Soil Moisture Controlled Subsurface Drip Irrigation on Sandy Soils

M. D. Dukes, J. M. Scholberg

Abstract. *Subsurface drip irrigation (SDI) is being adopted in areas to conserve water while maintaining economical production of crops. These systems have not been evaluated on sandy soils common to Florida. An SDI system was installed on a well−drained sandy soil for sweet corn production in Florida. SDI tubing was buried under each row (76−cm spacing) at either two depths of 23 or 33 cm below the ground surface to result in two experimental treatments. Additionally, two methods of irrigation scheduling were imposed on the SDI treatments. One scheduling treatment was the initiation and termination of irrigation based on soil moisture measured by time domain reflectometry (TDR) probes installed 5 cm above the drip line. The other scheduling treatment was a daily irrigation event at rates consistent with typical practice in the region. Sprinkler irrigation scheduled similar to farmer practices in the region and non−irrigated control treatments were also established. The soil moisture based irrigation scheduling regime resulted in high frequency short duration (30−min) irrigation events to meet crop water needs. The 23−cm deep soil moisture−based treatment resulted in similar yields and similar water use in 2002 and reduced water use 11% with similar yields compared to sprinkler irrigation in 2003. This indicates that 23−cm deep SDI is feasible for sweet corn production under these conditions. The combination of optimum yield and minimum water use was achieved with soil moisture based set points of 10% to 12% by volume (on−off). The 33−cm depth SDI treatment was found to be too deep for optimal yield results on sweet corn under the type of sandy soil in the study. Time−based SDI treatments were under−irrigated but showed evidence of considerable drainage based on soil moisture measurements due to single daily irrigation events that promoted movement of irrigation water below the root zone. Comparison of drainage calculations beneath the SDI treatments and sprinkler treatments indicated that up to 24% less drainage may have occurred on SDI plots compared to sprinkler plots largely because SDI applied water to the root zone and not the furrows.*

Keywords. *SDI, Subsurface drip, Automatic irrigation,* Zea mays*, Irrigation water use efficiency, High frequency irrigation, Sweet corn, Time domain reflectometry (TDR).*

In 2001−2002, vegetable production in Florida covered approximately 118,000 ha with a value of $1.7 billion annually. Of this production, sweet corn (*Zea mays*.) covered 16,000 ha and had a value of $122 million. While agriculture is only second in value to tourism in the state's economy, increased competition for water resources between urban, recreational, industrial, and agricultural users challenge the long−term viability of these industries, as they currently exist.

Florida has the second largest withdrawal of ground water for public supply in the United States (Solley et al., 1998) and ranks thirteenth nationally for agricultural self−supplied water use; yet, it is the top water user in this category in the humid region (Solley et al., 1998). Agricultural self−supply is the largest component of freshwater use with 45% of the total withdrawals in Florida (Marella, 1999). Although rainfall is plentiful in this region, optimal yields are assured with supplemental irrigation.

Sweet corn in Florida is typically irrigated via overhead sprinklers (e.g. solid set or center pivot). Although this method has the potential to have acceptable water use efficiencies, over−irrigation is a common occurrence due to inadequate irrigation scheduling and the low soil water holding capacity (6% to 10%) of the sandy soils common to Florida. Subsurface drip irrigation (SDI) is a relatively new technology that can be very efficient in terms of water use (Lamm and Trooien, 2002).

Sorenson et al. (2001a) described a subsurface drip irrigation system (SDI) designed for peanut, cotton, and corn research in the southeastern United States (Georgia). Irrigation events were scheduled based on measured climatic parameters and estimated evapotranspiration (ET) coupled with crop coefficients specific to the region. In another study in Georgia, Sorensen et al. (2001b) found that SDI resulted in 38% more pod yield for peanuts compared to non−irrigated treatments, but found that there was no difference in pod yield due to drip tube spacing, amount of irrigation water applied over several treatments, or emitter spacing. Compaction of upper surface layers has been found to limit the effectiveness of SDI compared to rain fed wheat, soybean, and cotton in the Southeast (Camp et al., 1999). Research data for one growing season in the North Carolina Coastal Plain showed that yields of cotton under SDI exceeded sprinkler irrigated yields while peanuts had similar yields for SDI and sprinkler irrigated

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treatments receiving 163 and 127 mm of irrigation, respectively (Grabow et al., 2002).

Subsurface drip irrigation systems may increase water use efficiency due to reduced soil and plant surface evaporation and because only the root zone or the partial root zone is irrigated as opposed to sprinkler irrigation where the entire field area is wetted. Lamm and Trooien (2002) reviewed 10 years of SDI research on corn in the Great Plains and reported that water savings of 35% to 55% were possible compared to traditional forms of irrigation such as sprinkler and furrow. Automation of SDI systems based on soil moisture sensors may further improve water use efficiency. Shae et al. (1999) described an SDI system coupled with tensiometers and pressure transducers that initiated irrigation of potato when soil tension exceeded 30 kPa. This approach resulted in significantly less irrigation water applied (129 mm) compared to a surface drip irrigation treatment that was scheduled based on a soil moisture balance (220 mm). Similar yields were reported for both treatments.

Many researchers have investigated automation of irrigation systems and the use of soil moisture sensing devices such as tensiometers. Automation generally consists of a soil moisture or water level sensor, a control system, and irrigation system components. Switching tensiometers have been used in various sandy soil applications such as fresh market tomatoes (Clark et al., 1994; Smajstrla and Locascio, 1994; Muñoz−Carpena et al., 2003), citrus (Smajstrla and Koo, 1986), and bermudagrass (Augustin and Snyder, 1984) to automatically control irrigation events based on preset soil matric potential limits. Smajstrla and Koo (1986) discussed the problems associated with using tensiometers to initiate irrigation events in Florida. Problems included entrapped air in the tensiometers, organic growth on the ceramic cups, and the need for re−calibration. Torre−Neto et al. (2000) described an automated irrigation system for citrus production based on tensiometers and wireless communication that is able to account for spatial production variables (e.g. different levels of maturity or varying soil types).

Tensiometers have typically been used to initiate a preset timed irrigation event; therefore, the irrigation event was stopped after a preprogrammed irrigation time rather than actual soil moisture conditions (Smajstrla and Koo, 1986; Smajstrla and Locascio, 1994; Clark et al., 1994; Phene and Howell, 1984; Torre−Neto et al., 2000). Phene and Howell (1984) used a customized soil matric potential sensor to control subsurface drip irrigated processing tomatoes. Their results indicated that tomato yields with the automated system were similar to yields from a pan evaporation scheduled treatment; however, with the potential to use less irrigation water. Phene et al. (1992) used an automated Class A evaporation pan to initiate irrigation on cotton. Other sensors used to automate irrigation systems include turgor potential (Sharon and Bravdo, 2001) and sap flow (Nadezhdina and Jones, 2000) sensors. A float level switch has also been used to control a seepage irrigation system under potato production to achieve an 8% increase in irrigation system efficiency (Smajstrla et al., 1984). Smajstrla and Locascio (2000) used a float level switch to automate a subsurface drip irrigation system and a seepage irrigation system used for potato production. They found that the two systems produced similar yield; however, the subsurface drip system used approximately 36% less irrigation water compared to the seepage system. Dukes et al. (2003) found a 50% reduction in water use with soil moisture based automatically irrigated bell pepper when compared to once daily manually irrigated treatments that had similar yields.

