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AGRONOMY AND SOILS

Management of Cotton Grown Under Overhead Sprinkle and Sub-surface Drip Irrigation

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ABSTRACT

Irrigation improves the consistency of cotton (*Gossypium hirsutum* L.) yield during seasons with inadequate or poor rainfall distribution, but comparisons of irrigation methods, including overhead sprinkle (OSI) and sub-surface drip (SSD), are limited. Irrigation may affect the response of cotton to mepiquat chloride and the response of glyphosate resistant cotton to glyphosate. The objectives of this study were to compare the response of cotton with OSI and SSD irrigation and to determine if any responses to glyphosate and mepiquat chloride were different between irrigation systems. Field trials were conducted from 2001 through 2003 at the Peanut Belt Research Station in North Carolina to evaluate eight treatment combinations of glyphosate application method, mepiquat chloride application, and irrigation method. Glyphosate isopropylamine salt at 0.84 kg acid equivalent (a.e.) ha^{-1} was applied over-the-top at the four-leaf stage or non-precision post-directed at the eight-leaf stage. Mepiquat chloride was applied according to North Carolina Extension Service recommendations. Lint yield, which averaged 1400 and 1470 kg ha^{-1} under OSI and SSD, respectively, was not affected by mepiquat chloride application. Non-precision post-directed glyphosate reduced lint yield by 160 kg ha^{-1} in 2002, but did not affect yield in 2001 or 2003. Compared with untreated cotton, cotton treated with mepiquat chloride was 31 cm shorter with 2 fewer nodes in 2001 and 2003, and averaged 0.6 fewer first position bolls and 0.2 mm longer fiber. The two irrigation systems produced similar yields, and non-precision glyphosate applications reduced yield. In this study, irrigated cotton did not exhibit sufficient vegetative growth to benefit from the recommended applications of mepiquat chloride.

Successful cotton production and profitability are achieved through best management practices that maximize yield while maintaining acceptable lint quality. Yields and profitability of non-irrigated systems are closely related to natural precipitation, which is unpredictable (Quisenberry and Roark, 1976). Because of the rising cost of agricultural inputs, growers are considering options, including installing irrigation systems, to improve yield stability for their cropping systems. Irrigation systems consistently give positive cotton yield results in arid regions and help to maintain yield stability in traditionally non-irrigated systems, such as in the eastern United States (Dloomy, 2000; Droogers et al., 2000). Research is needed to evaluate the options for irrigation systems and how they may affect current production practices in these regions. Although irrigation does not guarantee superior yields to non-irrigated systems, it may provide yield sustainability over time and reduce long-term risks. The 2002 Census of Agriculture reported that 37.4% of Upland cotton grown in the United States was irrigated, which is considerably more than the 2.6% of cotton that is irrigated in North Carolina (USDA-NASS, 2002).

Maintaining adequate soil moisture to avoid water deficit is not an option for growers without irrigation. As a perennial plant, cotton produces fruit over a long period of time, so the crop is able to compensate for brief periods of early season stress when the remainder of the growing season is

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favorable (Jones and Snipes, 1999). After drought is incurred and metabolism is interrupted (Boyer, 1971) the maximum potential of the crop is no longer attainable (Grimes and Yamada, 1982; Hanks, 1992). If irrigation is adopted in these regions, investigation into glyphosate resistant cotton management must be studied. Current methods for mepiquat chloride application must also be examined to determine if they are effective in managing irrigated cotton in the eastern United States.

The precision and efficiency at which various irrigation systems supply water will influence the capital required for installation. In a study comparing economics between irrigation systems, SSD systems were more economical than OSI systems in fields smaller than 26 ha (O'Brien et al., 1998). This economic advantage is further evident when considering the option to design a SSD system to effectively cover an irregularly shaped field that would not be totally covered with an OSI system (Bosch et al., 1992). As emphasized by Bosch et al. (1992) and O'Brien et al. (1998), SSD systems have a near-static cost per hectare compared with OSI systems, where cost decreases linearly as the size of the system increases. Overhead sprinkler irrigation systems are the most common, because they are easy to assemble, durable, and do not require elaborate filtering systems because of the large orifice through which they deliver water. Once water is emitted in an OSI system, its fate may be affected by wind, and water losses to evaporation can occur before it reaches the soil surface and becomes available for crop use. Also, applying water directly to the leaves and fruit of a crop, such as with OSI, increases the possibility of fungal and bacterial diseases and may adversely affect pollination (Guinn, 1998).

On the other hand, water delivered through a SSD system is placed directly in the rhizosphere of the crop at a slow rate, so the soil surface has less chance to become wet and less soil water is lost through evaporation. With SSD, weeds in the middle of rows also have less chance to germinate before crop canopy closure is reached during periods of infrequent precipitation. Once a SSD system is in place, tillage practices must be altered to protect drip tubing. The SSD systems deliver water through very small emitters, which can be plugged by sand particles, algae, or other debris, if the water supply is not properly filtered. Since each emitter serves several plants and movement of water in soil is restricted, reduced or lost flow by one emitter cannot be compensated for by the system. These problems often go unnoticed and are not repaired until the crop plants over the plugged emitter have suffered severe water deficit to the point of wilting (Kramer, 1983). The OSI systems need to be moved several times per season to facilitate planting, cultivation, spraying, and harvest, while SSD systems are usually left undisturbed for several years. Soil type affects the performance and movement of water delivered by both OSI and SSD systems. Soils with slow infiltration characteristics may cause puddling and runoff from water delivered through OSI, while sandy soils have poor water retention and distribution properties, requiring more frequent irrigation from SSD.

