ABSTRACT

NUTI, RUSSELL. Improving Cotton Production Margins through Management Decisions and Use of New and Standard commercial Products to Improve Quality and Profits. (Under the direction of Dr. Keith Edmisten and Dr. Randy Wells)

Cotton (*Gossypium hirsutum* L.) is a perennial plant managed as an annual crop for production of fiber and cottonseed oil. Modern cotton production requires optimizing yield and fiber quality while managing inputs to maximize profit. Through improvements made by transgenic breeding, cotton production has been simplified. Cotton cultivars are available that are resistant to the non-selective herbicide glyphosate and are capable of producing of *Bacillus thuringiensis* (Bt) endotoxin which is toxic to the boll-feeding lepidopteran complex. Cultural practices including use of the plant growth regulator, mepiquat chloride, and optimizing planting date contribute to crop uniformity and decrease some risk involved with drought and poor late-season harvest conditions. These field experiments were designed to develop sound recommendations for successful cotton production in North Carolina. Comparisons were made between conventional and transgenic weed and insect management systems, optimal and late planting dates, overhead sprinkle irrigation and drip irrigation, and use of mepiquat chloride. Cotton planted at optimal dates had better yield than cotton planted late. Mepiquat chloride did not always provide an advantage, however never caused an undesirable response. At times, cotton plants treated with mepiquat chloride showed improved micronaire, compensation for boll loss, and earlier maturity. Glyphosate applied broadcast at the eight-leaf stage reduced yield of optimal-planted cotton in 1 of 3 years and 2 of 3 years in late-planted cotton. Plants with glyphosate contact after the four-leaf stage in 2 of 3 years shifted the majority of bolls above node 10. Lint yield results were variable between overhead sprinkle and drip irrigation systems. Mepiquat chloride did not affect yield in irrigated cotton, however did control plant height, and improve fruit retention and cotton maturity. Non-labeled glyphosate applications reduced maturity in each irrigation system in 1 of 3 years. Cotton injury caused by conventional herbicides resulted in yield loss and poor returns compared to glyphosate systems. Early-season weed competition from low input herbicide programs caused cotton biomass reduction. High costs of conventional herbicide programs offset the available profit margin compared to glyphosate systems when yields were similar. Glyphosate systems provided excellent control of all weed species, while conventional herbicides gave acceptable control in most cases. Cultivars with combined glyphosate resistance and in-plant Bt endotoxin production, returned more profit than those with glyphosate resistance alone. Glyphosate resistant cotton cultivars with had better yield and returned more profit than the same cultivars treated with conventional herbicides.

IMPROVING COTTON PRODUCTION MARGINS THROUGH MANAGEMENT DECISIONS AND USE OF NEW AND STANDARD COMMERCIAL PRODUCTS TO IMPROVE QUALITY AND PROFITS

by

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A dissertation submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

DEPARTMENT OF CROP SCIENCE

Raleigh

2004

APPROVED BY:

Co-chair of Advisory Committee

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DEDICATION

This dissertation is dedicated to my parents, Ralph and Mary Rita Nuti, grandparents, and great-grandparents for their unconditional support, example, and love extended to help me reach all my goals. It is also dedicated to improving the knowledge base available for efficient agricultural production in the United States.

BIOGRAPHY

Russell Carlo Nuti was born to Ralph and Mary Rita Nuti on March 21, 1975 in Reno, Nevada. He graduated from Smith Valley High School in June of 1993. He received his Bachelor of Science in Agronomy from Texas A&M University in May of 1998. After completing athletic eligibility, Russell was employed by the Cotton Physiology Workgroup at Texas A&M as an undergraduate student-worker for one year. He completed a Master of Science degree under the direction of Dr. J. Tom Cothren in Agronomy in May of 2001 at Texas A&M. Russell went to North Carolina State University to pursue a PhD in the Crop Science Department under the direction of Dr. Keith Edmisten and Dr. Randy Wells in May 2001, and will graduate in December 2004. Russell resides at 6906 Baywood Drive in Raleigh, North Carolina and is currently pursuing employment.

ACKNOWLEDGEMENTS

I would like to extend appreciation to the following individuals and organizations for the support and inspiration that was necessary to earn my PhD. My eagerness to learn was instilled at an early age and continues to be driven by individuals with influence in my life. Appreciation is extended to various teachers, coaches, professors, and colleagues for their positive influences and confidence in me.

I want to thank my graduate committee for advising me during these projects. Special appreciation is given to Dr. Ryan Viator, Shaun Casteel, and Jennifer Harriss as they provided daily support for me during this educational experience. Research technicians and other employees in the Cotton Team at North Carolina State University are thanked for the many hours spent in research. Faculty and staff members at the Peanut Belt Research Station, Upper Coastal Plain Research Station, Central Crops Research Station, and the Cherry Farm Unit are appreciated for their cooperation in field research. Finally, I thank Cotton Incorporated and the North Carolina Cotton Producers Association for supporting this research.

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Effect of Planting Date, Mepiquat Chloride, and Glyphosate Application to Glyphosate Resistant Cotton in North Carolina

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ACKNOWLEDGEMENTS

Cotton Incorporated and the North Carolina Cotton Grower's Association supported this research. Appreciation is also given to the staff at the Upper Coastal Plain Research Station.

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Effect of Planting Date, Mepiquat Chloride, and Glyphosate Application to Glyphosate Resistant Cotton in North Carolina

ABSTRACT

Field studies were conducted near Rocky Mount, North Carolina in 2001, 2002, and 2003. Objectives were to determine if planting date affected the ability of glyphosate [*N*-(phosphonomethyl)glycine] resistant (GR) cotton (*Gossypium hirsutum* L.) to compensate for fruit loss from glyphosate and evaluate mepiquat chloride's (MC) (1,1-dimethyl piperidinium chloride) contribution to fruiting compensation. Cotton was planted at optimum and late dates each year. Five glyphosate treatments were evaluated, including one no-herbicide treatment. All glyphosate treatments were sprayed over-the-top (OT) at the four-leaf stage (4OT), and three received additional glyphosate at the eight-leaf stage consisting of an OT (8OT), non-precision post-direct (PD) (8 non-Prec PD), and a precision post-direct (8 Prec PD) at 0.84 kg a.e. (acid equivalent) ha^{-1} glyphosate. The 10 planting date and glyphosate combinations were factored across programs using MC and no MC as needed according to present conditions. Optimal-planted cotton yielded more than late-planted cotton. Glyphosate 8OT reduced optimal-planted cotton yield in 2001and late-planted cotton yield in 2001 and 2002. Yield was improved by MC in 1 of 2 years. Glyphosate did not affect total bolls per plant but decreased first-position sympodial bolls and increased monopodial bolls. Optimal-planted cotton retained a higher portion of sympodial bolls below node 10 than late-planted cotton. Plants with glyphosate contact after the 4-leaf stage in 2001 and 2002 shifted the majority of fruitload to above node 10. Cotton treated with MC set the majority of bolls lower in the profile. Micronaire of late-planted cotton was

positively affected by MC.

Abbreviations: GR, glyphosate-resistant; MC, mepiquat chloride; OT, over-the-top; 4OT, over-the-top at four-leaf stage; 8OT, over-the-top at eight-leaf stage; PD, post-directed; 8 non-Prec PD, non-precision post-directed at eight-leaf stage; 8 Prec PD, precision post-directed at eight-leaf stage; a.e., acid equivalent; PGR, plant growth regulator; CP4-EPSPS, 5-enolpyruvylshikimate-3-phosphate synthase.

Cotton (*Gossypium hirsutum* L.) is grown worldwide for the essential commodities of fiber, seed, and oil. Cotton is a perennial plant, exhibiting indeterminate growth and fruiting habits and is grown as an annual crop, thereby increasing the necessity of intense management for profitable production (Cothren, 1994). Provision of sufficient resources, such as fertilizer and adequate soil moisture, is required to insure profitable yield. However, these inputs may contribute to excessive vegetative growth, causing low efficiency in plant resource utilization. Plant growth regulators alter plant growth with the potential for improving efficient plant resource allocation (Cothren, 1994). Over the past 25 years, PGRs have been marketed for use in cotton for purposes that vary from increasing seedling vigor, suppressing vegetative growth, and increasing yield.