Although used extensively in the past to automate irrigation systems, tensiometers tend to require more maintenance compared to solid−state sensors such as Granular Matrix Sensors (GMS) or Time Domain Reflectometry (TDR) sensors. Granular Matrix Sensors are similar to tensiometers in that they are made of a porous material that reaches equilibrium with the soil moisture tension. The soil moisture tension is correlated with an electrical signal based on a calibration equation. These sensors have been used to automatically irrigate tomato (Muñoz−Carpena et al., 2003), cotton (Meron et al., 1996), onion and potato (Shock et al., 2002), roses in greenhouse production (Hansen and Pasian, 1999), and urban landscapes (Qualls et al., 2001). Generally, these sensors have been found to require less maintenance than traditional tensiometers. Similar to many of the automatic tensiometer controlled irrigation systems, Shock et al. (2002) described a system that used GMS to initiate a timed irrigation event. Although GMS and TDR sensors both provide a mechanism to control irrigation systems, GMS sensors may not provide adequate control for crop irrigation since factory calibration equations for generic soil types do not match those for Florida sandy soil types (Irmak and Haman, 2001; Muñoz−Carpena et al., 2003).

The objectives of this study were to: 1) compare SDI versus sprinkler irrigation impact on water use and marketable yield of sweet corn, 2) compare the effect of time−based scheduling versus soil moisture controlled SDI on water use and marketable yield of sweet corn, and 3) determine a feasible drip tube depth for sandy soils and sweet corn production.

MATERIALS AND METHODS

The study was conducted at the University of Florida Plant Science Research and Education Unit (PSREU) near Citra, Florida with sweet corn (*Zea mays*) in 2002 and 2003. In the spring of 2002, the SDI system was installed. It consisted of an irrigation control shed which included totalizing flow meters with pulse output for data acquisition, 200 mesh disk filter, pressure regulation to 103−kPa, electric solenoid valves, air/vacuum relief valves, and low pressure drains prior to connection to distribution manifolds. Water was supplied to the shed by a continually pressurized supply main. Plots were 4.5 m wide and 15 m long (fig. 1). Drip tube (Typhoon 630, Netafim USA, Fresno, Calif.) had a flowrate of 0.98 L/h at 69 kPa for each emitter, a 30−cm emitter spacing, and a 0.33−mm wall thickness. The drip system operated at an average pressure at the plots of 69 kPa. Pressure regulation at the control shed of 103 kPa accounted for head losses to the furthest plots. Drip tube was positioned at the required soil depth with a soil shank using a row spacing of 76 cm. The irrigation system was controlled by a datalogger (CR−10X, Campbell Scientific, Inc., Logan, Utah) coupled with time domain reflectometry (TDR) probes (CS−615, Campbell Scientific, Inc., Logan, Utah). These TDR probes have been used on several previous projects and the factory calibration has been found to be accurate to within 1% to 2% (by volume) compared to the soil moisture content determined gravimetrically. The probes were not specifically calibrated for the field site. Details of the installation and initial testing of the control system were described by Nogueira et al. (2003). Sodium hypochlorite (10% solution) was injected into the system for 1 h (4.6 mm/event) approximately bi−weekly in 2002. Since the groundwater quality was found to be good, the chlorine injection was modified to 1 h every three to four weeks in 2003 to prevent microbial growth. In addition, the system was flushed periodically at approximately the same interval. Filters were cleaned approximately weekly. Irrigation water use efficiency was calculated as,

$$IWUE = MY/IRRIG \quad (1)$$

IWUE = irrigation water use efficiency (kg/m^3)
MY = marketable yield (kg)
IRRIG = seasonal irrigation water use (including sprinkler applications to all plots) (m^3)

The soil was mapped as consisting of a Candler sand and a Tavares sand (Buster, 1979). These soils are well drained, consist in excess of 97% sand, and have a field capacity of 5.0% to 7.5% by volume (all soil water content in this paper expressed as percent by volume) in the upper 100 cm of the soil profile (Carlisle et al., 1978).

Five irrigation treatments plus a non−irrigated control were established (table 1, fig. 1). Treatments consisted of sprinkler irrigation and two SDI depths (23 and 33 cm). These two depths were selected because the 23−cm depth was the shallowest that could be used multiple years with minimum tillage. The 33−cm depth or deeper would be preferred to minimize tillage damage and to allow more aggressive mechanical tillage; however, in the fine sandy soils of the region it is unlikely that drip tube deeper than 33 cm would be effective since the capillary rise is limited in these soils.

The SDI treatments were further divided into two treatments per depth based on scheduling of the irrigation system. The first scheduling type was intended to simulate what might be typical farmer practices in this region of Florida. Subsurface drip irrigation is not widely used in Florida; therefore, the typical practices used with surface drip irrigation were adapted. Under vegetable production on sandy soils, drip irrigation is normally applied each day for a fixed time in one to two events depending on crop growth stage. Although sweet corn is not typically produced using drip irrigation in Florida, this time−based scheduling practice was adapted. Sprinkler irrigation is normally applied every day or every other day in amounts increasing with growth stage. The second SDI scheduling method was based on soil moisture thresholds according to TDR measurements. A programmed low soil moisture threshold was used to open a solenoid valve and a high soil moisture threshold was used to close the solenoid valve. Sprinkler plots were irrigated with three sprinklers (concave single pad #14 LDN nozzles regulated at 137 kPa, Senninger, Inc., Orlando, Fla.) from a linear move irrigation system. Since the sprinklers covered an approximate width of 10 m, a border plot on each side was established to eliminate influence of sprinkler irrigation over other treatments (fig. 1). Sprinkler application depth was measured several times throughout the experimental study with 15.9−cm diameter catch cans, 20 cm tall, and spaced at 1−m intervals along the sprinkler and border plots. SDI and non−irrigated plots were established in a randomized complete block design with four replicates. The sprinkler plots were randomly located along the linear move system but sprinkler plots in replicates A and C as well as B and D were aligned so that the linear move system could irrigate the sprinkler plots in one pass (fig. 1).

Time domain reflectometry sensors were installed in the SDI plots of two replicates. One probe was buried horizontally 5 cm above the drip irrigation tubing and another 60 cm below and horizontal to the ground surface. The probes above the drip tube were used for irrigation control while the 60−cm deep probes were used to indicate over−irrigation (Nogueira et al., 2003). Sensors were queried each minute by the datalogger and readings were stored as an average over each 15−min interval.

Automatic treatments in 2002 were set to irrigate between the limits of 10% to 14% soil moisture. Adjustments were made in the beginning of the season until the limits were changed to allow irrigation between 7% and 11%; whereas, the limits were set to allow irrigation between 10% and 12% in 2003 the entire season. Sprinkler irrigation events consisted of two events each week of 13−19 mm each in the first 3 to 4 weeks of the season and the rest of the season consisted of three 25−mm events each week.

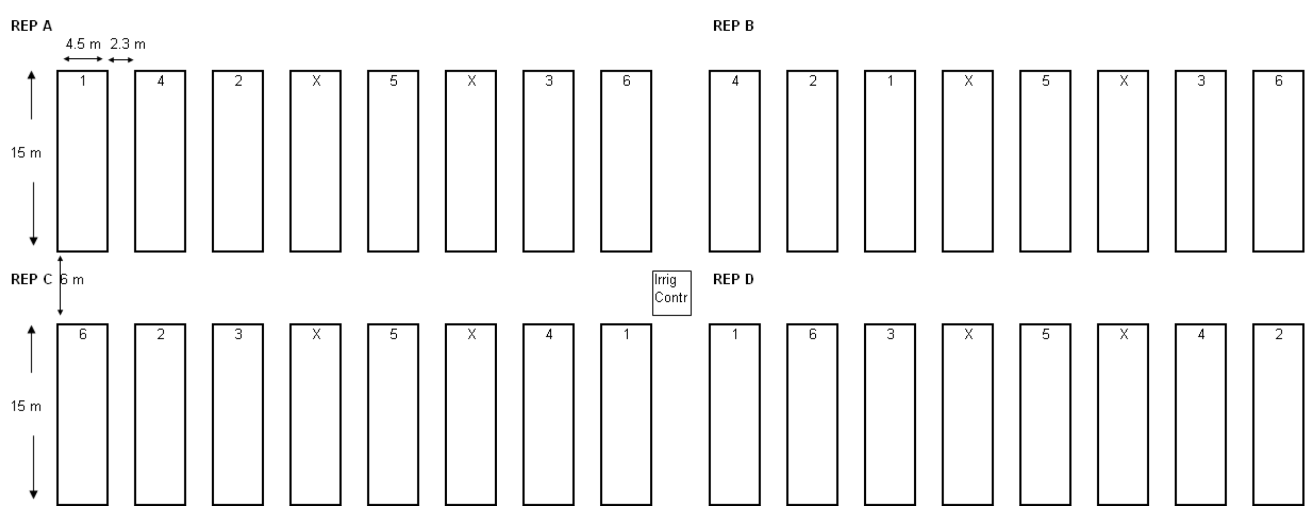


Figure 1. Experimental layout showing treatments as indicated in table 1, as well as sprinkler border plots (X), experimental replicates (A, B, C, D), and the irrigation control and supply shed (Irrig Contr).