Because cotton is perennial, it may revert to vegetative growth at any time during the life cycle, which requires a constant supply of resources. Providing sufficient resources, such as fertilizer and water, improves yield potential, but these inputs may contribute to excessive vegetative growth, causing reduced efficiency in the utilization of plant resources for producing fiber. Abundant moisture and nutrients, as well as fruit abortion, may trigger excessive vegetative growth, requiring plant growth regulators. Plant growth regulators improve the potential to enhance plant resource allocation (Guthrie, 1986). The most commonly used plant growth regulator in cotton is mepiquat chloride. Plant growth regulators like mepiquat chloride can inhibit shoot growth without affecting leaf production and development and suppress excessive vegetative growth (Dicks, 1980; Han, 1991). Cotton plants are capable of supporting a large fruit load depending on the availability of carbohydrates and other resources (Eaton, 1955), which suggests that it would be more efficient to invest photoassimilates in fruit production instead of using them for excessive vegetative growth. In ^{14}C studies conducted to quantify distribution of photosynthate resources, bolls immediately adjacent to the main stem received proportionately higher ^{14}C concentration from ^{14}C-labeled CO_2 than bolls on distal positions of the same sympodial node (Ashley, 1972; Wullschleger and Oosterhuis, 1990). This is due to the morphological order in which cotton initiates flowering from the bottom to the top of the plant and out to successive positions on the sympodial nodes. The first position bolls are a stronger sink for photoassimilate accumulation than those at more proximal positions on any given main stem position (Kerby and Ruppenicker, 1992). Mepiquat chloride is routinely used to control plant height and promote earliness, and shifts in biomass partitioning from vegetative to reproductive tissue have been documented, but consistent yield improvements have been rare (Boman et al., 1998; Chaney, 1998). Positive yield results with plant growth regulators are generally variable, which is most likely caused by unpredictable environmental conditions (Lege et al., 1996). Mepiquat chloride increases leaf density and chlorophyll content per unit leaf area, which potentially increases the photosynthetic capacity of cotton leaves (Fernandez et al., 1991; Gausman et al., 1980). Wells (1997) and Oosterhuis et al. (1998) found that mepiquat chloride improved leaf photosynthesis and dry matter partitioning from vegetative to reproductive tissue in cotton, but no differences in canopy photosynthesis were found with mepiquat chloride treatments when compared with non-treated cotton (Wells and Edmisten, 1998).

Roundup Ready cotton was commercially released in 1997 (Faircloth et al., 2001; Ellis and Griffin, 2002). This technology has been overwhelmingly accepted by producers with more than two-thirds of the U. S. cotton crop in 2003 being glyphosate resistant (Ihrig et al., 2003). Over 95% of the North Carolina cotton crop in 2003 was glyphosate resistant (USDA-AMS, 2003). Glyphosate is a member of the glycine herbicide family and non-selectively controls a broad spectrum of economically significant grass and broadleaf weed pests (Wilcut et al., 1996). Weed management in glyphosate resistant cotton requires less herbicide and fewer applications to produce the same yield and net economic return as conventional systems (Culpepper and York, 1998).

Subsequent to its introduction, glyphosate resistant cotton treated with glyphosate, showed increased boll abscission, fruit malformation, and yield fluctuations compared with conventional cotton cultivars (Jones and Snipes, 1999). Numerous field studies have been conducted, including on- and off-label glyphosate applications to glyphosate resistant cotton, to determine injurious rates and application timings. Many agree that pollination is negatively affected with off-label applications. Poor pollination decreases seed production that causes misshapen bolls and, in severe cases, abortion of affected bolls. Yield damage, however, is only evident when environmental conditions limit resources and do not allow sufficient time for compensation of fruit loss and underdeveloped bolls (Jones and Snipes, 1999; McCloskey and Moser, 2002).

The apparent problem with Roundup Ready cotton technology is that it does not provide adequate tolerance in reproductive tissue to commonly used glyphosate rates. Over-the-top or non-precision post-directed glyphosate applications after the four-leaf stage hinder healthy pollen development and pollen deposition, which may consequently cause yield loss (May et al., 2004; Pline-Srnic et al., 2004). A controlled environment study using ^{14}C-glyphosate exhibited that glyphosate accumulation in cotton fruiting structures was directly correlated to boll abscission (Viator et al., 2003). Further research indicated that intolerance of reproductive tissues to glyphosate was a result of poor expression of the genes producing the alternative non-glyphosate binding enzyme 5-enolpyruvylshikimate-3-phosphate synthase (Pline et al., 2002). These findings reinforced the label restrictions for glyphosate applications to glyphosate resistant cotton (Anonymous, 1999). Crop safety cannot be guaranteed unless directed applications after the four-leaf stage avoid spray contact to cotton leaves (Ihrig et al., 2003). If glyphosate damage occurs, the capability to irrigate and avoid water stress increases the opportunity for yield compensation.