Cotton remains vegetative throughout the blooming period, which requires a constant supply of resources. A commonly used PGR on cotton is MC (McCarty and Hedin, 1994). An early study including 14 cultivars and 8 environments determined that cotton cultivars respond similarly when treated with MC (York, 1983). By reducing vegetative growth of cotton, a potential enhancement of reproductive growth may be realized. Biles and Cothren (2001) reported increased numbers of flowers in cotton treated with MC. Mepiquat chloride inhibits gibberellic acid synthesis, via blocking the cyclization of geranylgeranyl pyrophosphate to copalyl pyrophosphate and also blocks further transformation of copalyl pyrophosphate to ent-kaurene in the gibberellic acid biosynthesis pathway (Halmann, 1990). A common response of cotton treated with MC is reduced internode length, reducing overall plant height (Kerby, 1985; McCarty and Hedin, 1994). Excessive moisture and nutrients, as well as fruit abortion, may trigger rank growth (Guthrie, 1986). Plant growth regulators like MC can inhibit shoot growth and suppress excessive vegetative growth without affecting leaf production and reproductive development (Dicks, 1980; Han, 1991). Using fewer plant resources for vegetative growth may cause a desirable shift in photoassimilate allocation to fruiting structures, increasing the economic yield potential of a crop on the same resource budget. Cotton plants are capable of supporting a large fruit load depending on the availability of carbohydrates and other resources (Eaton, 1955), which readily suggests that it would be more efficient to invest photoassimilates toward fruit production rather than being spent on excessive vegetative growth. Cotton producers routinely use MC to control plant height and promote earliness. Although shifts in biomass partitioning from vegetative to reproductive tissue have been documented, consistent yield improvement is a rare response (Boman et al, 1998; Chaney, 1998). Plant growth regulator performance is generally highly variable, which is caused mostly by unpredictable environmental conditions (Lege et al., 1996). Mepiquat chloride allows producers to regulate vegetative growth to match current environmental conditions (Landivar et al., 1996). Mepiquat chloride usually causes cotton leaves to turn darker green within a few days of treatment compared to untreated cotton foliage (Cothren et al., 1977; Gausman et al., 1980). Mepiquat chloride has caused increased cotton leaf density and chlorophyll content per unit leaf area, potentially increasing the photosynthetic capacity of cotton leaves (Gausman et al., 1980; Fernandez et al., 1991). Wells (1997) and Oosterhuis et al. (1998) found that MC improved leaf photosynthesis and dry matter partitioning from vegetative to reproductive tissue in cotton. However, no differences in canopy photosynthesis were found with MC treatments when compared to a control (Wells and Edmisten, 1998).

Glyphosate resistant cotton was commercially released with the trade name, Roundup Ready®, in 1997 (Faircloth, et al., 2001; Pline, et al., 2001). This technology has been overwhelming accepted by producers with more than two-thirds of the 2003 United States cotton crop being planted with Roundup Ready® seed (Ihrig et al., 2003). Over 95% of the 2003 North Carolina cotton crop consisted of transgenic cotton (USDA-AMS, 2003). Glyphosate, a member of the glycine herbicide family, non-selectively controls a broad-spectrum of economically significant grass and broadleaf weed pests (Ellis and Griffin, 2002). The transgenic cotton GR weed management system is an effective alternative to conventional methods, requiring less herbicide and fewer applications to produce the same yield and net economic return (Culpepper and York, 1998).

Herbicides may be post-directed under cotton, however cotton seedling growth is relatively slow compared to most weed species. Weed competition may affect cotton growth if the necessary height differential between the crop and weed targets is not established for safe PD herbicide applications (Culpepper and York, 1998; Wilcut et al., 1997). Therefore, cotton producers favor OT herbicide applications because they require less precision and can be done with larger equipment requiring less time (Jennings et al., 1999).

Glyphosate resistant cotton has been associated with boll abscission, fruit malformation, and yield fluctuations compared to non-GR cotton cultivars. These problems have been noticed by producers and documented by researchers (Jones and Snipes, 1999). Numerous field studies have been conducted including recommended and off-label OT and PD glyphosate applications to GR cotton to determine injurious rates and timings. Many concur that pollination in GR cotton is negatively affected, however yield losses are only evident in situations where environmental conditions limit resources and do not allow sufficient compensation for fruit loss and underdeveloped bolls (Jones and Snipes, 1999; McCloskey and Moser, 2002). Even non-GR cotton has exhibited compensatory ability after damaging foliar contact from drift rates of glyphosate where neither crop maturity or yield were affected (Ellis and Griffin, 2002).

The apparent problem with the current Roundup Ready® technology is that it does not provide sufficient gene expression and subsequent glyphosate tolerance in some flower tissues to prevent toxicity by common glyphosate rates used in modern cotton production practices (Pline et al., 2002). Over-the-top or non-precision PD glyphosate applications after the four-leaf stage hinder healthy pollen development and pollen deposition causing pollination problems, which may consequently accrue yield loss (May et al., 2004; Pline et al., 2002). A controlled environment study using ^{14}C-glyphosate documented that as glyphosate accumulation in cotton fruiting structures increased, boll abscission increased (Viator et al., 2003). Further research suggests that intolerance of reproductive tissues to glyphosate was a result of poor expression of the genes responsible for producing the alternative non-glyphosate binding enzyme, CP4-EPSPS (Pline et al., 2002). These findings reinforced the label restrictions for glyphosate applications to GR cotton. Ensuring crop safety cannot be guaranteed unless growers avoid PD applications after the four-leaf stage that cause glyphosate contact to cotton leaves (Ihrig et al., 2003). Research regarding the absorption and movement of ^{14}C-glyphosate in GR cotton showed that bolls and squares accumulated greater amounts of glyphosate due to their affinity for metabolites during growth (Pline et al., 2001). Pline et al. (2001) also reported that cotton stem tissue absorbed considerable amounts of glyphosate and that more glyphosate was absorbed by cotton plants when treated PD rather than OT at four growth stages ranging from four-leaf to 2 wk after first bloom.

A limit of two broadcast applications of glyphosate may be made to GR cotton from emergence through the 4-leaf stage and at least two nodes of growth with ten days in between applications is required (Anonymous, 1999). Precision PD or hooded glyphosate applications are allowed after the five-leaf stage until first bloom as long as contact with foliage, green stems, and fruit are avoided. The precision of many PD herbicide applications may be sacrificed in order to achieve ample coverage of weed targets. If there is damage to the first initiated fruit, new fruit will be initiated, and their fate in contribution to yield is dependent on the conditions of the environment (Jones and Snipes, 1999).

Being presented with the fact that the northern portion of the cotton belt has a limited season and knowing that glyphosate use may cause a fruiting shift delaying maturity, leads us to focus on manipulating cotton planting date. Late-planted cotton will start anthesis later in the growing season causing bolls to develop during a later period, which is usually in cooler conditions (Gormus and Yucel, 2002). Adjusting planting date is a cultural practice which may be used to help combat late-season maturity problems. With the possibility of fruit abortion or abnormal boll development, which may result in yield loss from glyphosate use in GR cotton, cultural practices, including planting date and use of MC, were addressed in the planning of this study. The primary objective was to determine if late-planted cotton responds differently to glyphosate over a range of application timings and methods. The secondary objective included examining how the use of MC according to current North Carolina Cooperative Extension recommendations affects fruiting compensation.

MATERIALS AND METHODS

Field studies were conducted at the Upper Coastal Plain Research Station near Rocky Mount, North Carolina in 2001 on Marvyn sandy loam (fine-loamy, kaolinitic, thermic Typic Kanhapludults), 2002 on Lynchburg fine sandy loam (fine-loamy, siliceous, semiactive, thermic Aeric Paleaquults), and 2003 on Norfolk loamy sand (fine-loamy, kaolinitic, thermic Typic Kandiudults).

A factorial treatment arrangement was used with two planting dates and five glyphosate application methods, including one with no glyphosate. Each planting date and glyphosate combination was present with and without MC. Treatments were replicated four times and arranged in a randomized complete block design. An optimal planting date for cotton in North Carolina is usually during the last week of April or first week of May. More importantly, it is recommended to plant cotton once soil temperatures have risen above 18^{o} C by mid-morning and a week of dry and warm weather is forecasted being favorable to germination and acceptable seedling growth (Edmisten, 2004a). The optimal and late planting dates for this study were during the first week of May and June, respectively. In 2004, USDA-NASS reported that an average of 94% of the total 1999 to 2003 North Carolina cotton hectarage had been planted before 1 June. Conditions causing growers to plant after 1 June are usually associated with wet early season weather, greater time commitment to other crops, and equipment breakdown, however is not a recommended practice. Cotton planting date trials in North Carolina show an average lint loss of 13.5 kg ha^{-1} d^{-1} for cotton planted after 5 May (Edmisten, 2004a).