Table 1. Treatments grouped by irrigation type, scheduling method, and seasonal average soil moisture content under sweet corn.

Treatment	Irrigation Method	Drip Tape Depth (cm)	Irrigation Scheduling Method	2002 Shallow Soil Moisture[a] Average (m^3/m^3)	2002 Shallow Soil Moisture[a] CV (%)	2002 Deep Soil Moisture[b] Average (m^3/m^3)	2002 Deep Soil Moisture[b] CV (%)	2003 Shallow Soil Moisture Average (m^3/m^3)	2003 Shallow Soil Moisture CV (%)	2003 Deep Soil Moisture Average (m^3/m^3)	2003 Deep Soil Moisture CV (%)
1	Subsurface drip irrigation	23	Time[c]	0.086	21.5	0.104	5.4	0.109	26.4	0.111	10.7
2	Subsurface drip irrigation	23	Sensor	0.082	15.6	0.111	6.7	0.112	11.9	0.118	11.7
3	Subsurface drip irrigation	33	Time	0.084	17.8	0.125	6.3	0.096	25.6	0.121	8.2
4	Subsurface drip irrigation	33	Sensor	0.091	16.5	0.099	8.2	0.123	19.7	0.082	14.4
5	Linear move sprinkler	N/A	Depth	−−	−−	−−	−−	−−	−−	−−	−−
6	Non−irrigated	N/A	N/A	−−	−−	−−	−−	−−	−−	−−	−−

[a] Shallow indicates TDR measured soil moisture at 18 cm depth for treatments 1−2 and 28−cm depth for treatments 3−4.
[b] Deep indicates TDR measured soil moisture at 60−cm depth.
[c] Time−based treatments applied 4.6 mm/h of irrigation run time.

In addition to buried TDR probes to monitor and control irrigation on SDI plots, access tubes were installed for a separate capacitance based soil moisture sensor (model Diviner 2000, Sentek Sensor Technologies, Pty Ltd.,Stepney, Australia). The tubes were installed in mid April of 2002 in two replicates of all plots except the non−irrigated control plots. In those plots, tubes were installed in two replicates. Soil moisture measurements were made approximately every 7 to 10 days in 2002. Tubes were removed after the end of the season in 2002 and not installed in 2003 since they were originally dedicated to another project.

Sweet corn was planted on 26 March 2002 and 5 March 2003 and harvested 31 May 2002 and 20 May 2003 for a total season of 67 and 77 days in 2002 and 2003, respectively. Typically, producers use fertigation to supply most of the nutrients in drip−irrigated systems. In this work, it was decided not to use fertigation because the comparison between sprinkler irrigation and SDI would be confounded with different sources of fertilizer. Therefore, granular fertilizer was used on all treatments.

Fertilization in 2002 consisted of granular 6−12−12 or 18−4−17 with a total of 218 kg/ha N applied over three application periods during the season. In 2003, 13−13−9 or 17−7−18 was applied five times during the first half of the season for a total of 466 kg/ha of N applied. More N was applied in 2003 compared to 2002 to replace fertilizer that was removed due to several intense storm events at the beginning of the season in 2003 (fig. 2). This early rainfall promoted leaching and runoff of fertilizer and resulted in signs of nutrient deficiency early in the growing season until additional N applications were made. In 2002, five sprinkler irrigation events (51−mm total) were applied to all plots to incorporate granular fertilizer under dry conditions and to ensure uniform soil moisture conditions at planting. In 2003, sufficient soil moisture was available at planting due to rainfall just before planting; however, sprinkler irrigation was applied to all plots six times (82−mm total) through 14 April to incorporate granular fertilizer. Other management practices consisted of herbicides to clear the weeds

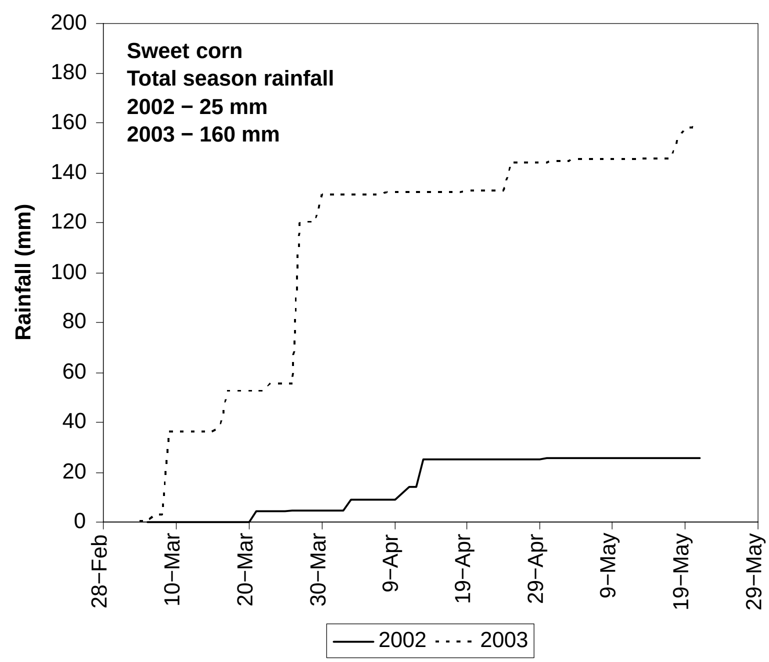


Figure 2. Cumulative rainfall measured at the research site for sweet corn in 2002 and 2003.

pre−plant and as necessary to maintain weed control throughout the season.

Meteorological parameters such as precipitation, air temperature, solar radiation, wind speed, and relative humidity were monitored by a Florida Automated Weather Network (FAWN, available at http://fawn.ifas.ufl.edu) weather station that is located within 500 m of the field site. Daily grass reference ET is estimated by the FAWN network via a modified Penman equation (Jones et al., 1984). Crop coefficients as given by Doorenbos and Pruitt (1975) were used to calculate ETc.

A 2×2 factorial design with ordinary contrasts was used to test for irrigation depth and scheduling type as a main effect as well as check for interactions. Duncan's Multiple Range Test was used to identify mean differences. The PROC GLM procedure was used to perform statistical analyses (SAS, 2003).

Results and Discussion

Soil Moisture−Based Subsurface Drip Irrigation

In 2002 the initial thresholds for soil moisture−based irrigation (see table 1 for treatment descriptions) were set at 10% soil moisture content as the low limit and 14% as the high limit for treatments 2 and 4 (10% to 14%). Figure 3 shows the volumetric soil moisture content averaged across two replicates for treatments 2 and 4. It was observed in the first week (up to 5 April) that the irrigation frequency of the sensor−based treatment 2 was high, with 17 irrigation events occurring from 1 April through 5 April and a soil moisture amplitude of 4% (fig. 3A). Initially, this over−irrigation was tolerated since the soils are fine sands with low water holding capacity and this was thought necessary to move soil moisture content up in the soil profile as high as possible because 2002 was a particularly dry year (fig. 2). However, it is unlikely in these sands that soil moisture was greatly increased close to the surface. Irrigation water from SDI treatments was never observed at the surface despite irrigation events in excess of an hour of run time. Soil moisture levels above 10% to 11% showed rapid drainage as evidenced by vertical changes in soil moisture contents (fig. 3).