Use of glyphosate in glyphosate resistant cotton is limited to two broadcast applications from emergence through the four-leaf stage. The second broadcast application is allowed after 10 d and at least two nodes of growth have occurred following the first application. Precision post-directed or hooded glyphosate applications are allowed from the five-leaf stage until first bloom, as long as contact with foliage, green stems, and fruit is avoided (Anonymous, 1999). Many post-directed applications are not directed precisely beneath the crop in order to get ample coverage of weed targets. With non-precision post-directed applications of glyphosate, the earliest initiated fruit are likely to be negatively impacted, so new fruit is initiated, and their contribution to yield is dependent on environmental conditions (Jones and Snipes, 1999).

This study addresses the effectiveness of OSI and SSD irrigation within existing cultural practices to produce a consistent quality crop. The primary objective was to determine the differences between cotton crops produced under SSD and OSI systems, and the ability of these systems to supplement natural precipitation in North Carolina. Secondary objectives were to determine if the compensatory ability of cotton to overcome stress from non-precision post-directed applied glyphosate was better in either SSD or OSI systems, and to determine if the current North

Carolina Extension recommendations for mepiquat chloride are applicable in irrigated cotton.

MATERIALS AND METHODS

Field trials were conducted in 2001, 2002, and 2003 at the Peanut Belt Research Station located near Lewiston-Woodville, NC, on a Norfolk sandy loam soil (fine-loamy, siliceous, thermic, Typic Paleudults) with pH 6.1 and 2.3% organic matter. Cotton cultivar Suregrow 501 BR (Delta and Pine Land Co.; Scott, MS) was planted 10, 8, and 9 May in 2001, 2002, and 2003, respectively. The experimental design was a strip-split-plot with a factorial arrangement of three treatments (Gomez and Gomez, 1984) that included two irrigation methods, two glyphosate treatments, and two mepiquat chloride treatments. Irrigation was stripped as the vertical factor, mepiquat chloride application was the horizontal block sub-factor, and the glyphosate applications were randomly assigned to sub-sub-plots within mepiquat chloride blocks. Individual sub-sub-plots were four, 91-cm rows each 9 m long. Treatments were replicated four times. The two glyphosate treatments were either over-the-top at four-leaf or non-precision post-directed at the eight-leaf cotton growth stages. Non-precision post-directed applications were made so that the lower 15 cm of plants had contact with glyphosate.

Plant growth was monitored and mepiquat chloride (Mepex, Griffin LLC-Dupont; Wilmington, DE) was applied as needed according to the modified early bloom method (Edmisten, 2004a). This method used a combination of plant height and internode length, specifically the largest of either the third or fourth internode from the top of the plant, to trigger mepiquat chloride application. Plants were evaluated for growth characteristics between 10 and 14 d after first square, at early bloom, and 10 to 14 d after first bloom. The rate of mepiquat chloride was dependant on a combination of the current plant height and whether prior mepiquat chloride applications had been made. Applications of glyphosate and mepiquat chloride were made with a compressed CO_2 backpack sprayer calibrated to deliver 140 L ha^{-1}. Treatments receiving mepiquat chloride in 2001 required one application at 24.5 g a.i. ha^{-1} on 28 June. Two applications of mepiquat chloride were required in 2002, each at 24.5 g a.i. ha^{-1} on 24 June and 10 July. In 2003, mepiquat chloride treatments were 18.5, 24.5, and 30.6 g a.i. ha^{-1} on 30 June, 7 July, and 21 July, respectively.

Glyphosate (Roundup UltraMAX, Monsanto Co.; St. Louis, MO) was applied at 0.84 kg a.e. ha^{-1} for both treatments. Over-the-top glyphosate treatments were made to four-leaf cotton on 6, 3, and 16 June in 2001, 2002, and 2003, respective. Non-precision post-directed glyphosate applications were made to eight-leaf cotton on 21, 24, and 30 June in 2001, 2002, and 2003, respectively. Management decisions and cultural inputs, except for mepiquat chloride and glyphosate applications, including planting, fertilizer, weed control, and defoliation, were made to all plots according to North Carolina Extension recommendations (Crozier, 2004; Edmisten, 2004b; Koenning, 2004; Spears, 2004). In 2001 and 2003, 38 kg ha^{-1} N fertilizer was used, and 61 kg ha^{-1} N fertilizer was applied in 2002.

In early April 2001, soil was disked twice and field cultivated to prepare the field for installation of SSD. Drip tubing was installed with a ripper-bedder at a depth of 25 cm in rows spaced 91 cm apart. Cotton was grown in half of the field and was in annual rotation with peanut (*Arachis hypogaea* L.) (Lanier et al., 2004). Beds were established each year in OSI plots with a disk-bedder equipped with in-row ripper shanks (ripping depth of 25 cm). Beds in the SSD blocks of the field were reestablished in 2002 and 2003 using a bedder without ripper shanks. Water was pumped from an irrigation pond to a 22,710 L reservoir tank, which supplied water for both irrigation systems. Water from the reservoir tank was supplied with a centrifugal pump (Challenger Water Pump, Model 35-5460, Pentair Pool Products; St. Paul, MN) through a sand filter system (Flow Guard Sand Filter System, Model 215S, Flow Guard Filtration Products; Selma, CA) and through a disk filtration system [ARKAL Disk Filter (140 mesh by 100 micron), Netafim; Tel Aviv, Israel] to remove fine particulates. Filtered water flowed through the main manifold to drip lines that were laid in their respective blocks. Control of water application was by an electric water control console valve and electronic solenoid (Orbit Electric Water Control, Model 57540, Orbit Irrigation Products Inc.; Bountiful, UT). Flow meters (ABA Flow Meters, Model 98604940, Senniger Irrigation, Inc.; Orlando, FL) were used to measure flow rates and record water application in SSD. Pressure regulators followed the flow meters to reduce pressure to 69 kPa. Drip tubing used for SSD was model TSX2 510-12-450 T-Tape (T-Systems Inc.; Queensland, Australia) and was 25 mm in diameter with emitters spaced at 30 cm. The SSD system was designed to deliver 102 L min^{-1}.