Planting dates for these studies were optimum (1 May 2001; 30 April 2002; 7 May 2003) and late (6 June 2001; 4 June 2002; 2 June 2003). Cotton cultivar ‘DP 451 B/RR’ was planted on 91 cm beds. Plots were four rows wide by 12 m long, and data were obtained from the middle two plot rows. All treatments with glyphosate were sprayed 4OT, and three received an additional application at the 8-leaf stage consisting of 4OT + 8OT, 4OT + 8 non-Prec PD, and 4OT + 8 Prec PD at 0.84 kg a.e. ha^{-1} glyphosate. Glyphosate treatments were not intended to contribute to weed control and were made solely for the investigation of physiological effects. Plots were maintained weed-free via tillage and conventional herbicides in order to prevent weed-crop competition. The 10 planting date and glyphosate combinations were factored across programs using MC and no MC as needed equaling a total of twenty treatments in 2001 and 2002. All cotton was treated with the MC program in 2003, decreasing treatments to 10, thus 2001 and 2002 data were analyzed and reported separately from 2003 data. Decisions on rate and timing of mepiquat chloride applications were based on the Modified Early Bloom Method according to North Carolina Extension recommendations (Edmisten, 2004b).

Plant mapping data was obtained from a six-plant sub-sample from each plot prior to harvest each year. Data were recorded for harvestable bolls and missing positions on sympodial branches as well as harvestable bolls retained on monopodial branches (Mauney and Stewart, 1986). Mapping data were analyzed to determine total bolls $plant^{-1}$, monopodial bolls $plant^{-1}$, boll distribution by sympodial position, and percent of total bolls within sympodial node zones of 0 to 5, 6 to 10, 11 to 15, and 16 to 20. Plots were defoliated and harvested separately by planting date if maturity was different between planting dates. The middle two rows of plots were machine harvested, and seedcotton sub-samples were taken from each plot for high volume instrument analysis by Cotton Incorporated in Cary, NC.

Data were analyzed in SAS under the general linear model and means were separated using Fisher's Protected LSD at either α=0.05 or 0.10. Treatment effect F tests were carried out with their specific error source. In statistical analyses, years were treated as a random source of replication, and year by main effect interactions were ignored when main effects were strong and did not crossover between years (Gomez and Gomez, 1984).

RESULTS AND DISCUSSION

Cotton planted at optimal dates yielded more than ($p \leq 0.0001$) late-planted cotton, regardless of glyphosate or MC treatments, by 1370 and 930 kg seedcotton ha^{-1} in 2001-2002 and 2003, respectively. Gormus and Yucel (2002) and Guthrie (1991) reported a respective yield loss for 3 cotton planting dates and that each later date required more days to reach maturity. Optimal-planted cotton in 2001 suffered 820 kg ha^{-1} or 20% seedcotton yield losses from 4OT + 8OT glyphosate application (Table 1) and late-planted cotton in 2001 was affected in the same way, losing 780 kg ha^{-1} or 10% compared to cotton not receiving glyphosate. In a similar study by Jones and Snipes (1999), consistent yield losses are reported when GR cotton was treated with glyphosate OT at five- or six-leaf stages. Optimal-planted cotton was not affected by glyphosate in 2002, however late-planted cotton lost 340 kg seedcotton ha^{-1} from 4OT + 8 non-Prec PD glyphosate plus an additional 700 kg from 4OT + 8OT application. It is valuable to growers to consider this example where late-planted cotton was less able to physiologically compensate for non-precision PD glyphosate applications. The fact that a non-precision PD application gave an intermediate yield drop in 2002 late-planted cotton suggests that an application does not have to be later than four-leaf and OT to cause irreversible damage, if the environmental conditions are not favorable for fruiting compensation. Yield was not affected in either planting date in 2003 by glyphosate application. The erratic and unexplainable reports of yield responses of GR cotton compared to non-GR cultivars in the past may be explained by some of these results. Glyphosate applications made in accordance with label recommendations never affected yield in these trials and no yield differences have been reported by other researchers with off-label applications compared to GR cotton not treated with glyphosate (McCloskey and Moser, 2002). The fact that optimal-planted cotton in 2002 and both optimal- and late-planted cotton in 2003 did not have a yield penalty for off-label glyphosate applications suggests considerable ability to compensate for fruiting loss after non-precision application and poor application timing under favorable environmental circumstances.

Mepiquat chloride improved seedcotton yield ($p = 0.0062$) in 2001 by 280 kg ha^{-1} or 11%, but did not affect yield in 2002 (data not shown). Early cool temperatures in 2001 stopped development of bolls, and contributed to yield loss in later maturing cotton, including late-set bolls in cotton not treated with MC.

Growth measurements taken during plant mapping suggest that late-planted cotton has a tendency to grow more vegetatively. Cotton planted late was 10 cm taller in 2001 and 2002 and 23 cm taller in 2003 compared to optimal-planted cotton (Table 2). Optimal-planted cotton in 2001 and 2002 had more nodes than late-planted cotton while the opposite was true in 2003. Regardless of contrasting node differences between the years, height-to-node ratio was greater for late-planted cotton in all years. Cotton planted at optimal dates in 2001 and

2002 set fruit an average of one mainstem node lower than late-planted cotton. Glyphosate applied 8 non-Prec PD and 8OT in 2003 caused plants to be shorter than plants treated 8 Prec PD (Table 3). Cotton treated 8OT with glyphosate in 2001 and 2002 had an average of a half node more plant^{-1} than the untreated check. In 2003, cotton treated with glyphosate after the four-leaf stage had an average of 1.1 more nodes than the untreated check. Height-to-node ratio was not affected by glyphosate in 2001 and 2002, but the combined effect of shorter plants and more nodes in cotton treated with 8 non-Prec PD and 8OT glyphosate in 2003 caused shorter average internode length compared to cotton not receiving glyphosate. Glyphosate application method did not influence which sympodial branch retained the first boll in any year. The increase of node initiation with more glyphosate contact to plant tissue at the eight-leaf stage suggests a reversion to vegetative growth due to reduced boll load on lower nodes. Mepiquat chloride performed as expected, reducing plant height and keeping internodes short (Kerby, 1985; York, 1983). Use of MC in 2001 and 2002 caused plants to be an average of 21 cm shorter, have 1.4 fewer nodes, and have an average of 0.8 cm shorter internodes (Table 4). Mepiquat chloride caused fruit to be retained almost a full node lower in late-planted cotton in 2001. First-position bolls are usually considered the largest contributors to final yield, however, in this study, plants treated with MC had fewer first position bolls and this result did not affect yield. This study suggests that MC provides yield benefit by managing plant growth to minimize affects from exposure to stressful environmental conditions. Cotton yield was always similar to or superior to untreated cotton when treated with MC. Use of a sound MC program in this case provided retention of a higher portion of the crop in the lower part of the fruiting profile, which could result in early and uniform maturity, enhanced defoliation efficiency, and improved harvest conditions.

Planting cotton at optimal and late calendar dates caused numerous differences but revealed relatively inconsistent results for boll set and uniformity of boll retention for the 3 years of this study. The optimal-planted cotton had more bolls than late-planted cotton by an average of 1.6 bolls plant^{-1} in 2001, and the opposite was true in 2002 and 2003 by 4.5 and 1.4 bolls plant^{-1}, respectively (Table 5). Optimal-planted cotton produced 1.5 more bolls plant^{-1} on monopodial branches in 2002 than late-planted cotton. In contrast, the growing conditions in 2003 caused 0.4 more bolls plant^{-1} to be produced in late-planted cotton on monopodial branches than in optimal-planted cotton. The effect of planting date on sympodial boll retention was more consistent within each year than monopodial and total bolls. Optimal-planted cotton retained more first, second, and outer position sympodial bolls than late-planted cotton in 2001. Late-planted cotton in both 2002 and 2003 retained more bolls on first, second, and outer sympodial positions, with the exception of first position bolls in 2003.

Glyphosate application did not affect total bolls plant^{-1} (Table 6). Glyphosate applied 8OT increased the amount of bolls produced on monopodial branches, except when compared to 8 non-Prec PD in 2001 and 2002. In 2001 and 2002, 8OT glyphosate applications decreased first position sympodial bolls plant^{-1} compared to the untreated check. This comparison reversed as second and outer sympodial position bolls plant^{-1} increased in 2001 and 2002. Glyphosate did not affect first or second position boll retention in 2003, however there were more outer position bolls with treatments causing glyphosate contact to leaves after the four-leaf stage compared to no glyphosate that year. Increased contact of glyphosate to cotton leaves in some cases caused a decrease in first-position sympodial bolls and inversely increased bolls on second and outer positions, effectively demonstrating compensation by the plants. Compensation of this nature was observed and described by Jones and Snipes (1999).