Based on the observation of rapid drainage early in the season, sensor−based treatments (2 and 4) were set to irrigate between 8% and 12% volumetric soil moisture content after 5 April. Two irrigation events occurred on treatment 2 between 5 April and 19 April when automatic irrigation on treatment 2 occurred two to three times each day and irrigation did not occur on treatment 4 until 25 April (fig. 3B). Soil moisture−based irrigation was delayed because 16 mm of rainfall occurred between 5 April and 19 April and due to biweekly chlorination injection and flushing of the system. After 19 April it was hypothesized that the corn roots were able to extract water out of the irrigated zone (fig. 3A; 23−cm deep drip tube). A total of 19 irrigation events occurred on treatment 2 between 19 and 25 April (fig. 3A), whereas irrigation did not occur on treatment 4 until 25 April (fig. 3B). Additional time was required for corn roots to establish at the 33−cm depth and begin to extract water, which resulted in stress to the crop on treatment 4. On 25 April soil moisture limits for treatments 2 and 4 were changed to 7% and 11%, where they remained throughout the corn season. It is important to note that the soil moisture sensors controlling irrigation were placed 5 cm above the drip tube in both treatments 2 and 4 resulting in sensors buried 18 and 28 cm from the surface, respectively. This sensor configuration was done to provide a uniform method of controlling the treatments although it resulted in more time required for plants to establish roots at the 28−cm depth and extract water (treatments 3 and 4). If the probes had been placed at equal depths (e.g. 18 cm) on both treatments, then treatment 4 would have resulted in long irrigation events if the same thresholds were used for both treatments because soil water would not move 15 cm from the drip tube up to the soil moisture sensor.

Figure 4 presents soil moisture data measured down to 100 cm on two dates during the sweet corn growing season. Treatment 2 clearly had a high soil moisture content at the 40−cm depth and the sprinkler treatment had an elevated soil moisture content in the top 30 cm of the profile. Other SDI treatments showed elevated moisture levels at depth when compared to sprinkler irrigation; however, treatment 2 showed the highest moisture levels in the 40−cm depth due to frequent cycling of the system.

Table 1 shows the seasonal average soil moisture content on each SDI treatment averaged across two replicates at each depth. In 2002, treatment 4 had the highest average shallow (measured 5 cm above drip tube) soil moisture content at 0.091 m^3/m^3, while treatments 1−3 ranged from 0.082 to 0.086 m^3/m^3 at the shallow depth. Conversely, treatment 4 had the lowest soil moisture content 60 cm deep followed by treatments 1, 2, and 3 in order of increasing soil moisture. Treatment 2 had the lowest average soil moisture above the drip tube, the second highest 60 cm deep soil moisture content, and the highest yields among SDI treatments (see below). The coefficient of variation (CV) of soil moisture content on treatment 2 was the lowest, indicating a more stable soil moisture content 5 cm above the drip tube compared to the other SDI treatments (table 1) which may have been conducive to higher yields. The relatively large soil moisture irrigation range (7% to 11%) may have resulted in deep percolation. In all treatments, the relatively high average soil moisture content at 60 cm was higher than the 5% to 7.5% tabulated field capacity (table 1; Carlisle et al., 1978). In addition, it can be seen in figure 3A that leaching likely occurred on the 23−cm sensor−based treatment as evidenced by the sharp drop in soil moisture after each irrigation event. Again in 2003, only small average differences in soil moisture content were measured, but treatment 2 had a CV less than half that compared to the time−based treatments (table 1). This result indicates that the 23−cm deep soil moisture−based treatment with the 10% to 12% irrigation range had a relatively constant soil moisture content within root zone throughout the season despite increased evaporative demands. The average soil moisture content over the season is not an acceptable measure of performance for this system, particularly since the shallow probes are at different depths due to placement of the drip tape.

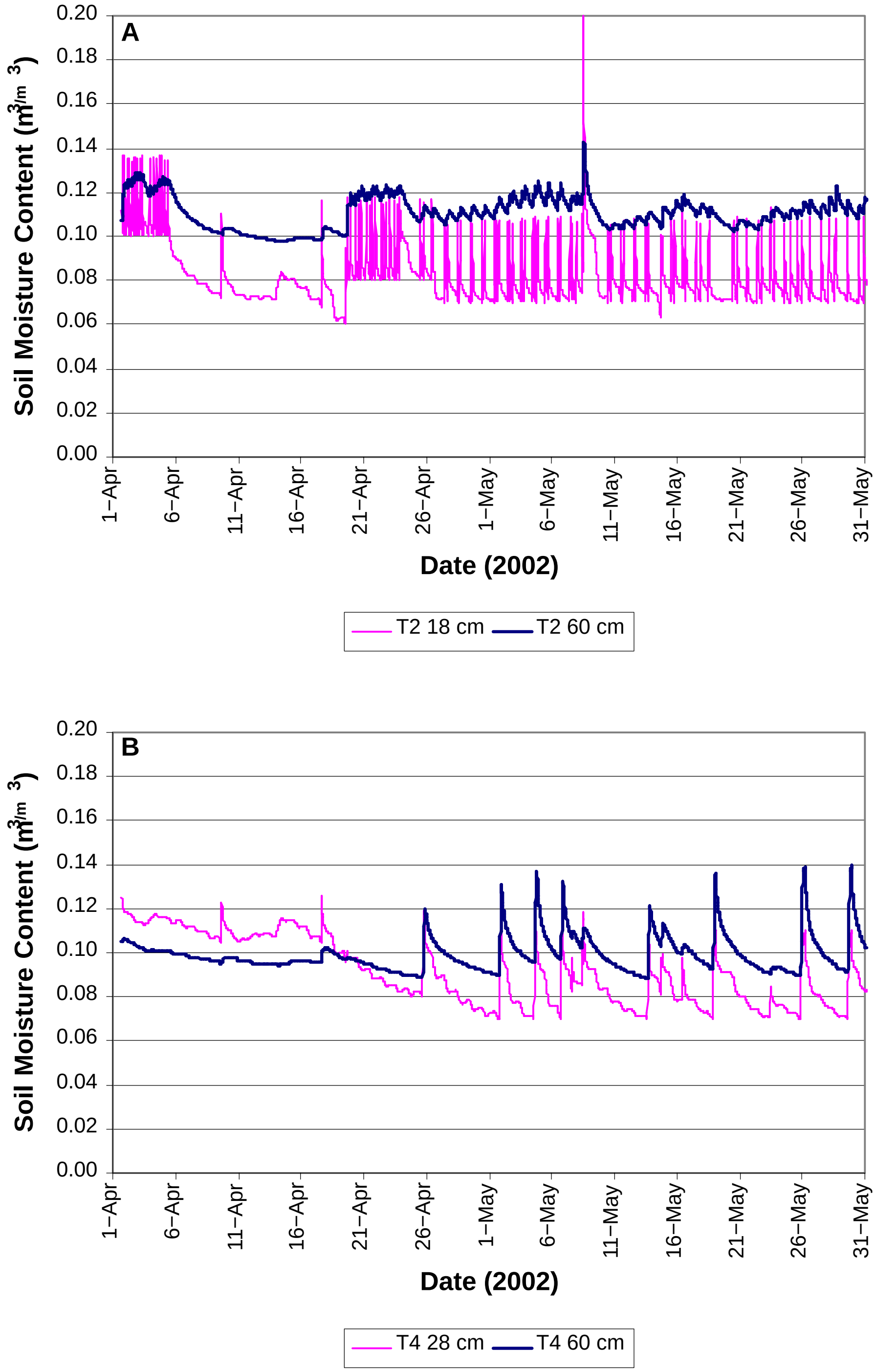
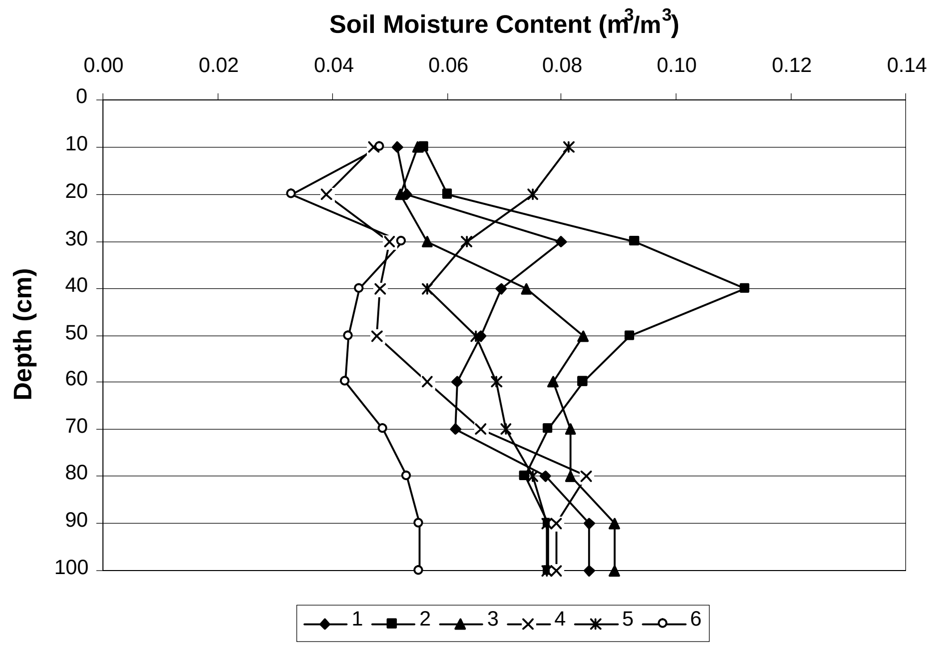