The OSI irrigation system consisted of six irrigation heads spaced 6.1 m apart (OSI System 20H, Nelson Irrigation Sprinkler Heads; Walla Walla, WA) established on a single irrigation line placed down the middle of each OSI plot. Water use in OSI was recorded with Taylor model 2715 (Taylor USA; Oak Brook, Illinois) rain gauges. A series of 10 rain gauges were spaced equally through the radius of the area covered by the sprinkler nozzle on either side of OSI pipe. Frequency and amount of irrigation was based on recommendations from the Irrigator Pro model for peanut (Davidson et al., 1998). This decision based software program used temperature data from thermocouple probes established 5 cm below the soil surface and daily meteorological data to prompt irrigation. Overhead sprinkle irrigation was supplied as sequential applications of 18 mm to satisfy irrigation requirements. Irrigation was done during the morning hours to avoid wind and optimize water distribution. A total of 128, 144, and 138 mm water was provided by OSI in 2001, 2002, and 2003, respectively (Table 1). In 2001, 2002, and 2003, 164, 139, and 143 mm water was applied, respectively, through SSD during the season between 2 July and 20 September. Water was applied each day with SSD from Monday through Friday at a rate of approximately 5 mm d^{-1} as needed to satisfy recommendations by Irrigator Pro. Irrigation was reinitiated 4 d after rainfall in excess of 18 mm and was continued when rainfall events were less than 18 mm. This study does not include non-irrigated comparisons, because the size and shape of the field where the irrigation equipment was established could not support another treatment factor. As a reference to the effect that irrigation had on yield at this site, non-irrigated cotton of the same cultivar, planting date, and management practices grown adjacent to this study for each year are discussed in the results. The non-irrigated cotton used for comparisons was not treated with mepiquat chloride or glyphosate.

Table 1. Annual overhead sprinkler (OSI), sub-surface drip (SSD) irrigation and rainfall totals during the irrigation period

Year^z	Rainfall (mm)	OSI (mm)	OSI + Rainfall (mm)	SSD (mm)	SSD + Rainfall (mm)
2001	220	128	348	164	384
2002	330	144	474	139	469
2003	477	138	615	143	620

^{z} The irrigation period was 2 July to 20 September each year.

Six plants per plot were mapped prior to harvest on 12, 27, and 15 September in 2001, 2002, and 2003, respectively. Data were recorded for harvestable bolls, missing boll positions on sympodial branches, and harvestable bolls retained on monopodial branches (Mauney, 1986). Mapping data were analyzed to determine total bolls per plant, monopodial bolls per plant, boll distribution by sympodial position, and percentage boll retention. The middle two rows of each plot were machine harvested, and seedcotton sub-samples were collected from each plot for high volume instrument analysis. Due to differences in plant maturity between irrigation systems, harvest of SSD plots in 2001 was 5 October and OSI plots were harvested 26 October. In 2002 and 2003, both irrigation methods produced cotton with similar maturity and were harvested 17 and 24 October, respectively. About 25% of plants were lodged as early as the eight-leaf stage in 2001. Plants were considered lodged when the main stem was not perpendicular to the ground surface. Visual rating of the percentage of lodged plants was recorded 9 September 2001.

Data were subjected to analysis of variance using the general linear model procedure in the Statistical Analysis System software (SAS Institute Inc., version 8e, release 8.2; Cary, NC, 2001). In the statistical analyses, years were treated as a random source of replication and all main factors and main factor interactions were tested with their specific error term. Year by main effect interactions were ignored when main effects were strong and did not cross over between years (Gomez and Gomez, 1984). If the year term for a specific main effect was not significant ($P > 0.250$), it was removed from the model and the term was tested with the overall error term. Main effect means were separated using Fisher's Protected LSD test at $P = 0.05$. Main effect means were pooled across years and other main factors when the interaction was not significant between them.