Although MC did not affect total bolls (Table 7), and did increase yield in 2001 (data not shown), first position sympodial bolls plant^{-1} were lower in plants treated with MC in 2001 and 2002. Mepiquat chloride-treated plants produced more bolls on monopodial branches than those not treated with MC. The fact that MC affected the node of first retained boll in late-planted cotton in 2001 but did not have an affect in 2002 or optimal-planted cotton in 2001, reveals the opportunity for occasional benefit of earlier fruit set with MC use under short-season conditions. An increased portion of boll retention and location on either monopodial branches or outer sympodial positions is a sign of compensation for fruit loss on the first and second sympodial positions. This response is constantly influenced by the inherent nature of cotton to shift and compensate growth due to resource availability and variable environmental stress levels, which may cause primary-set fruit to be lost.

Since there were differences in sympodial boll retention, it is necessary to determine where those shifts occurred within the fruiting profile. Optimal-planted cotton in 2001 and 2002 had a higher portion of total sympodial bolls in node zone 0 to 5 than late-planted cotton and the same was true in 2002 and 2003 for node zone 6 to 10 (Table 8). A higher percentage of the total sympodial boll load was set within node zone 11 to 15 for late-planted cotton in all 3 years. At the top of the plant, node zone 16 to 20 revealed converse results with optimal planted cotton having 1.7% more sympodial bolls in 2001 and 2002 and late-planted cotton in 2003 having 7.2% more in that zone. Optimal-planted cotton tended to initiate and retain a higher percentage of its boll load on sympodial nodes 6 to 10, while late-planted cotton set more of it's crop above node 11.

Jones and Snipes (1999) reported an overall decrease in boll retention for cotton treated with glyphosate at five- and six-leaf stages compared to untreated cotton, although yield was not affected. In this study, glyphosate applications at 8OT decreased the percent of bolls set on sympodial nodes 6 to 10 compared to cotton not having glyphosate contact to leaves after the four-leaf stage in 2001 and 2002 (Table 9). Glypohsate did not affect the distribution of bolls regarding node zones in 2003. An evident shift and compensation for early boll loss in 2001 and 2002 cotton sprayed 8OT with glyphosate is found where a smaller portion of bolls was on nodes 6 to 10, and results in a higher portion of bolls on nodes 11 to 15. Pline-Srnic et al. (2004) reported variable results including fewer bolls on nodes 1 to 10 in GR cotton treated with glyphosate at the seven-leaf stage compared to untreated GR cotton. Mepiquat chloride caused more bolls to be set lower in the fruiting profile compared to untreated cotton. In 2001, 1.8 % and 17.2% more bolls were located in node zones 0 to 5 and 6 to 10, respectively, for cotton treated with MC (Table 10). Cotton not treated with MC produced 13.8% more of its sympodial bolls on nodes 11 to 15 and 3.9% of the crop above node 15. A shift in boll load toward the upper portion of the plant, as in this case, would not favor early maturity, and can affect yield as described by Zhao and Oosterhuis (2000).

Fiber quality was not affected by planting date in 2001. Optimal-planted cotton produced 0.7 and 1.0 mm longer fibers than late-planted cotton in 2002 and 2003, respectively (Table 11). The base length for cotton fiber is 27 mm and discounts are taken for fiber shorter than the base (Hake et al., 1996). Fiber length uniformity was better in late-planted cotton in 2002, and better in optimal-planted cotton in 2003. The same was true of fiber strength, where late cotton in 2002 and optimal cotton in 2003 were 22 and 10 kN m kg^{-1} stronger than their planting date counterparts. Late-planted cotton in 2002 and optimal-planted cotton in 2003 produced a lower percentage of short fibers than optimal and late-planted cotton each year. Micronaire is an estimation of fiber thickness, measured by surface area, which accounts for fiber perimeter and is affected by maturity and surface characteristics (Hake et al., 1996). The base ranges for micronaire are 3.5 to 3.6 and 4.3 to 4.9, with premiums given for readings between 3.7 and 4.2. Micronaire was not affected by planting date or glyphosate application (data not shown), however MC improved micronaire over a range of environmental conditions (Table 12). In 2001, MC increased the average micronaire reading for late-planted cotton by 0.31 and lowered the reading by 0.26 in 2002 late-planted cotton. There were no differences in micronaire readings with MC in optimal planted cotton, however late-planted cotton was affected variably between years. Late-planted cotton in 2001 exhibited low micronaire, and MC increased micronaire compared with untreated cotton. The environmental conditions in 2002 favored high micronaire and late-planted cotton treated with MC had lower micronaire than late-planted cotton not in the MC program that year. Mepiquat chloride marginally improved fiber length and strength in 2001 and 2002. Gylphosate application method did not affect fiber quality (data not shown). Optimal-planted cotton in 2002 had more short fiber content probably due to the fact that the early part of the growing season was under droughty conditions, and irrigation timing coupled with late-season rains relieved water stress in later-planted cotton, but could not alleviate previous water stress symptoms in the earlier-planted treatments. In both high and low micronaire environments, the MC program improved micronaire readings to more acceptable ranges. Fiber quality differences were most likely due to environmental conditions present before harvest and their concordant harvest timing for each planting date. Mepiquat chloride has some affect on maturity, and it can also affect fiber quality in relation to harvest timing and weather conditions (Zhao and Oosterhuis, 2000).

Cotton under the MC program did not experience any decrease in quality or yield. In fact, when significant differences were associated with MC, they were in favor of improving yield and quality of the crop. Mepiquat chloride had positive effects on lint quality, improved micronaire in late-planted cotton under variable environments, and consistently improved fiber length and strength regardless of planting date. This suggests that the modified early bloom method for MC recommendations works reliably in North Carolina. Roundup Ready® technology in conjunction with non-precision glyphosate applications can result in yield losses, especially in late-planted cotton, when the remainder of the growing season may not be favorable to fruiting compensation with a prolonged maturation and harvest period. With the findings of this study and efforts of other extension and research, growers should have the information to be well familiar with the safe management practices of glyphosate application to GR cotton. The most important rule to follow is to minimize glyphosate spray solution contact to GR cotton plants after the four-leaf stage. The optimal window in the northern region of the cotton belt is narrow between the time when conditions favor emergence and vigorous seedling growth, thus planting in this window should be given priority.

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Table 1. Effect of glyphosate application method on seedcotton yield in Rocky Mount, NC.

	2001‡		2002		
Glyphosate†	Planting Date				
application method	Optimal	Late	Optimal	Late	2003§
	kg ha^{-1}				
None	4050 a#	1870 a	2010	2040 a	2980
4OT¶	4060 a	1810 a	2400	2110 a	2880
4OT + 8 Prec PD	4050 a	1900 a	2450	1990 ab	3030
4OT + 8 non-Prec PD	3900 a	1700 a	2600	1700 b	2700
4OT + 8OT	3240 b	1120 b	2280	1000 c	2739
P value	0.0001	0.0001	0.2656	0.0001	0.3824

†Each glyphosate application was 0.84 kg ha^{-1}.

‡2001 and 2002 data are pooled over mepiquat chloride and are separate to show year and planting date interaction.

§2003 data are pooled over planting dates.

¶4OT, 4-leaf over-the-top; 8 Prec. PD, 8-leaf precision post-direct; 8 non-Prec. PD, 8-leaf non-precision post-direct; 8OT, 8-leaf over-the-top.

#Means followed by the same letter within a column are not statistically different according to Fisher's Protected LSD at a=0.05.

Table 2. Effect of planting date on plant growth characteristics in Rocky Mount, NC.

	Plant height		Nodes		HNR‡		FND	
Planting date†	2001 and 2002§	2003¶	2001 and 2002	2003	2001 and 2002	2003	2001 and 2002	2003
	cm		plant^{-1}		cm node^{-1}			
Optimal	80	69	18.3	16.9	4.4	4.1	6.1	6.7
Late	90	92	17.5	18.3	5.1	5.0	7.1	6.8
P value	0.0001	0.0017	0.0001	0.0459	0.0001	0.0014	0.0041	0.6188

†Optimal planting dates were 1 May, 30 April, and 7 May in 2001, 2002, and 2003 respectively. Late planting dates were 6, 4, and 2 June in 2001, 2002, and 2003 respectively.

‡HNR, height to node ratio; FND, first sympodial branch with a retained boll.

§2001 and 2002 data are pooled over mepiquat chloride and glyphosate application methods

¶2003 data are pooled over glyphosate application methods.

Table 3. Effect of glyphosate application method on plant growth characteristics in Rocky Mount, NC.