Figure 3. Volumetric soil moisture content for automatic soil moisture initiated irrigation treatments 2 (A; 23−cm deep drip tube) and 4 (B; 33−cm deep drip tube) on sweet corn in 2002.

In contrast to 2002, the 2003 sweet corn season commenced at the end of a moderately wet winter and optimal soil moisture conditions (fig. 2). However, six sprinkler irrigation events were applied through mid April to incorporate fertilizer. Irrigation limits were set at 10% and 12% (on and off) for the entire season on treatments 2 and 4 since the 7% to 11% setting of the previous season resulted in wide fluctuations in soil moisture. A total of 131 mm of rainfall occurred at the beginning of the season (5 to 30 March) such that irrigation on treatment 2 did not occur until 5 April (fig. 5A). When irrigation on treatment 2 began early in the season, events were initiated two to three times per day and transitioned to 6−12 events/day at the end of the season when crop water requirements were greatest. During this time period, maximum ETc is 5 mm/day and assuming a 30−cm root zone with a field capacity of 7% and an allowable depletion of 50%, 10 mm may be withdrawn from the root zone before irrigation is required. This calculation would result in a theoretical irrigation schedule of every other day, which occurred on the sprinkler plots at the peak water use period in the last third of the season. Irrigation first occurred for treatment 4 on 11 April (fig. 5B) and was delayed



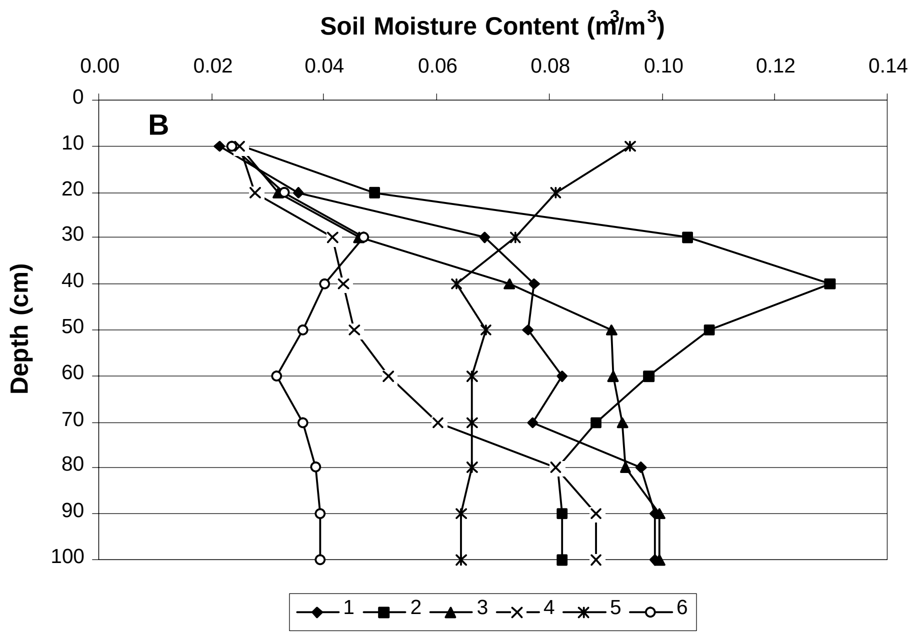


Figure 4. Volumetric soil moisture content across treatments throughout the soil profile as measured on A) 26 April 2002 and B) 28 May 2002. Treatments are: 1) 23−cm deep SDI farmer practice, 2) 23−cm deep SDI soil moisture based, 3) 33−cm deep SDI farmer practice, 4) 33−cm deep SDI sensor based, 5) sprinkler, 6) non−irrigated control.

compared to treatment 2 due to increased time required for corn roots to grow and extract moisture at the 33−cm soil depth similar to the previous year. This caused stress in the crop that impacted seasonal yield as discussed later.

Once the early season rainfall ended in 2003, soil moisture just above the drip tube for treatments 2 and 4 was kept between the irrigation limits of 10% to 12%. Over−irrigation began to occur in the last week of the season on treatment 2 after 12 May as can be seen by the rapidly increasing soil moisture content at the 60−cm depth (fig. 5A). The over−irrigation was caused by one shallow soil moisture sensor reading low soil moisture values. When the two replicates with soil moisture sensors were averaged, soil moisture was less than the 10% threshold for irrigation. The cause of this problem is unknown and this particular plot did not show stress as a result of water depravation. There were no leaks discovered nor sensor wires severed and the problem stopped on 18 May just before the end of the season. Since most of this water was leached below the root zone (see fig. 3 for an example showing drainage to approximate field capacity of 7% within 24 h on T2 18 cm, 11 April), the total water applied was adjusted by averaging the previous seven days of irrigation volume and using that volume for the final week of irrigation. Prior to adjustment, treatment 2 used