RESULTS AND DISCUSSION

Yield, lint turnout, and fiber quality. Lint yields in 2001, 2002, and 2003 in non-irrigated cotton were 1140, 1010, and 950 kg ha^{-1}, respectively. Non-irrigated cotton yield was approximately 15% lower in 2001 and 46% lower in 2002 compared with OSI. Compared with SSD, non-irrigated yield was 21% lower in 2001 and 49% lower in 2002. Irrigated and non-irrigated cotton yields were similar

Table 2. Probabilities of main effects and main effect interactions for yield, lint turnout, fiber quality, lodged plants, first sympodial branch with a retained boll (FSRB), final plant height, nodes per plant, and height to node ratio (HNR)

Source	*P* value									
	Yield	Lint turnout	Micronaire	Fiber length	Fiber strength	Lodged plants	FSRB	Plant height	Nodes	HNR
Irrigation (Irr)	**0.5441**	**0.1310**	**0.7894**	**0.0102**	**0.4026**	**0.0004**	**0.8329**	**0.0024**	**0.0034**	**0.2039**
Year x Irr	**0.0003**	**0.1014**	**0.1519**	**0.6703**	**0.4251**	**--**	**0.0009**	**0.5127**	**0.9556**	**0.5903**
Mepiquat chloride (MC)	**0.2980**	**0.0580**	**0.9492**	**0.0487**	**0.3987**	**0.0163**	**0.9372**	**0.1093**	**0.1183**	**0.1068**
Year x MC	**0.3018**	**0.9758**	**0.0261**	**0.5051**	**0.3850**	**--**	**0.5112**	**0.0006**	**0.0075**	**0.0277**
Irr x MC	**0.2431**	**0.5431**	**0.8581**	**0.9526**	**0.3364**	**0.1032**	**0.6301**	**0.1663**	**0.0927**	**0.7732**
Glyphosate (Gly)	**0.6781**	**0.1390**	**0.6038**	**0.4735**	**0.0218**	**0.3787**	**0.4603**	**0.8705**	**0.8135**	**0.4854**
Year x Gly	**0.0211**	**0.1561**	**0.4893**	**0.2754**	**0.3871**	**--**	**0.2217**	**0.6933**	**0.1518**	**0.9644**
Gly x MC	**0.4435**	**0.6421**	**0.5554**	**0.7922**	**0.5143**	**0.3787**	**0.2042**	**0.2689**	**0.6909**	**0.1289**
Irr	**0.1153**	**0.4288**	**0.8503**	**0.7400**	**0.2529**	**0.3103**	**0.5094**	**0.4807**	**0.9699**	**0.3873**
Irr X Gly	**0.3436**	**0.3981**	**0.1927**	**0.3715**	**0.8719**	**0.2999**	**0.5630**	**0.5061**	**0.4173**	**0.3985**

in 2003. As mentioned previously, the size of the irrigation systems did not allow a comparison of all treatment combinations in the non-irrigated system, and therefore could not be compared statistically. These data indicate that cotton responded positively to irrigation in 2 of the 3 yr.

Interactions between mepiquat chloride application and other main effects for yield were not significant (Table 2). Year by irrigation method and year by glyphosate treatment interactions were significant and were reported by year. Mepiquat chloride application did not affect yield, and this response was consistent across irrigation and glyphosate factors with yields averaging 1420 to 1450 kg lint ha^{-1}. Boman et al. (1998) reported no differences in yield between cotton treated with mepiquat chloride products and untreated cotton under high yield conditions. A 240 kg ha^{-1} improvement in lint yield from SSD over OSI irrigation was observed in 2001 (Table 3). Cotton yield between irrigation systems was similar in 2002 and 2003. Yield of cotton receiving non-precision post-directed glyphosate at the 8-leaf stage was 160 kg ha^{-1} less in 2002 compared with cotton receiving glyphosate over-the-top at the 4-leaf stage. Cotton yields were similar across glyphosate treatments in 2001 and 2003. Compensation for early glyphosate damage can be achieved when environmental conditions and resource availability are favorable (Jones and Snipes, 1999). Cotton yield was higher in 2002 than in 2001 or 2003. The 2002 yield difference with glyphosate cannot be explained by a difference in boll numbers. Average bolls produced per plant were between 7.7 and 8.0 for both glyphosate treatments each year. The assumption could be made that plants treated over-the-top with glyphosate at the 4-leaf stage had larger bolls compared with plants with the non-precision post-directed glyphosate at the 8-leaf stage, but individual boll weights were not recorded.

Main effect and main effect interactions for lint turnout were not significant (Table 2). Although a common response with mepiquat chloride is increased seed size (Biles and Cothren, 2001; Cothren and Jost, 1998), which reduces lint turnout (Cathey and Meredith, 1988; Kerby, 1985), this response was not observed in this study.

Table 3. Lint yields for interactions between irrigation method and glyphosate application method by year across mepiquat chloride treatments

Year	Lint yield (kg ha^{-1})					
	Irrigation method[y]			Glyphosate[z]		
	OSI	SSD	*P* value	4 OT	8 PD	*P* value
2001	**1360**	**1600**	**0.0007**	**1470**	**1490**	**0.6889**
2002	**1820**	**1900**	**0.1885**	**1940**	**1780**	**0.0087**
2003	**1010**	**910**	**0.0663**	**940**	**980**	**0.4265**
Years combined	**1400**	**1470**	**0.5441**	**1450**	**1420**	**0.6781**

[y] OSI = overhead sprinkler irrigation; SSD = sub-surface drip irrigation.

[z] Glyphosate applications made at 0.84 kg a.e. ha^{-1}; 4 OT = four-leaf post emergence over-the-top; 8 PD = eight-leaf non-precision post-directed.

There was a significant interaction between mepiquat chloride application over years for micronaire, which was reduced from 4.5 to 4.4 by mepiquat chloride in 2001, and not affected in 2002 or 2003 (data not shown). Positive effects of mepiquat chloride on micronaire have been observed for both reducing high readings and increasing low readings in non-irrigated cotton when the growing season is short (Nuti et al., 2004). Proper use of mepiquat chloride will promote a compact fruit load with uniform maturity and the potential for earliness (Stewart, et al., 2001; York, 1983). Neither irrigation method nor glyphosate treatment affected micronaire in the present study.