Glyphosate† application method	Plant height		Nodes		HNR‡		FND	
	2001 and 2002§	2003¶	2001 and 2002	2003	2001 and 2002	2003	2001 and 2002	2003
	cm		plant^{-1}		cm node^{-1}			
None	85	81 ab††	17.6 b	16.8 c	4.8	4.8 a	6.7	6.4
4OT#	85	81 ab	17.9 b	17.5 bc	4.7	4.6 ab	6.6	6.7
4OT + 8 Prec PD	83	86 a	17.8 b	17.7 ab	4.7	4.8 a	6.5	7.0
4OT + 8 non-Prec PD	86	77 b	17.8 b	18.3 a	4.8	4.2 b	6.5	6.8
4OT + 8OT	87	73 b	18.4 a	17.7 ab	4.8	4.3 b	6.8	6.7
P value	0.7363	0.0237	0.0824	0.0495	0.8870	0.0173	0.1627	0.2881

†Each glyphosate application was 0.84 kg ae ha^{-1}.

‡HNR, height to node ratio; FND, first sympodial branch with a retained boll.

§2001 and 2002 data are pooled over mepiquat chloride and planting dates.

¶2003 data are pooled over planting dates.

#4OT, 4-leaf over-the-top; 8 Prec. PD, 8-leaf precision post-direct; 8 non-Prec. PD, 8-leaf non-precision post-direct; 8OT, 8-leaf over-the-top.

††Means followed by the same letter within a column are not statistically different according to Fisher's Protected LSD at α=0.05.

Table 4. Effect of mepiquat chloride on plant growth characteristics in Rocky Mount, NC.

	Plant height	Nodes	HNR‡	FND			
				2001		2002	
				Planting date			
Plant growth regulator	2001 and 2002§	2001 and 2002	2001 and 2002	Optimal	Late	Optimal	Late
	cm	plant^{-1}	cm node^{-1}				
None	96	18.6	5.2	6	7.3	6.5	7.3
Mepiquat chloride	75	17.2	4.4	5.8	6.4	6.3	7.4
P value	0.0001	0.0001	0.0001	0.1501	0.0023	0.1089	0.7432

†Mepiquat chloride rates and application timings were according to North Carolina Extension recommendations for the modified early bloom method.

‡HNR, height to node ratio; FND, first sympodial branch with a retained boll.

§2001 and 2002 data are pooled over planting date and glyphosate application methods.

¶2003 data are pooled over glyphosate application methods.

Table 5. Effect of planting date on cotton fruiting pattern and total harvestable bolls per plant in Rocky Mount, NC.

	Sympodial positions														
	First			Second			Outer‡			Monopodial			Total§		
Planting date†	2001¶	2002	2003#	2001	2002	2003	2001	2002	2003	2001	2002	2003	2001	2002	2003
	bolls plant^{-1}														
Optimal	4.9	4.2	5.1	1.9	1.4	1.6	0.4	0.1	0.2	0.8	1.9	1.1	8.1	6.1	8.0
Late	4.1	5.8	5.1	1.4	2.5	1.9	0.2	0.4	0.8	0.8	0.4	1.5	6.5	10.6	9.4
P value	0.0001	0.0001	0.9210	0.0010	0.0001	0.0849	0.0439	0.0046	0.0457	0.8965	0.0001	0.0602	0.0001	0.0001	0.0084

†Optimal planting dates were 1 May, 30 April, and 7 May in 2001, 2002, and 2003 respectively. Late planting dates were 6, 4, and 2 June in 2001, 2002, and 2003 respectively.

‡Outer includes all bolls set on third, fourth, and positions further out on sympodial branches.

§Total bolls per plant include those set on both sympodial and monopodial branches.

¶2001 and 2002 data are pooled over mepiquat chloride and glyphosate application method and separated by year to show year and planting date interaction.

#2003 data are pooled over glyphosate application methods.

Table 6. Effect of glyphosate application method on cotton fruiting pattern and total harvestable bolls per plant in Rocky Mount, NC.

	Sympodial positions									
Glyphosate†	First		Second		Outer‡		Monopodial		Total§	
application method	2001 and 2002¶	2003#	2001 and 2002	2003	2001 and 2002	2003	2001 and 2002	2003	2001 and 2002	2003
	bolls plant^{-1}									
None	5.2 a‡‡	5.2	1.5 c	1.5	0.2 b	0.3 c	0.9 b	1.1 b	7.75	7.94
4OT††	4.7 ab	5.5	1.7 bc	1.7	0.2 b	0.3 bc	0.7 b	1.0 b	7.29	8.44
4OT + 8 Prec PD	4.8 ab	4.8	1.7 bc	2.0	0.2 b	0.4 bc	0.9 b	1.17 b	7.68	8.33
4OT + 8 non-Prec PD	4.7 ab	5.2	2.0 ab	1.8	0.4 ab	0.8 a	1.0 ab	1.33 b	7.98	9.08
4OT + 8OT	4.4 b	5.1	2.2 a	2.0	0.5 a	0.7 ab	1.4 a	1.98 a	8.44	9.77
P value	0.0062	0.7093	0.0118	0.4683	0.0177	0.0163	0.0956	0.0832	0.4219	0.1716

†Each glyphosate application was 0.84 kg ae ha^{-1}.

‡Outer includes all bolls set on third, fourth, and further positions on sympodial branches.

§Total bolls per plant include those set on both sympodial and monopodial branches.

¶2001 and 2002 data are pooled over mepiquat chloride and are separate to show year and planting date interaction.

#2003 data are pooled over planting dates.

††4OT, 4-leaf over-the-top; 8 Prec. PD, 8-leaf precision post-direct; 8 non-Prec. PD, 8-leaf non-precision post-direct; 8OT, 8-leaf over-the-top.

‡‡Means followed by the same letter within a column are not statistically different according to Fisher's Protected LSD at a=0.05.

Table 7. Effect of mepiquat chloride on cotton fruiting pattern and total harvestable bolls per plant for 2001-2002 in Rocky Mount, NC. Data are pooled over glyphosate application methods and planting dates.

Plant growth† regulator	Sympodial positions First	Sympodial positions Second	Sympodial positions Outer‡	Monopodial	Total§
	bolls plant^{-1}				
None	5.0	1.7	0.3	0.8	7.8
Mepiquat chloride	4.6	1.9	0.3	1.1	7.9
P value	0.0113	0.3982	0.6369	0.0683	0.9092

†Mepiquat chloride rates and application timings were according to North Carolina Extension recommendations for the modified early bloom method.

‡Outer includes all bolls set on third, fourth, and further positions on sympodial branches.

§Total bolls per plant include those set on both sympodial and monopodial branches.

Table 8. Effect of planting date on percent of harvestable boll distribution by node zone in Rocky Mount, NC.

	Node zones‡								
	0 to 5		6 to 10			11 to 15		16 to 20	
Planting date†	2001 and 2002¶	2003#	2001	2002	2003	2001 and 2002	2003	2001 and 2002	2003
	%§								
Optimal	2.5	1.3	55.2	59.5	58.4	35.1	37.6	5.1	2.7
Late	1.4	1.4	53.2	48.5	39.6	44.3	49.2	3.4	9.9
P value	0.0175	0.9068	0.4736	0.0039	0.0104	0.0001	0.0084	0.0841	0.0407

†Optimal planting dates were 1 May, 30 April, and 7 May in 2001, 2002, and 2003 respectively. Late planting dates were 6, 4, and 2 June in 2001, 2002, and 2003 respectively.

‡Node zones are groups of 5 considering the cotyledonary node as 0.

§Percent distribution by node zone represents the portion of total harvestable bolls set on sympodial branches within each zone.

¶2001 and 2002 data are pooled over mepiquat chloride and glyphosate application method and separated by year to show year and planting date interaction when necessary.

#2003 data are pooled over glyphosate application methods.

Table 9. Effect of glyphosate application method on percent of harvestable boll distribution by node zone in Rocky Mount, NC.

	Node zones‡											
Glyphosate†	0 to 5			6 to 10			11 to 15			16 to 20		
application method	2001¶	2002	2003#	2001	2002	2003	2001	2002	2003	2001	2002	2003
	%§											
None	2.6		1.7	56.5 a‡‡		54.7	37.7 b		41.1	3.2		2.5
4OT††	2.4		1.4	57.3 a		48.8	36.7 b		44	3.6		5.8
4OT + 8 Prec PD	1.8		2.2	57.8 a		45.4	37.0 b		45.4	3.2		7.1
4OT + 8 non-Prec PD	1.8		0.7	52.0 ab		45.2	41.1 ab		42.2	5.1		10
4OT + 8OT	1.2		0.6	46.7 b		51.0	45.9 a		42.3	6.2		6.1
P value	0.2697		0.6791	0.0081		0.3103	0.0493		0.8711	0.1711		0.1962

†Each glyphosate application was 0.84 kg ha^{-1}.

‡Node zones are groups of 5 considering the cotyledonary node as 0.

§Percent distribution by node zone represents the portion of total harvestable bolls set on sympodial branches within each zone.

¶2001 and 2002 data are pooled over mepiquat chloride and are separate to show year and planting date interaction.