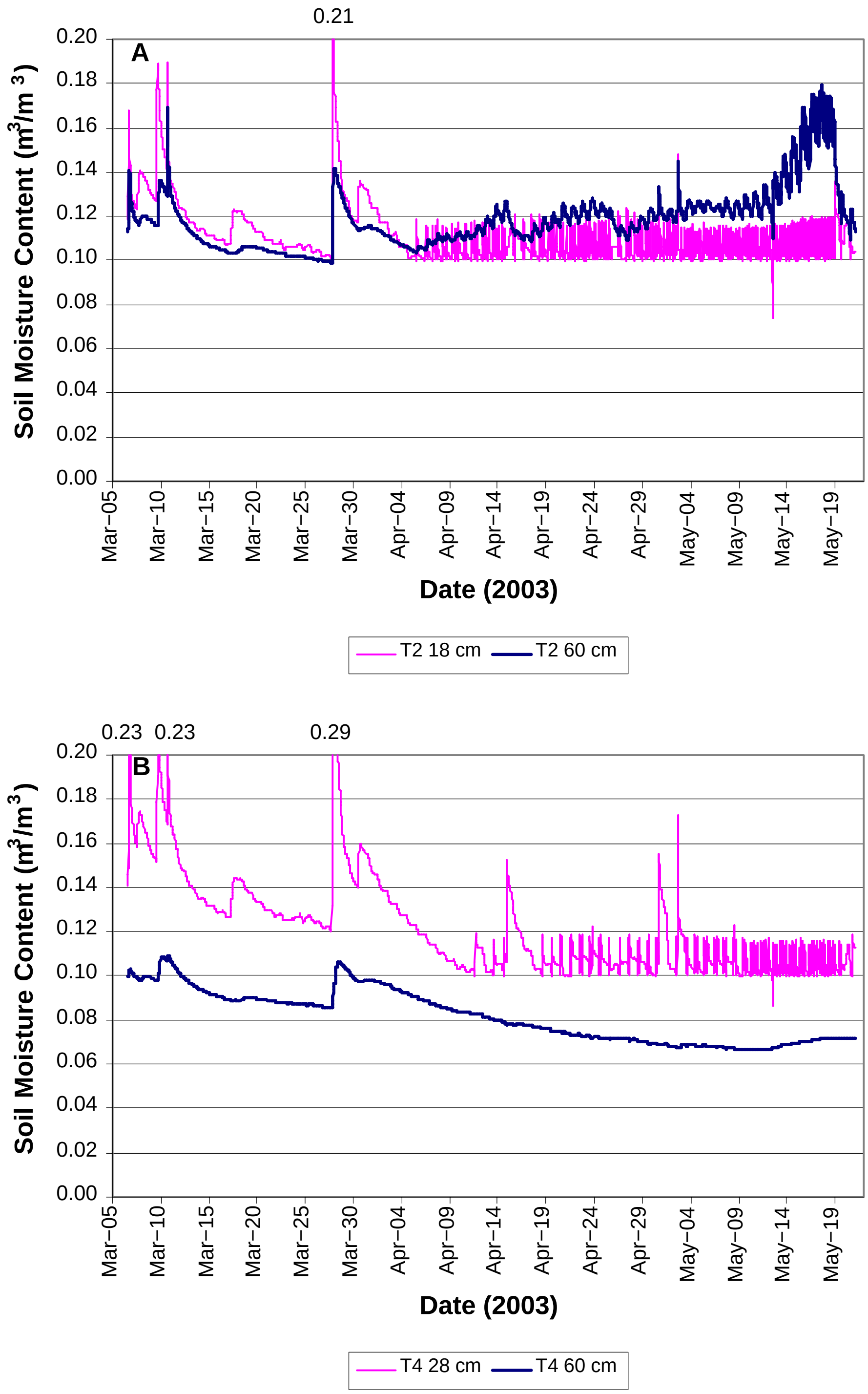


Figure 5. Volumetric soil moisture content for automatic soil moisture initiated irrigation treatments 2 (A; 23−cm deep drip tube) and 4 (B; 33−cm deep drip tube) on sweet corn in 2003.

432 mm of irrigation water over the season (1.2 mm/event) and after adjustment, 374 mm of irrigation water (1.0 mm/event; table 2). Since the soil moisture content stayed elevated at the 60−m depth on treatment 2 after high frequency events started, over−irrigation occurred with the limits set to irrigate 10% to 12%. Treatment 2 resulted in 361 total irrigation events over the season. There were 311 irrigation events prior to the equipment problem that began on 12 May.

The main effect of drip tube depth (P = 0.0054) and the interaction between drip tube depth and scheduling method (P < 0.001) on marketable yield were significant in 2002. Interaction between drip tube depth and scheduling method for IWUE was also significant (P = 0.0051). The highest marketable yield in 2002 was found on the 23−cm deep soil moisture−based SDI treatment (15,130 kg/ha), which was statistically similar to sprinkler (12,905 kg/ha) and 33−cm deep time−based SDI (13,793 kg/ha; table 2). These yields were slightly lower than the state average of 16,400 kg/ha (NASS, 2003). These low yields were a result of difficulties encountered in the first year growing a crop on land that had previously been pasture. As such, weed pressure during the

Table 2. Irrigation depth, calculated ETc, number of seasonal irrigation events, marketable yield, and irrigation water use efficiency across treatments for sweet corn.

Treatment	2002 Seasonal Irrigation Depth[a] (mm)	2002 ETc (mm)	2002 Irrigation Events[b] (#)	2002 Marketable Yield[c] (kg/ha)	2002 Irrigation Water Use Efficiency[c] (kg/m^3)	2003 Seasonal Irrigation Depth (mm)	2003 ETc (mm)	2003 Irrigation Events (#)	2003 Marketable Yield (kg/ha)	2003 Irrigation Water Use Efficiency (kg/m^3)
1	373	262	58	11,438 b	3.07 a	289	258	51	11,165 b	3.86 b
2	467	262	99	15,130 a	3.24 a	432 (374)[d]	258	361	19,425 a	5.19 a
3	378	262	58	13,793 ab	3.65 a	279	258	51	13,440 b	4.82 ab
4	310	262	7	6,535 c	2.11 b	174	258	110	6,643 c	3.82 b
5	445	262	24	12,905 ab	2.90 a	488	258	22	20,490 a	4.20 ab
6	51	−−[e]	5	0	0	82	−−	6	0	0

[a] Control plot sprinkler irrigation applied to all plots for fertilizer incorporation.
[b] Number of irrigation events include only drip events on SDI treatments (1−4). Irrigation events indicated on treatment 6 used to incorporate fertilizer on all plots.
[c] Different letters indicate different means significant at the 95% confidence level.
[d] Irrigation depth adjusted by assuming that irrigation depth in excess of field capacity did not substantially contribute to crop water use and drained below the root zone due to an equipment problem.
[e] Non−irrigated plots were not well−watered and thus did not use the calculated ETc.

beginning of the growing season may have affected the experiment. In any case, the weed pressure was distributed relatively uniformly throughout the entire experiment. The lowest yield was from the 33−cm deep sensor−based SDI treatment with 6,535 kg/ha, which was a direct reflection of only having seven irrigation events the entire season. Placing the soil moisture sensor shallower would have resulted in more irrigation events for this treatment, but due to the coarse soil texture over−irrigation would have occurred. The lowest water use efficiency was on treatment 4 at 2.11 kg/m^3, while treatment 2 resulted in a water use efficiency of 3.24 kg/m^3, which was statistically similar to all treatments except for treatment 4 (table 2).

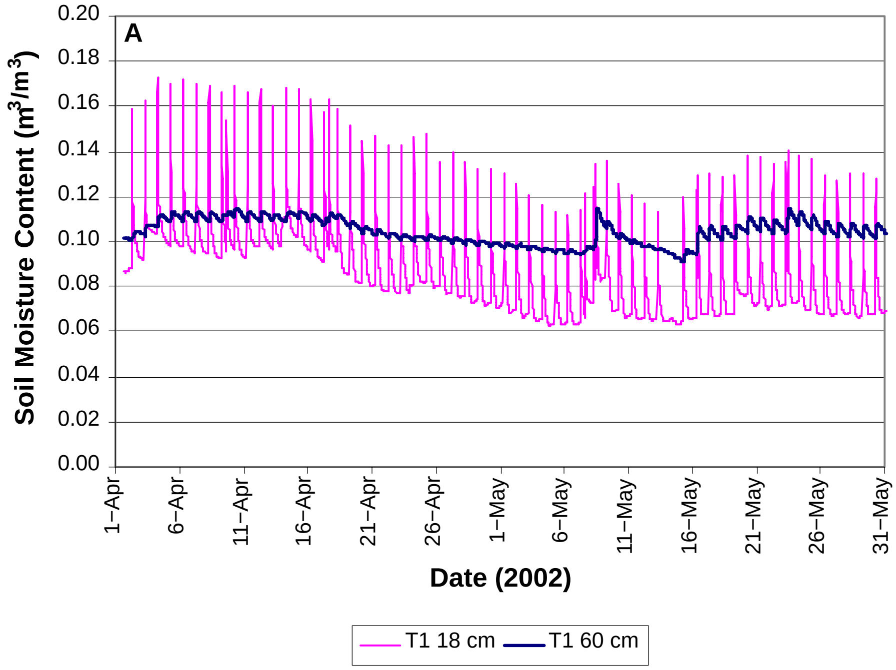
Interaction between drip depth and scheduling method in 2003 ($P < 0.001$) and the main effect of SDI depth ($P = 0.002$) were significant, similar to the previous year. Sprinkler irrigation (treatment 5) used the most irrigation water (488 mm) in 2003, but also had the highest marketable yield of 20,490 kg/ha. Treatment 2 (23−cm deep SDI) yield was not statistically different (19,425 kg/ha) and used 11% less irrigation water (23% after adjustment described previously). Although less irrigation water was used on treatment 2 compared to treatment 5, over−irrigation occurred as can be seen by the soil moisture content above the drip tube ranging from 10% to 12% (fig. 5A) and the soil moisture content at 60 cm averaging 0.118 m^3/m^3 (table 1). These measured soil moisture contents are in excess of tabulated field capacity values for this soil type as described previously. This method might be improved by setting the irrigation limits closer to, but slightly higher than, field capacity such as 8% to 10%. Although over−irrigation did occur, it was localized to an area directly under the rows where the drip tube was located. Since the furrow area was not irrigated compared to sprinkler irrigation, water savings was possible in that region; however, leaching under the row was probably more pronounced than in sprinkler irrigation. It is important to note that farmers in the region typically use approximately 500 mm of sprinkler irrigation on sweet corn when rainfall is minimal as was the case during both years of this study. Treatment 4 resulted in the lowest marketable yield and the non−irrigated control resulted in no measurable yield (table 2). Treatment 4 resulted in 110 irrigation events (0.8 mm/event) over the season but suffered from water stress early in the season due to irrigation control based on measurements at the 28−cm depth, which delayed irrigation.