There were no significant main effects or main effect by year interactions for fiber length or fiber strength. Fiber length was not affected by glyphosate (data not shown), but was improved from 26.94 to 27.25 mm by SSD irrigation compared with OSI and was also significantly improved from 26.98 to 27.21 mm when mepiquat chloride was used. The average fiber length in 14 studies over 3 yr for cultivar Suregrow 501 BR was 26.92 mm (Bowman, 2003). In the current study, treatments without mepiquat chloride and under OSI irrigation would have received a market price discount based on the Commodity Credit Corporation loan schedule, since the average fiber length was less than base of 26.99 mm (NCCA, 2004). Neither irrigation method nor mepiquat chloride affected fiber strength; however, fiber strength was improved from 276 to 282 kg N m kg^{-1} when glyphosate was applied non-precision post-directed compared with over-the-top. Other fiber quality parameters including fiber length uniformity, reflectance, brightness, and short fiber content were not affected by the experimental treatments (data not shown).

It was noted as early as the eight-leaf stage that cotton plants in 2001 were lodging. Lodged plants were short with thick main-stems, and heavy boll-loads, but none were up-rooted. Lodged plants were susceptible to greater exposure to glyphosate during non-precision post-directed application. Glyphosate had no effect on lodging, and there were no significant interactions between glyphosate and irrigation or mepiquat chloride application. Under OSI, 25% of the plants were lodged and 5% were lodged under SSD. In this field experiment, 21% of the plants treated with mepiquat chloride were lodged compared with 9% in plots without mepiquat chloride. Because plants treated with mepiquat chloride were shorter, they should have been more resistant to lodging, but for unknown reasons, plants treated with mepiquat chloride lodged more in this study. After harvest-aids were applied and bolls opened, all plants were upright enough for machine harvest, so lodging did not affect yield. Plants did not lodge in 2002 or 2003.

Plant mapping. Plants were mapped after all bolls that contributed to yield were set and when about half of the fruit had reached maturity in order to quantify earliness between treatments. Two data parameters recorded during plant mapping were the position of the first sympodial branch on the main stem and the first sympodial branch that retained a boll. Proper irrigation to preventing water stress aids in the retention of early-set fruit. In combination with reducing vegetative growth, mepiquat chloride can cause the fruit-load to be set lower on the plant (Kerby et al., 1986; McCarty and Hedin, 1994), and maintain plants with higher boll retention on lower nodes (Kerby et al., 1986). Boll development is a temperature dependant phase directly related to the amount of heat units accumulated from pollination to boll maturity (Gipson, 1986). This is especially important for cotton produced in the northeastern region of the Cotton Belt. In this study, there were no significant main effects or main effect by year interactions for the main stem position of the first sympodial branch (data not shown). A significant interaction was observed between year and irrigation method for the sympodial branch where the first boll was set. The first boll was set on a higher sympodial branch by 0.6 branches in 2001 and 0.4 branches in 2003 for cotton under OSI than under SSD but was not affected in 2002 (data not shown). Neither glyphosate nor mepiquat chloride affected the position where the first fruit was set on the main stem (data not shown).

A significant mepiquat chloride by year interaction was observed for plant height, nodes per plant, and height to node ratio; however, the interactions between mepiquat chloride and glyphosate or irrigation method for plant growth characteristics were not significant. Plants treated with mepiquat chloride were shorter by 25 cm in 2001 and 36 cm in 2003 than untreated plants (Table 4). The reduction in plant height for plants treated with mepiquat chloride was reflected in 1.4 fewer total nodes per plant in 2001 and 2.2 fewer nodes in 2003. The combined effect of shorter plants and fewer nodes resulted in a lower height to node ratio by 1.2 in 2001 and 1.5 in 2003. Plants treated with mepiquat chloride in 2002 did not exhibit reduced growth compared with untreated plants. No response to mepiquat chloride has previously been recorded and is often reported as being due to environment conditions affecting growth characteristics (Kerby, 1985; York, 1983). It is evident that the method used for mepiquat chloride recommendations in this study was not consistently effective across environments. Plants in SSD plots were 23 cm taller and had 0.8 more nodes than plants under OSI irrigation, but height to node ratio was not affected by irrigation method (data not shown). Glyphosate did not affect plant height or node production (data not shown).