#2003 data are pooled over planting dates.

††4OT, 4-leaf over-the-top; 8 Prec. PD, 8-leaf precision post-direct; 8 non-Prec. PD, 8-leaf non-precision post-direct; 8OT, 8-leaf over-the-top.

‡‡Means followed by the same letter within a column are not statistically different according to Fisher's Protected LSD at a=0.05.

Table 10. Effect of mepiquat chloride on percent of harvestable boll distribution by node zone in Rocky Mount, NC. Data are pooled over glyphosate application methods and planting dates.

Plant growth† regulator	Node zones‡						
	0 to 5		6 to 10		11 to 15		16 to 20
	2001	2002	2001	2002	2001	2002	2001 and 2002
	%§						
None	2.2	0.8	45.8	52.1	46.0	40.6	6.2
Mepiquat chloride	4.0	0.7	63.0	55.9	32.2	40.0	2.3
P value	0.0254	0.8019	0.0001	0.3059	0.0001	0.7897	0.0001

†Mepiquat chloride rates and application timings were according to North Carolina Extension recommendations for the modified early bloom method.

‡Node zones are groups of 5 considering the cotyledonary node as 0.

§Percent distribution by node zone represents the portion of total harvestable bolls set on sympodial branches within each zone.

Table 11. Effect of planting date on fiber quality properties in Rocky Mount, NC.

	Staple			Length uniformity			Strength			Short fiber content		
Planting date†	2001‡	2002	2003§	2001	2002	2003	2001	2002	2003	2001	2002	2003
	mm			index			kN m kg^{-1}			%		
Optimal	42.3	43.0	45.0	82.2	82.8	83.7	252	277	286	9.4	11.6	9.6
Late	42.5	42.3	44.0	82.3	84.4	82.6	254	299	276	9.1	8.9	10.2
Significance		**	*		**	**		**	**		**	**

†Optimal planting dates were 1 May, 30 April, and 7 May in 2001, 2002, and 2003 respectively.
Late planting dates were 6, 4, and 2 June in 2001, 2002, and 2003 respectively.

‡2001 and 2002 data are pooled mepiquat chloride and glyphosate application method and separated by year to show year and planting date interaction.

§2003 data are pooled over glyphosate application method.

*,** Significant within a column at the 0.10 and 0.05 probability levels, respectively.

Table 12. Effect of mepiquat chloride on fiber quality properties in Rocky Mount, NC.

	Micronaire					
	2001‡		2002			
Plant growth†	Planting date				2001 and 2002§	
regulator	Optimal	Late	Optimal	Late	Staple	Strength
	micronaire reading				mm	kN m kg^{-1}
None	3.34	3.05	4.47	4.47	27.7	267.7
Mepiquat chloride	3.16	3.36	4.57	4.21	28.0	272.6
P value	0.2073	0.0194	0.4426	0.0024	0.0175	0.0006

†Mepiquat chloride rates and application timings were according to North Carolina Extension recommendations for the modified early bloom method.

‡2001 and 2002 data are pooled over glyphosate application methods and are separate to show year and planting date interaction for micronaire response.

§2001 and 2002 data are pooled over glyphosate application methods and planting date. Mepiquat chloride did not affect staple, strength, or reflectance in 2003.

CHAPTER II

TITLE: Management of Cotton (*Gossypium hirsutum*) Grown Under Overhead Sprinkle and Sub-surface Drip Irrigation in North Carolina

DISCIPLINE: Agronomy & Soils

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ACKNOWLEDGMENTS: Partial funding was provided by the cotton growers of North Carolina through Cotton Incorporated's State Support Program and the North Carolina Peanut Growers Association with the North Carolina Agricultural Foundation.

ABBREVIATIONS: ae, acid equivalent; GR, glyphosate resistant; MC, mepiquat chloride; OSI, overhead sprinkle irrigation; SDI, sub-surface drip irrigation.

ABSTRACT

Irrigation systems, whether used to supplement rain-fed systems or being the main source of water for crop use, consistently show positive results regardless of delivery method compared to non-irrigated cotton (*Gossypium hirsutum* L.). Research comparing overhead sprinkle irrigation (OSI) and sub-surface drip irrigation (SDI) methods in cotton is limited. Providing water by irrigation may affect the need for mepiquat chloride (MC) and alter glyphosate resistant cotton response to glyphosate. The objectives of this study were to compare OSI and SDI in cotton and determine if cotton response to glyphosate and MC was different between irrigation systems. Cotton field trials were conducted in 2001, 2002, and 2003 at the Peanut Belt Research Station in North Carolina. Treatments consisted of OSI and SDI methods factored over glyphosate treatments of 0.84 kg ae ha^{-1} applied at either four-leaf POST or non-precision PD at eight-leaf. Each of these irrigation and glyphosate combinations was treated with or without MC in a standard program. Lint yield results varied between irrigation systems over years, and was not affected by MC. Non-precision applied glyphosate reduced yield in one of three years. Longer fiber was produced under SDI compared to OSI and fiber length also improved with MC. Plant height was consistently controlled and node production was reduced when MC was used. Glyphosate applied non-precision reduced percent open bolls in each irrigation system in one of three years. Increased fruit retention and percent open bolls were observed in cotton treated with MC.

Key Words: Irrigation, cotton, overhead sprinkle, trickle, sub-surface drip, mepiquat chloride, glyphosate, plant mapping.

INTRODUCTION

Successful cotton (*Gossypium hirsutum* L.) production and profitability are achieved through best management practices which maximize yield without receiving fiber quality discounts. Irrigation systems consistently increase cotton yield in arid regions and help to maintain yield stability in rainfed systems (Dloomy, 2000; Droogers et al., 2000). The majority of cotton produced in North Carolina is managed under rain-fed conditions. The 2002 census of agriculture reported that 37.4% of upland cotton grown in the United States was irrigated, which is considerably more than North Carolina at 2.6% (USDA-NASS, 2002). Irrigation could possibly become more common if it were proven that risks could be consistently decreased in regions where cotton production has historically been rain-fed, such as in the eastern United States. Maintaining adequate soil moisture to avoid water deficit is not an available management options for growers in rain-fed systems. Timing and intensity of rainfall events may be irregular and not reliable. Yield and profitability in rain-fed systems are in turn unpredictable, and could become more consistent and less risky if irrigation systems were in place.

Installing irrigation systems, although uncommon in eastern United States cotton production, to supplement rainfall may be a viable option for preventing water stress and avoiding some cotton production risks. Cotton is a perennial plant and produces fruit over a long period of time. Cotton is, therefore, able to compensate for brief periods of early season stress given that a favorable growing season remains (Jones and Snipes, 1999). Once drought is incurred, however, the maximum potential of the crop is no longer attainable.

Various irrigation systems exist, and the precision and efficiency at which they apply water generally determine their required capital investment. Solid-set overhead sprinkler irrigation (OSI) systems are the most common because they are easy to assemble, durable, and do not require elaborate filtering systems due to the large orifice through which they deliver water. Once water leaves an OSI system, its fate may be affected by wind and volume reduced by evaporation before it reaches the soil surface. Applying water directly to the leaves and fruit of a crop increase the possibility of fungal and bacterial diseases and may adversely affect pollination (Guinn, 1998). Water delivered through a sub-surface drip irrigation (SDI) system is placed directly in the rhizosphere of the crop at a slow rate, so the soil surface may never be wet and less soil water is lost through evaporation. Row-middle weed seeds have less chance to germinate before crop canopy closure is reached in SDI in periods of infrequent natural precipitation. Once a SDI system is in place, tillage practices must be altered to avoid damaging the system. The SDI systems deliver water through very small openings called emitters, which are prone to being plugged by sand particles, algae, or other debris if the water supply is not properly filtered. The drip tape used had emitters spaced at 30 cm, thus each emitter serves several plants and movement of water in soil is restricted to locality, reduced or lost flow by one emitter cannot be made up by the system. These problems are not noticed and 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 SDI systems are usually left in place for several years. Soil characteristics affect the performance and movement of water delivered by both OSI and SDI systems. Soils with slow infiltration characteristics may cause puddling and runoff or evaporation from OSI delivered water, while a sandy soil may not retain water requiring more frequent irrigation and reduced distribution of water from SDI applications.

Due to cotton's perennial habits, 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, ensures a profitable yield. However, these inputs may contribute to excessive vegetative growth, causing low efficiency in plant resource utilization.

