05$). Conversely, the greater seed yield of the SS was more attributed to a greater number of seeds because it had the least 100-seed^{-1} weight of 2.70 g ($P = 0.05$). There was no significant effect of irrigation upon 100-seed weight ($P = 0.25$). These variations in yield based on cultivar suggest that blends of cultivars might be useful. Such cultivar blends were found to provided a significant increase for wheat yield in North Carolina by Cowger and Weisz

Table 9
Wheat seed yield (Mg ha^{-1}) as influenced by water management with treated swine wastewater

	Cultivar[b]				
Water treatment[a]	VT	USG	SS	PI	Mean[c]
A	0.53ef	1.01cd	1.01cd	1.51a	1.13a
B	0.50f	0.78cdf	0.97cde	1.34abc	0.90a
C	0.76edf	1.02bcd	1.36abc	1.40abc	1.14a
Mean[c]	0.60c	0.94b	1.27a	1.42a	

[a]Water treatment: A, ET irrigation and 0.97 m spacing; B, ET irrigation and 1.93 m spacing; and C, nonirrigated.
[b]Cultivar: VT, Vigoro Tribute; PI, Pioneer 26R61; USG, Unisouth Genetics 3209; and SS, Southern States FFR566.
[c]Means with similar letters are not different by least significant means at 0.05%.

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Table 10
Wheat seed weight (g 100-seed^{-1}) as influenced by water management with treated swine wastewater

	Cultivar[b]				
Water treatment[a]	VT	USG	SS	PI	Mean[c]
A	2.91bcd	2.83cde	2.64e	3.68a	3.02a
B	2.82de	3.03bc	2.64e	3.56a	3.01a
C	2.82ed	3.07b	2.80ed	3.60a	3.10a
Mean[c]	2.86c	2.98b	2.70d	3.60a	

[a]Water treatment: A, ET irrigation and 0.97 m spacing; B, ET irrigation and 1.93 m spacing; and C, nonirrigated.
[b]Cultivar: VT, Vigoro Tribute; PI, Pioneer 26R61; USG, Unisouth Genetics 3209; and SS, Southern States FFR566.
[c]Means with similar letters are not different by least significant means at 0.05%.

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(2008). In their study at three locations in North Carolina, they reported yields in the range of 4 to 5 Mg ha^{-1}. In contrast, the wheat yields of the current investigation are low even when compared to the nonirrigation yields on a coastal plain loamy sand soil by Hunt et al. (2004). In that experiment on a Norfolk loamy sand with both conventional tillage and conservation tillage, the wheat yield 4-year means ranged from 2.59 to 3.24 Mg ha^{-1}. In another wheat–cotton experiment with Coker 9227 wheat under conservation tillage on a Norfolk loamy sand, Hunt, Bauer, and Matheny (1997) obtained a 4-year mean yield of 1.83 Mg ha^{-1}. In the current experiment, the poor wheat yield of the nonirrigated treatment was neither enhanced nor diminished by SDI with treated swine wastewater.

Relative to seed N content, there were significant irrigation and cultivar effects (Table 11). The PI had the greatest seed N content, 2.58% N, and the VT had the least, 2.38% N ($P = 0.05$). The subsurface drip line spacing treatments were not significantly different, but they were both significantly lower than the 2.56% N of the nonirrigated treatment. The shoot dry-matter accumulations of wheat ranged from 3.42 to 5.31 Mg

Table 11
Wheat seed N content (%) as influenced by water management with treated swine wastewater in 2005

	Cultivar[b]				
Water treatment[a]	VT	USG	SS	PI	Mean[c]
A	2.31e	2.38ed	2.54abc	2.61ab	2.46b
B	2.39ed	2.43cde	2.52abc	2.50bcd	2.45b
C	2.43cde	2.55abc	2.60ab	2.64a	2.56a
Mean[c]	2.38c	2.45b	2.55a	2.58a	

[a]Water treatment: A, ET irrigation and 0.97 m spacing; B, ET irrigation and 1.93 m spacing; and C, nonirrigated.
[b]Cultivar: VT, Vigoro Tribute; PI, Pioneer 26R61; USG, Unisouth Genetics 3209; and SS, Southern States FFR566.
[c]Means with similar letters are not different by least significant means at 0.05%.