The focus of plant mapping was to record where bolls were retained on plants, including their position on sympodial branches and the position of sympodial branches on the main stem where bolls were located. Bolls set on the first and second sympodial positions are generally larger than bolls set on positions ≥3, because they are set earlier and are closer to the main stem, which makes them preferential metabolic sinks (Kerby and Ruppenicker, 1992; Parvin and Atkins, 1997). No significant main effects or main effect by year interactions for the number of first position sympodial bolls were observed (Table 5). Neither glyphosate nor irrigation method affected the number of first position bolls. Plants without mepiquat chloride had an average of 0.6 more bolls on the first sympodial position (Table 6). A significant interaction was observed between mepiquat chloride and years for second and outer position boll number and for total bolls per plant. Plants treated with mepiquat chloride had 0.9 fewer bolls retained on the second position in 2003, while mepiquat chloride did not affect second position bolls in 2001 or 2002. Although irrigation did not affect first position boll counts, plants under SSD had an average of 0.4 more second position bolls than those under OSI. Outer sympodial bolls are set on positions further out than the second position, including third and fourth positions. In 2003, there were 0.6 more bolls set on outer positions on plants not treated with mepiquat

Table 4. Plant height, height to node ratio, and total nodes for the interaction between mepiquat chloride application (MC) and year

Year	Plant height (cm) ^{y}			Height to node ratio^y			Nodes (no. plant^{-1}) ^{y}		
	w/MC^z	wo/MC	*P* value	w/MC^z	wo/MC	*P* value	w/MC^z	wo/MC	*P* value
2001	65	90	0.0001	5.2	6.4	0.0001	12.6	14.0	0.0001
2002	92	100	0.3490	5.7	6.0	0.5884	16.2	16.7	0.4549
2003	76	112	0.0001	4.9	6.4	0.0001	15.4	17.6	0.0001

^{y} Data are the average of six plants per plot and were recorded 12, 27, and 15 September in 2001, 2002, and 2003, respectively.

^{z} Mepiquat chloride was applied as recommended by the modified early bloom method as described by Edmisten (2004a).

Table 5. Probabilities of main effects and main effect interactions for location of bolls on the plant and boll retention

Source	*P* value							
	Bolls plant^{-1}							Aborted fruiting sites
	First position	Second position	Third position	Total	Monopodial	Percentage open	Percentage retained	
Irrigation (Irr)	0.2253	0.0020	0.3132	0.0011	0.5958	0.2311	0.0316	0.6764
Year x Irr	0.1285	0.5308	0.5188	0.4958	0.8753	0.0694	0.8104	0.5470
Mepiquat chloride (MC)	0.0167	0.6065	0.5000	0.2774	0.0346	0.0056	0.0001	0.0001
Year x MC	0.7381	0.0006	0.0159	0.0030	0.9572	0.9600	0.0829	0.9242
Irr x MC	0.2916	0.0815	0.4665	0.1456	0.8171	0.8089	0.5656	0.0794
Glyphosate (Gly)	0.3074	0.2979	0.2871	0.3452	0.5492	0.4544	0.0792	0.8570
Year x Gly	0.6810	0.2640	0.5878	0.6285	0.6661	0.0170	0.9045	0.9213
Gly x MC	0.9123	0.0547	0.3216	0.0809	0.3629	0.1039	0.7474	0.8627
Irr	0.6216	0.4820	0.4640	0.3622	0.7418	0.7479	0.6831	0.4402
Irr x Gly	0.2382	0.3004	0.6976	0.3293	0.2044	0.7168	0.2078	0.0540
Year x Gly x Irr	0.2593	0.3802	0.8265	0.2285	0.9030	0.0076	0.7063	0.9826

Table 6. First, second, and outer position sympodial bolls and total mature bolls per plant for the interaction between mepiquat chloride (MC) and year

Year	Sympodial positions (bolls plant^{-1})^{y}									Total bolls^{y}		
	First			Second			Outer					
	w/MC^{z}	wo/MC	*P* value	w/MC^{z}	wo/MC	*P* value	w/MC^{z}	wo/MC	*P* value	w/MC^{z}	wo/MC	*P* value
2001	4.8	5.3	0.0472	1.8	1.8	0.9999	0.3	0.1	0.1722	6.8	7.1	0.4094
2002	4.7	5.3	0.0328	2.1	1.8	0.1989	0.3	0.4	0.5871	7.1	7.5	0.4270
2003	5.3	6.0	0.0142	2.3	3.2	0.0023	0.6	1.2	0.0480	8.1	10.4	0.0012
Years combined	4.9	5.5	0.0167	2.1	2.3	0.6065	0.4	0.6	0.5000	7.3	8.3	0.2774

[y] Data are the average of six plants per plot and plant mapping was conducted on 12, 27, and 15 September in 2001, 2002, and 2003, respectively. Outer includes all bolls set on positions ≥3 on sympodial branches. Total bolls include all bolls retained on sympodial branches.

[z] Mepiquat chloride (MC) was applied as recommended by the modified early bloom method described by Edmisten (2004a).

chloride; however, mepiquat chloride did not affect the amount of outer position bolls in 2001 or 2002. Plants produced 2.3 fewer bolls when treated with mepiquat chloride in 2003. Since mepiquat chloride did not affect yield but reduced boll number in 2003, non-treated cotton required more yield contributing bolls to attain similar yield that year. Plants with more bolls may have matured later, since they were probably set over a longer period of time. Regardless of mepiquat chloride use, plots under SSD had 0.9 more harvestable bolls per plant than those under OSI. Cotton plants can fill space between rows and especially between plants within rows when a poor plant stand is established by increasing resource allocation to monopodial branches. Monopodial branches bear sympodial branches with the ability to bear fruit (Davidonis et al., 2004).

There were no significant main effects or main effect by year interactions for bolls set on monopodial branches. An average of 1.1 to 1.3 bolls per plant was located on monopodial branches in this study. Plants treated with mepiquat chloride had 0.2 more monopodial bolls than plants not treated with mepiquat chloride. Irrigation method and glyphosate application method did not affect monopodial boll production (data not shown).