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 (Cothren, 1994). Mepiquat chloride (MC) (1,1-dimethyl piperidinium chloride) is the most commonly used plant growth regulator in cotton. Plant growth retardants like MC 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 readily suggests that it would be more efficient to invest photoassimilates in fruit production instead of using them for excessive vegetative growth. Cotton producers routinely use MC to control plant height and promote early fruit maturity. Shifts in biomass partitioning from vegetative to reproductive tissue have been documented. However, consistent yield improvements have been a rare response (Boman et al., 1998; Chaney, 1998). Plant growth regulator performance is generally highly variable, which is caused mostly by unpredictable environmental conditions (Lege et al., 1996). Mepiquat chloride has increased leaf density and chlorophyll content per unit leaf area, potentially increasing the photosynthetic capacity of cotton leaves (Fernandez et al., 1991; Gausman et al., 1980). Wells (1997) and Oosterhuis et al. (1998) found that MC improved leaf photosynthesis and dry matter partitioning from vegetative to reproductive tissue in cotton. However, no differences in canopy photosynthesis were found with MC treatments when compared to non-treated cotton (Wells and Edmisten, 1998).

Roundup Ready® or glyphosate-resistant (GR) cotton was commercially released in 1997 (Ellis and Griffin, 2002; Faircloth et al., 2001). This technology has been overwhelming accepted by producers, with more than two-thirds of the 2003 United States cotton crop being planted with GR seed (Ihrig et al., 2003). Over 95% of the 2003 North Carolina cotton crop was GR (USDA-AMS, 2003). Glyphosate [*N*-(phosphonomethyl)-glycine], non-selectively controls a broad spectrum of economically deliterious grass and broadleaf weeds (Wilcut et al., 1996). Weed management in GR cotton requires less herbicide and fewer applications to produce the same yield and net economic return compared with herbicide systems used for non-transgenic cottons (Culpepper and York, 1998).

Since its introduction, GR cotton when treated with glyphosate, has been associated with boll abscission, fruit malformation, and yield fluctuations compared to non-transgenic cotton cultivars. These problems have been observed by producers and their advisors (Jones and Snipes, 1999). Numerous field studies have been conducted, including on and off-label glyphosate applications to GR cotton, to determine injurious rates and timings. Many concur that pollination in GR cotton is negatively affected. Poor pollination decreases seed production causing 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 compensation for fruit loss and underdeveloped bolls (Jones and Snipes, 1999; McCloskey and Moser, 2002).

The apparent problem with the current Roundup Ready® technology is that it does not provide sufficient gene expression and subsequent glyphosate tolerance in some flower tissues to prevent toxicity by common glyphosate rates used in modern cotton production practices (Pline et al., 2002). Over-the-top or non-precision PD glyphosate applications after the four-leaf stage hinder healthy pollen development and pollen deposition causing pollination problems, which consequently may cause yield loss (May et al., 2004; Pline et al., 2002). A controlled environment study using ^{14}C-glyphosate proved that as glyphosate accumulation in cotton fruiting structures increased, boll abscission increased (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 CP4-EPSPS (Pline et al., 2002). These findings reinforced the label restrictions for glyphosate applications to GR cotton (Anonymous, 1999). Ensuring crop safety cannot be guaranteed unless directed applications after the four-leaf stage avoid spray contact to cotton leaves (Ihrig et al., 2003).

Use of glyphosate in GR cotton is limited to two broadcast applications from emergence through the four-leaf stage. The second broadcast application is allowed after 10 days and at least two nodes of growth have occurred since the first application. Precision post-directed or hooded glyphosate applications are allowed after 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 of glyphosate come in contact with cotton foliage in order to get ample coverage of weeds. If there is damage to the first initiated fruit, new fruit will be initiated, and their contribution to yield is dependent on the conditions of the environment (Jones and Snipes, 1999). Prior research is in broad accordance that glyphosate contact to

GR cotton prior to the four-leaf stage is safe, however damage is more likely when applications contacting cotton tissue are made after that stage (Ferreira et al., 1998; Kalaher and Coble, 1998; Vargas et al., 1998; Jones and Snipes, 1999; and Pline-Srnic, et al., 2004).

Cost of irrigation equipment, installation and maintenance, and the availability of a reliable water source of acceptable water quality are the main concerns that should be addressed when considering irrigation. This study does not address these concerns, and only compares the effectiveness of OSI and SDI systems within existing cultural practices to produce a consistent quality crop. Our primary objective was to determine the differences between cotton crops produced under SDI and OSI systems supplementing natural precipitation in North Carolina. Secondary objectives were to determine if the compensatory ability of cotton to overcome stress from non-precision applied glyphosate was better in either SDI or OSI systems, and to evaluate the current recommendations made by North Carolina Cotton Extension for MC use in these two irrigation systems.

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 (fine-loamy, siliceous, thermic, Typic Paleudults) with pH 6.1 and 2.3% organic matter. Cotton cultivar 'SG 501BR' was planted 10, 8, and 9 May in 2001, 2002, and 2003, respectively. The experimental treatment design was a strip-split-plot with a three-factor factorial arrangement (Gomez and Gomez, 1984) consisting of two irrigation treatments, two glyphosate treatments, and two MC treatments. Irrigation was stripped as the vertical factor, MC was the horizontal sub-factor, and glyphosate was randomly assigned to plots within MC blocks. Treatments were replicated four times. Individual treatment plot size was four rows spaced 91- cm apart by 9 m. Glyphosate was applied at 0.84 kg ha^{-1} as either a four-leaf POST or non-precision PD at the eight-leaf cotton growth stage. Plant growth was monitored and MC was applied as needed according to the modified early bloom method (Edmisten, 2004a). Glyphosate and MC applications were made with a CO_2-pressurized backpack sprayer delivering 140 L ha^{-1} aqueous solution. Cotton in 2001 required one application of MC at 24.5 g ai ha^{-1} on 28 June. Two applications were required in 2002 each at 24.5 g ai ha^{-1} on 24 June and 10 July. The 2003 crop received 18.5, 24.5, and 30.6 g ai ha^{-1} MC on 30 June, 7 July, and 21 July, respectively. Broadcast glyphosate treatments were made to four-leaf cotton on 6, 3, and 16 June in 2001, 2002, and 2003, respectively. Non-precision PD glyphosate applications were made on 21, 24, and 30 June during these respective years. Up to 25% of plants were lodged as early as the eight- to nine-leaf stage in 2001. Plants were considered lodged when the mainstem was bent past 90 degrees parallel to the ground surface. Lodged plants were susceptible to near full coverage of glyphosate during the non-precision PD at eight-leaf. Management decisions and cultural inputs, except for MC and glyphosate, including planting, fertilizer, weed control, and defoliation, were made according to North Carolina Extension recommendations (Crozier, 2004; Edmisten, 2004b; Koenning, 2004; Spears, 2004).

In early April 2001, soil was disked twice and field cultivated to prepare the field for installation of SDI lines. Drip irrigation lines were 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 an annual rotation with peanut (*Arachis hypogaea* L.) for the 3 years of the study. Beds were established each year in OSI with a disk bedder equipped with in-row ripper shanks (ripping depth of 25 cm). Beds in the SDI area 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 the SDI system. Water from the reservoir tank was supplied with a centrifugal pump (Challenger 1.5 kW 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 particles from water preventing SDI emitter clogging. Filtered water flowed through the main manifold to drip lines stripped through respective plots. Control of water application was by an electric water control console and electric solenoid valves (Orbit Electric Water Control, Model 57540, Orbit Irrigation Products Inc., Bountiful, UT). Flow meters (ABB Flow Meters, 16 mm by 19 mm, Model 98604940, Senniger Irrigation, Inc., Orlando, FL) were used to measure flow rates. Pressure regulators followed the flow meters reduced pressure to 69 kPa. Drip tape model TSX 515-30-340 (T-Tape, T-Systems Inc., Queensland, Australia) is 16 mm in diameter with emitters spaced at 30 cm discharging 340 L per hr per 100m was installed 25 cm below the ground surface. The SDI system was designed to deliver 102 L m^{-1}, and supply 5 mm water d^{-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 strip of OSI plots. A total of 18 mm of water for the OSI treatment was applied over 1 hour from the same water source used for SDI. Cotton was irrigated with both systems to prevent water stress. OSI was supplied as sequential applications of 18 mm on consecutive days. Irrigation was applied during the morning to avoid wind and maximize even water distribution to plots. A total of 156, 155, and 137 mm water was provided by OSI in 2001, 2002, and 2003 respectively. In these respective years, 153, 154, and 143 mm water was applied through SDI during the season between 1 July and 15 September. SDI was applied each day from Monday through Friday at a rate of 2.5 to 5 mm d^{-1}. The SDI was reinitiated 4 d after rainfall in excess of 18 mm, and continued when rainfall was less than 18 mm.