Sweet corn consumptive use for 2003 was calculated to be 258 mm (table 2). This consumptive use would yield 174 mm of drainage in 2003 under treatment 2 (116 mm for adjusted data) and 230 mm of drainage for treatment 5. This simple soil moisture balance indicates that drainage was potentially reduced 24% on treatment 2 compared to treatment 5 (50% for adjusted data). In addition, less movement of agricultural chemicals below the root zone would be expected in the case where granular fertilizer was applied, such as this experiment. However, if fertigation were used with SDI (as would likely be the type of system adopted by producers), leaching of soluble chemicals could be increased compared to sprinkler since large amounts of irrigation are required at the beginning of the season to promote water movement up toward developing plant roots.

Time-Based Subsurface Drip Irrigation

Initially in 2002, irrigation limits were set at 60 min/day (4.6 mm/day) for treatments 1 and 3. Figure 6 presents the average of the TDR measured volumetric soil moisture content across two replicates for treatments 1 and 3. Since over irrigation was occurring on these treatments early in the season, after 5 April, time−based treatments (1 and 3) were set to irrigate 45 min each day (3.4 mm/day) until 14 May, when the rate was increased to 90 min/day (6.9 mm/day). A total of 58 irrigation events (average of 5.6 mm/event) occurred in treatments 1 and 3, whereas a total of 99 events occurred in treatment 2 (average of 4.2 mm/event) and 7 events occurred on treatment 4 (average of 56 mm/event). This number of irrigation events does not include sprinkler irrigation applied to all plots for establishment or fertilizer incorporation (table 2).

Time−based irrigation treatments were set at 30 min/day on treatments 1 and 3 in 2003 and increased to 60 min/day on 23 April. A total of 51 irrigation events (average of 4.0 mm/event) occurred over the season for each treatment. Soil moisture content on treatments 1 and 3 stayed very high initially as a combination of rainfall and irrigation everyday (fig. 7). Although daily soil moisture fluctuated for treatments 1 and 3 due to single irrigation events each day, average soil moisture 5 cm above the drip tube steadily decreased over the entire season (fig. 7). This decrease was likely because the application amount of 4.6 mm/day at the end of the season could not meet crop needs adequately despite the fact that maximum ETc is approximately



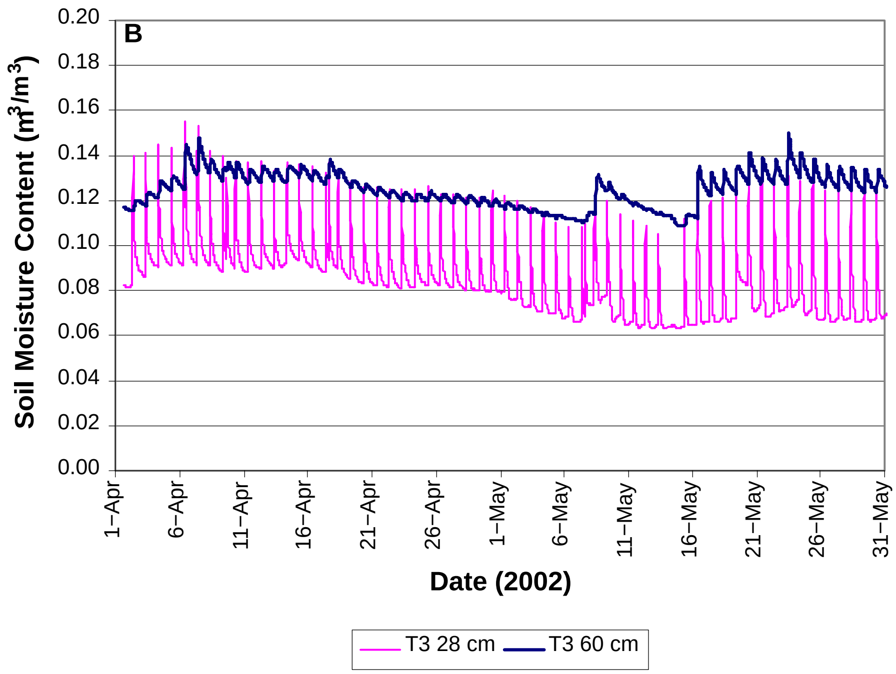
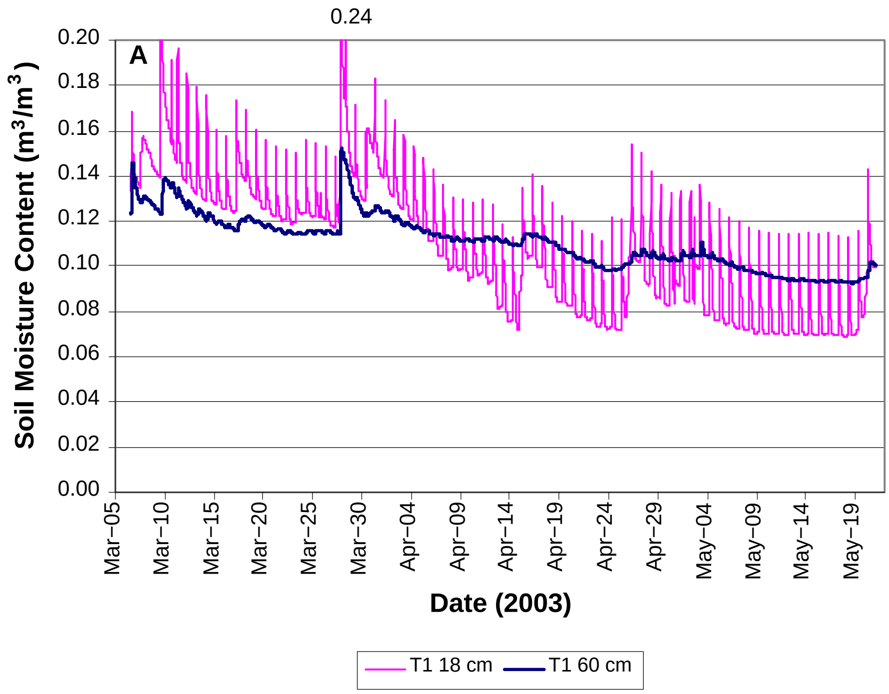


Figure 6. Volumetric soil moisture content for daily time−based irrigation treatments 1 (A; 23−cm deep drip tube) and 3 (B; 33−cm deep drip tube) on sweet corn in 2002.