Uniform crop maturity is a goal for producers and simplifies harvest preparation by improving harvest-aid performance. The northeastern region of the Cotton Belt can have periods of low temperatures in early fall preceding harvest. Cotton metabolism is driven by the accumulation of heat units, so delayed crop development decreases the effectiveness of plant hormone based harvest-aid products. These crop maturity data are based on the percentage of first position sympodial bolls that were open during plant mapping. In this study, a significant three-way interaction was observed between glyphosate, irrigation, and years. In 2002, OSI cotton that was treated with non-precision post-direct glyphosate was 11% less mature than cotton sprayed with glyphosate over-the-top (Table 7). Glyphosate did not affect maturity in OSI cotton in either 2001 or 2003. Cotton under SSD was 24% less mature when sprayed with non-precision post-direct glyphosate in 2001 compared with glyphosate over-the-top. There were no main effect interactions with mepiquat chloride or years. Plants treated with mepiquat chloride had 53% open first position sympodial bolls, while plants without mepiquat chloride were only 46% mature at the time of plant mapping. These results are in agreement with previous reports that cotton with mepiquat chloride was earlier maturing than untreated cotton (Kerby, 1985; Cathey and Meredith, 1988; York, 1983).

Table 7. Effect of the three-way interaction between irrigation method, glyphosate (Gly) application, and year on cotton maturity^{x}

Year	First-position open bolls (%)^{y}					
	Overhead sprinkler			Sub-surface drip		
	Gly (4 OT)^{z}	Gly (8 PD)^{z}	*P* value	Gly (4 OT)^{z}	Gly (8 PD)^{z}	*P* value
2001	36	36	0.7385	50	26	0.0031
2002	89	78	0.0009	80	70	0.1264
2003	39	39	0.9875	20	31	0.0586

[y] Maturity was recorded as the percentage of first position sympodial bolls that had cracked by 12, 27, and 15 September in 2001, 2002, and 2003, respectively. These data are the average of six plants per plot.

[z] Glyphosate applied at 0.84 kg a.e. ha^{-1}; 4 OT = four-leaf post emergence over-the-top; 8 PD = eight-leaf non-precision post-directed.

Since cotton initiates fruit over a long period of time, it does not retain every fruit that is set. Due to its perennial nature, cotton will abort small fruit when stressed and postpone reproductive activity until more favorable conditions. Each aborted fruit is a waste of resources, which could have contributed to overall yield in a non-stressed environment. Irrigation, when properly applied, supplies moisture necessary to alleviate drought stress; however, water supplied to a cotton crop after drought stress may also cause fruit abortion, if plants revert to vegetative growth. Data for total aborted sites and percentage fruit retention were only recorded in 2002 and 2003. There were no significant main effects or main effect by year interactions for boll retention. Cotton irrigated with SSD irrigation aborted an average of 1.3 more fruit than did OSI in this test. Use of mepiquat chloride caused 4.1 fewer aborted sites per plant than those not treated with mepiquat chloride and increased fruit retention from 39% to 44%. Glyphosate did not affect any plant mapping parameters, except for the interaction of irrigation systems on maturity across years (Table 7).

One intriguing response in this study was that fewer bolls were set on the first sympodial position in cotton treated with mepiquat chloride compared with untreated cotton. Results from mepiquat chloride use in cotton recorded in this study that are common include plant height control, earliness, greater fruit retention, and greater monopodial boll production compared with untreated cotton (Gausman et al., 1979). Through regulation of vegetative growth, mepiquat chloride can restructure the cotton plant and canopy to be more efficient, which is supported by higher fruit retention, fewer boll abortions (Kerby et al., 1986), and may result in production of larger bolls (York, 1983). Such results show that responses from mepiquat chloride treatments are highly variable and closely related to the environment in which the crop is grown (Lege et al., 1996).

Cotton irrigated with SSD exhibited more vigorous growth, improved fiber length, produced more second position and total bolls per plant, and improved percentage fruit retention. These results suggest that SSD supplies water in a manner that may be superior to OSI for cotton production. An advantage that SSD systems have over OSI systems is the ability to supply water to the crop after bolls are open. Because of this ability and the fact that SSD applies water in more precise increments, the SSD system was used after initial boll opening and provided superior yield in 2001 compared with OSI. There are many small and irregularly shaped fields in North Carolina, which may be more suited to SSD than OSI systems. Both irrigation systems allow cotton not managed with mepiquat chloride to have similar yield, although plants with uncontrolled vegetative growth may have increased problems with insecticide application, lodging, late maturity, and susceptibility to boll rot (*Phytophthora* sp.) (Gausman et al., 1979; Kerby, 1985; York, 1983). It was evident in 2002 that mepiqaut chloride did not provide results consistent with those in 2001 or 2003. Further research in irrigated cotton is needed to adjust either early mepiquat chloride rates or shortened monitoring intervals to address application timing for mepiquat chloride for the northeastern region of the Cotton Belt. Studies comparing these irrigation systems against proven non-irrigated production practices in direct economic comparisons are necessary to determine if the advantages of irrigation and yield stability observed in this study will be a sensible input for North Carolina cotton producers to consider.

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DISCLAIMER

Mention of trade names does not imply approval or recommendation of products nor excludes others which may be suitable.

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