Table 12
Wheat dry matter (Mg ha^{-1}) as influenced by water management with treated swine wastewater in 2005

	Cultivar[b]				
Water treatment[a]	VT	USG	SS	PI	Mean[c]
A	3.94ab	3.42b	4.68ab	5.31a	4.34a
B	3.46ab	4.06ab	4.30ab	4.57ab	4.10a
C	4.55ab	4.32ab	4.63ab	4.80ab	4.57a
Mean[c]	3.98ab	3.93b	4.54ab	4.89a	

[a]Water treatment: A, ET irrigation and 0.97 m spacing; B, ET irrigation and 1.93 m spacing; and C, nonirrigated.
[b]Cultivar: VT, Vigoro Tribute; PI, Pioneer 26R61; USG, Unisouth Genetics 3209; and SS, Southern States FFR566.
[c]Means with similar letters are not different by least significant means at 0.05%.

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ha^{-1} (Table 12). They were not significantly affected by irrigation ($P = 0.05$), cultivar, or the cultivar by irrigation interaction. The shoot N contents of wheat ranged from 1.55% to 1.90%. As with the dry-matter accumulation, shoot N content was not significantly affected ($P = 0.05$) by either irrigation or the cultivar by irrigation interaction. However, the SS wheat cultivar's shoot N of 1.88% was significantly greater than all other cultivars, which ranged from 1.71% to 1.74%. The shoot N accumulations of wheat ranged from 54 to 90 kg ha^{-1}. It was not significantly ($P = 0.05$) affected by irrigation, cultivar, or the cultivar by irrigation interaction. As with the soybean, the poor wheat growth and yield of the nonirrigated treatment were generally neither enhanced nor diminished by SDI. Thus, whether from abiotic or biotic factors, this particular Autryville loamy sand was unsuitable for good soybean/wheat production. Even though the SDI treatments of this experiment were equal to or better than the nonirrigated treatment in the soybean/wheat production, they did not significantly improve this generally poor crop growth and yield condition.

Soil Nitrogen and Carbon Contents

Soil nitrogen content was not significantly ($P = 0.05$) affected by SDI line spacing (Table 13), nor was there a difference between irrigated and nonirrigated soils ($P = 0.05$). The mean value for soil N in the 0- to 15-cm depth was 414 mg kg^{-1}. In the contiguous experiment with bermudagrass forage, the soil N content of the 0- to15-cm depth had similar values. Its soil N range was 432 to 574 mg kg^{-1} from 2003 to 2006 (Stone, Hunt, et al. 2008). With a bulk density of 1.6, the surface layer soil mean concentration of 414 mg kg^{-1} would convert to about 1 Mg ha^{-1}. This amount of N is considerably greater than the 0.345 Mg ha^{-1} soil N in the surface 0- to 15-cm depth of a Norfolk loamy sand that was in long-term conservation tillage and growing a corn–wheat–cotton rotation (Karlen, Hunt, and Matheny 1996). This is not an unexpected result because the Autryville soil of this experiment had received substantial swine anaerobic lagoon wastewater for several years. Accordingly, the soil N concentrations were more in line with the values reported by Siri-Prieto, Reeves, and Raper (2007) for a cotton–peanut rotation with winter-annuals grazed by yearling steers.

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Table 13
Nitrogen content (mg kg^{-1}) of the Autryville loamy sand during the subsurface drip irrigation experiment with soybean and wheat

	Depth (cm)				
Year	0–15	15–30	30–45	45–60	Mean[a]
2003	410b	194gf	211gef	161g	244b
2004	495a	257ed	200gef	185g	284ab
2005	338c	297cd	199gef	244def	269ab
Mean[a]	414a	250b	203c	197c	

[a]Means with similar letters are not different by least significant means at 0.05%.

Table 14
Carbon content (mg kg^{-1}) of the Autryville loamy sand during the subsurface drip irrigation experiment with soybean and wheat

	Depth (cm)				
Year	0–15	15–30	30–45	45–60	Mean[a]
2003	5821a	3559c	3326cd	2500ef	3802a
2004	6394a	3615c	2736de	2317efg	3765a
2005	4821b	2561def	1893gf	1643g	2730b
Mean[a]	5679a	3245b	2652c	2153d	

[a]Means with similar letters are not different by least significant means at 0.05%.