5 mm/day. This occurence was probably because the irrigation water moves downward rapidly as seen in the quickly decreasing soil moisture content after single time based irrigation events (figs. 6 and 7). The application time should have been increased to 90 min/day in the last third of the season similar to 2002 to help compensate for this problem.

Yields in 2002 for both time−based treatments were statistically similar to each other and yield from treatment 5, but above those from treatment 4. Although there were three yield groupings, irrigation water use efficiency showed less variability across treatments. Treatments 1, 2, 3, and 5 had statistically similar water use efficiencies ranging from 3.50 to 4.13 kg/m^3. These similar water use efficiency values indicate that although some treatments did have higher yields than others, this increase in yield was associated with increased water use. In 2003, Treatments 1 and 3 resulted in marketable yields lower than treatments 2 and 5. Yields for treatment 1 and 3 might have been increased by increasing the irrigation volume since 279 to 289 mm of irrigation water was applied on those treatments compared to 374 mm applied on treatment 2 and 488 mm applied on treatment 5. Yields for



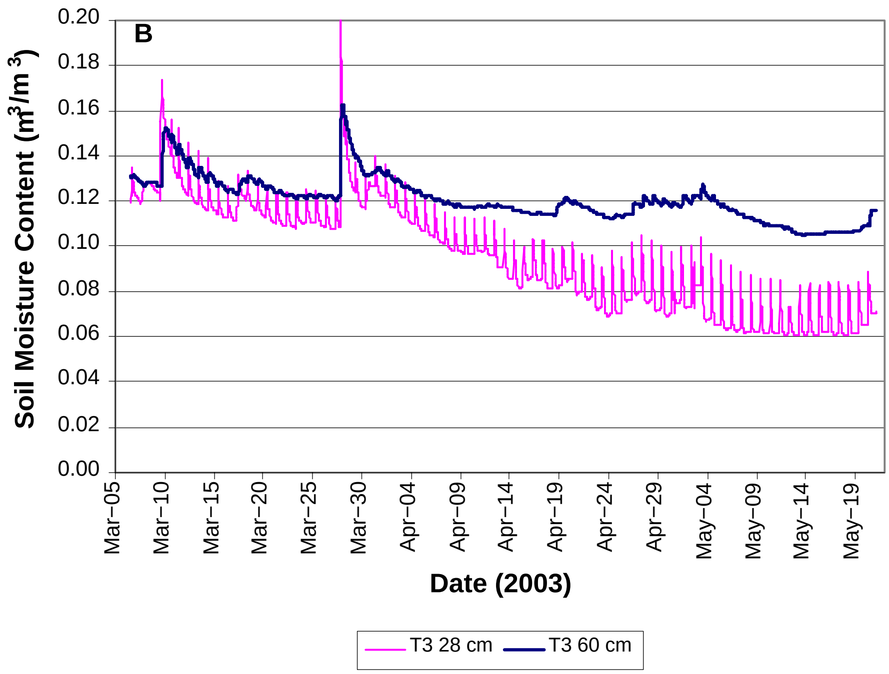


Figure 7. Volumetric soil moisture content for daily time−based irrigation treatments 1 (A; 23−cm deep drip tube) and 3 (B; 33−cm deep drip tube) on sweet corn in 2003.

treatments 2 and 5 exceeded 2003 state average yields of 16,100 kg/ha (NASS, 2003), while all other treatments resulted in lower than average state yields.

Similar to the previous year, 2003 water use efficiency fell into three groupings with treatments 2, 3, and 5 having the highest water use efficiency (4.20−5.19 kg/m^3; table 2). Since water use efficiency was relatively high on treatments 1 and 3, it is likely that these treatments could be improved by irrigating more each day; however, there is evidence that the use of single daily irrigation applications results in over−irrigation on sandy soils (Dukes et al., 2003). In this work, it can be seen that even though the soil moisture sensor−based treatments resulted in over−irrigation, the time based treatments probably resulted in greater over−irrigation as evidenced by the high spikes in soil moisture content during an irrigation event and the rapid drainage afterward (figs. 6 and 7). Multiple irrigation events could possibly be scheduled each day to minimize large soil moisture fluctuations and leaching of water through the root zone.

Over the first season of this experiment, irrigation water use ranged from a low of 310 mm on treatment 4 to a high of 467 mm on treatment 2 compared to ETc of 262 mm. These relatively high values indicate that there are considerable losses by irrigating the furrows where the crop may extract less water and due to surface evaporation from sprinkler irrigation. However, there were considerable losses in the SDI treatments due to soil moisture thresholds being set above field capacity, resulting in leaching of water below the root zone in those treatments and also due to single daily irrigation events that resulted in drainage due to large changes in the soil moisture content above field capacity. In the second season, less water was applied on the time−based treatments (289 and 279 mm on treatments 1 and 3, respectively) compared to a similar ETc of 258 to the first season. The yield results on these treatments were poor due to increased stress from only getting irrigation once each day and suffering stress early in the season before roots could become established at the drip tube depth. This result supports the theory that soil moisture settings should be set slightly above field capacity early in the season on SDI to promote vertical movement of water.

SUMMARY AND CONCLUSIONS

An experiment to investigate the use of SDI on sandy Florida soils was conducted. Subsurface drip irrigation treatments consisted of tubing buried at 23 and 33 cm below the soil surface. Also, each SDI depth treatment consisted of two scheduling treatments. The first method was time−based irrigation consisting of a fixed amount of time each day with time increasing according to crop growth stage. The other scheduling treatment consisted of automatic irrigation within a specified low and high soil moisture range based on measurements from buried TDR probes.

Similar sweet corn yields were measured between 23−cm deep sensor−based SDI and sprinkler irrigation, indicating that SDI at the 23−cm depth is a feasible alternative to sprinkler irrigation in sandy soils. In the first year, similar amounts of irrigation water were applied to the 23−cm deep sensor−based SDI treatment and the sprinkler irrigation treatment. In the second year approximately 11% less irrigation water was used (23% when corrected for excessive irrigation due to equipment problems) in the automatic sensor−based 23−cm deep SDI treatment compared to the sprinkler treatment. This savings was due to the narrow (10−12%) irrigation window used. This narrow window resulted in high frequency irrigation of 6 to 12 events per day with a total depth of 8 mm/day by the end of season. One advantage of soil moisture based SDI in that it can produce similar yields with less water. Yields may have been better on timed treatments in 2003 if the irrigation times have had been adjusted near the end of the season. This occurence underscores the convenience advantage of the soil moisture based system. Once the system thresholds are set, the sensor will initiate irrigation the required number of times each day to maintain soil moisture between the thresholds. If rainfall had occurred during the crop season, irrigation would have automatically been delayed until the crop removed moisture from the root zone such that irrigation would be initiated.

Drainage below the root zone may be reduced between the soil moisture−based SDI treatments compared to sprinkler. This is largely due to the SDI system not wetting the entire field area but just under the rows. Water use and drainage under SDI could probably be reduced further by setting irrigation thresholds 8% to 10% in this soil. Subsurface drip tubing buried at 33 cm resulted in poor yield under both scheduling regimes, with the worst performance being the soil moisture−based treatment. This yield reduction was due to the prolonged period of stress until plant roots could extract water at 33 cm. Time−based irrigation treatments on corn resulted in large soil moisture fluctuations. In future work, daily irrigation events should be split into several events during peak corn growth periods.

Two crop seasons of data collection resulted in two major system problems. One was damage of the drip tube due to an animal and the other was an equipment malfunction causing over−irrigation for approximately 6 days. Other challenges include planting rows above the drip tube and using tillage at a depth that does not damage drip tube at 23 cm. Perhaps the largest barrier to implementation of soil moisture−based SDI is the requirement of an on−demand continually pressurized water source. Electrical service is required, and in rural areas it may be prohibitively expensive to install electrical service.

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