The soil C content of this Autryville soil should have benefited from the absence of surface tillage in its previous forage management along with the conservation tillage management of the current experiment. The mean C content of the soil 0- to 15-cm depth was 5,679 mg kg^{-1} (Table 14). This value was considerably lower than the concentration of 7.9 g kg^{-1} reported by Hunt et al. (1996) for a Norfolk loamy sand after a decade of row crops under conservation tillage. In that experiment, the cropping rotation was corn, wheat, and cotton. Its wheat yield of 1.98 Mg ha^{-1} was also greater than that produced on the Autryville soil. The Autryville soil of the current experiment was also lower in C concentrations at the 15- to 30-cm and 30- to 45-cm depths. However, the C content of the 45- to 60-cm depth of 2,153 mg kg^{-1} was the same as the Norfolk soil (Hunt et al. 1996). The soil C of the current experiment was also lower than the soil C content of the previously discussed cropping and grazing experiment of Siri-Prieto, Reeves, and Raper (2007). It was lower than the 11.6 g kg^{-1} for a Decatur silt loam in northern Alabama when that soil was under a cotton–wheat–soybean rotation (Motta et al. 2007). Similarly, it was also lower than the soil organic C of two sandy soils (Bendale and Lindale) that were under conservation tillage in coastal plain region of Alabama (Motta, Reeves, and Touchton 2002). When the C and N were considered together, the mean C/N ratio of the Autryville soil of this experiment was 7.86. This low ratio is not a particularly desirable condition because it can be related to greater levels of nitrous oxide emissions (Hunt, Matheny, and Ro 2007; Klemedtsson et al. 2005).

While the SDI irrigation of a soybean and wheat cropping system did not do well on the converted bermudagrass forage/pasture site, it did do well when installed into the existing bermudagrass forage/pasture of this site (Stone, Hunt, et al. 2008). Accordingly, forage/pasture for SDI of the treated wastewater would seem to be a better management approach for many sandy soils of the coastal plain.

Conclusion

Relative to irrigation water flow, the screen filters for both well water and wastewater along with the media filter with sand and gravel provided adequate filtration of the irrigation waters.

In all aspects of soybean and wheat production, the SDI treatment was equal to or better than the nonirrigated treatment.

The effectiveness of the SDI was diminished by the soil's low unsaturated hydraulic conductivity. At soil water field capacity (33 kPa), the unsaturated hydraulic conductivity was 0.0017 ± 0.0023 mm h^{-1}. This caused problems with water movement to either the soil surface or laterally to adjoining soybean and wheat roots.

In the first year of the experiment (a good rainfall year), the soybean yield was satisfactory and benefited from the supplemental irrigation. Nonirrigated and irrigated soybean mean yields were 1.55 versus 1.98 Mg ha^{-1}, respectively. In the second year, there was an early drought and complete stand failure. Although a good stand and acceptable early growth occurred in the third year, there was a late drought complicated by insect and wildlife damage. Yields were <0.2 Mg ha^{-1}.

The Deltapine 7220RR soybean cultivar was significantly greater than all other cultivar seed yield. The Northrop King 573Z5RR cultivar accumulated the most plant N.

The wheat mean yield of 1.06 Mg ha^{-1} was quite low. Moreover, wheat yields were not affected by irrigation. The Southern States FFR566 and Pioneer 26R61 were the highest-yielding cultivars with yields of 1.27 and 1.42 Mg ha^{-1}, respectively.

In regard to soil conditions, neither the soil N nor C was significantly impacted by the wastewater irrigation. The mean value for soil N in the 0- to 15-cm depth was 414 mg kg^{-1}. This soil N content was generally high relative to typical sandy coastal plain soils. This was most likely related to its history of receiving swine anaerobic lagoon wastewaters.

The mean C content of the soil 0- to15-cm depth was 5,679 mg kg^{-1}. This soil C content is not atypically high. In fact, it is lower than many coastal plain soils under long-term conservation tillage.

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