Six plants per plot were plant-mapped prior to harvest on 12, 27, and 15 September in 2001, 2002, and 2003, respectively. Data were recorded for harvestable bolls and missing positions on sympodial branches as well as harvestable bolls retained on monopodial branches (Mauney and Stewart, 1986). Mapping data were analyzed to determine total bolls $plant^{-1}$, monopodial bolls $plant^{-1}$, and boll distribution by sympodial position and percent of total bolls retained. The middle two rows of plots were machine harvested, and seedcotton sub-samples were taken from each plot for high volume instrument analysis. Difference in maturity between irrigation systems caused SDI harvest to be 5 October and OSI was harvested 26 October in 2001. In 2002 and 2003, plots were harvested 17 and 24 October, respectively.

Data were subjected to analysis of variance using the general linear model procedure in the Statistical Analysis System (SAS Institute Inc., version 8e, release 8.2,Cary, NC). In statistical analyses, treatment effect F tests were carried out for all main factors and main factor interactions with their specific error source. Years were treated as a random source of replication and if the year term was not significant ($p > .2500$), it was removed from the model and the term was tested with the overall error term. Year by main effect interactions were ignored when the main effect F value was 3 times greater than the respective interaction F value, and the interaction did not crossover between years (Gomez and Gomez, 1984). Main effect means were separated using Fisher's Protected LSD test at $\alpha=0.05$ or 0.10.

RESULTS AND DISCUSSION

Yield, lint turnout, and fiber quality. Interactions between MC and irrigation method or glyphosate treatment were not significant. Year by irrigation method and year by glyphosate treatment interactions were significant and are reported by year. Treatments including MC did not yield differently from those without MC, and this response was consistent across irrigation method and glyphosate treatments with yield averages of 1420 to 1450 kg ha^{-1} lint (p = 0.2980, data not shown). Boman et al. (1998) reported no yield difference between cotton treated with MC compared to non-treated cotton when boll loads were heavy from a reduced stress environment, such as in irrigated production systems. A 240 kg ha^{-1} lint yield increase was noted for SDI compared with yield under OSI in 2001 (p = 0.0007) (Table 1). However, this result was reversed in 2003 (p = 0.0663) by 100 kg ha^{-1}. Irrigation systems produced similar yields in 2002 (p = 0.1885).

Non-precision glyphosate application caused a 160 kg ha^{-1} yield loss in 2002 (p = 0.0087). However, this treatment did not affect yield in either 2001 (p = 0.6889) or 2003 (p = 0.4265). It is common that damage caused by glyphosate applied before squaring can be compensated for when environmental conditions and resource availability are favorable (Jones and Snipes, 1999). Cotton yield potential was higher in 2002 than in 2001 or 2003. These results suggest that cotton treated with non-precision PD glyphosate in 2002 was not able to compensate for boll loss and attain the full yield potential for the season.

Main effect interactions with ginout were not significant and ginout was not affected by MC or irrigation method. A common response from MC is increased seed size (Biles and Cothren, 2001; Cothren and Jost, 1998), which would reduce lint turnout, but was not evident in this study.

Non-precision PD glyphosate application caused an increase in lint turnout from 41 to 42% (*p* = 0.0015, data not shown). This unexpected response may be due to decreased seed size in bolls partially damaged from glyphosate but not aborted, and it is unlikely a cause of improved lint production per seed. The year by MC interaction was significant for micronaire. Micronaire reading was reduced from 4.5 to 4.4 by MC in 2001 (*p* = 0.0485, and not affected in 2002 or 2003 (data not shown). Positive affects of MC on micronaire have been found for both reducing high readings and increasing low readings depending on environment when the growing season is short (Nuti et al., 2004). In high-resource conditions, proper use of MC will cause a compact fruit load with more uniform fruit maturity, which allows earlier defoliation and better management of micronaire. Neither irrigation nor glyphosate affected micronaire in this study. There were no significant main effect or main effect by year interactions for fiber length or fiber strength. Fiber length was not affected by glyphosate, but was improved from 26.94 to 27.25 mm (*p* = 0.0102) by SDI compared to OSI and was also improved by 0.23 mm (*p* = 0.0487) when MC was applied (data not shown). In this study, treatments without MC and under OSI irrigation would have received a market price discount based on the Commodity Credit Corporation loan schedule for short fiber since the average fiber length measurement was less than 26.98 mm (Hake et al., 1996). Neither irrigation method nor MC affected fiber strength, however, fiber strength was improved from 276 to 282 kN m kg^{-1} when glyphosate was applied non-precision PD compared to 4 POST (*p* = 0.0218, data not shown). Other fiber quality parameters were tested including fiber length uniformity, elongation, reflectance, brightness, and short fiber content and were not affected by irrigation, MC, or glyphosate treatment (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 had heavy boll-loads. However none of the plants were up-rooted. Plants were considered lodged when the main-stem was bent past parallel to the ground surface, and visual rating of percent lodged plants was recorded 9 September 2001. Glyphosate had no effect on lodging, and there were no significant interactions with irrigation or MC. Plants under OSI were lodged 25% and SDI only had 5% lodging ($p = 0.0004$). In this field experiment, plants treated with MC were 21% lodged compared to 9% without MC ($p = 0.0163$). These results are contrary to popular thoughts that short compact plants, typical of MC use, are less prone to lodging. It was noted that the lodged plants had a heavy load of bolls, which appeared to be more than average for the size of the plant. After bolls opened, all plants were erect enough to machine harvest, thus lodged plants did not affect yield. Lodging was not noticed in either 2002 or 2003.

Plant Mapping. Plants were mapped after all yield-contributing bolls were set and when about half of the fruit had reached maturity in order to quantify crop development distinctions between treatments. Two data parameters included during plant mapping were the first sympodial branch and the first sympodial branch that retained a boll. Irrigation should allow plants to avoid water stress and prevent abortion of early fruit. The lower the fruit-load is set, the greater the possibility for earliness. Early crop development is a goal for most growers in the northern belt of cotton production in the United States. Boll development is dependent upon the time accumulated from flower pollination and fertilization to boll opening, which is a temperature-dependent phase directly related to the amount of heat units accumulated from the time of fertilization to boll maturity (Gipson, 1986). In combination with avoiding water stress, MC should further promote a lower set fruit-load and maintain plants with fewer aborted positions. In this study, there were no significant main effect or main effect by year interactions for the first sympodial branch, and none of the treatments affected where the first sympodial branch occured on plants. The sympodial branch on which the first boll was set had a significant year by irrigation method interaction and was higher for cotton under OSI than SDI in 2001 ($p = 0.0017$) and 2003 ($p = 0.0323$) by 0.6 and 0.4 branches, respectively. This parameter was not affected by irrigation in 2002 (data not shown). Glyphosate and MC, both of which could affect the sympodial branch where the first fruit was retained, did not do so in these tests (data not shown).

A significant interaction of MC and years was observed for plant height, nodes per plant, and height-to-node ratio. Mepiquat chloride did not interact significantly with glyphosate or irrigation method. Plants treated with MC were shorter by 25 and 36 cm in 2001 ($p = 0.0001$) and 2003 ($p = 0.0001$) respectively (Table 2). Total nodes per plant paralleled plant height when treated with MC, resulting in 1.4 and 2.2 fewer nodes produced in 2001 ($p = 0.0001$) and 2003 ($p = 0.0001$). The combined effect of shorter plants and fewer nodes resulted in a shorter height-to-node ratio in 2001 ($p = 0.0001$) and 2003 ($p = 0.0001$) by 1.4 and 2.2 cm, respectively. Plants treated with MC in 2002 exhibited similar responses as 2001 and 2003 with numeric trends of shorter plants, fewer total nodes, and shorter height-to-node ratios compared to those without MC. Plants in SDI plots were taller by 23 cm ($p = 0.0024$) and had 0.8 more nodes ($p = 0.0034$) than plants under OSI irrigation. Height-to-node ratio was not affected by irrigation (data not shown).

The basic purpose of plant mapping is to determine where bolls are retained on the plant, both their position on sympodial branches and how high up the mainstem the sympodial branches occur. Bolls set on the first and second positions are generally larger, because they are set earlier and are closer to the mainstem making them preferential metabolic sinks (Kerby and Ruppenicker, 1992; Parvin and Atkins, 1997). Also, bolls on the nodes in the lower part of the canopy are usually larger than the ones above them for the same reasons. In ^{14}C studies conducted to quantify distribution of photosynthate resources, it was found that the bolls immediately adjacent to the mainstem received proportionately higher ^{14}C concentration from ^{14}C-labeled CO_2 than bolls on distal positions on the same sympodial reproductive node (Ashley, 1972; Wullschleger and Oosterhuis, 1990). This occurrence is due to the morphological order in which cotton initiates flowers from the bottom of the plant to the top and also out to successive positions on the sympodial nodes. The first position bolls are a stronger sink for photoassimilate accumulation (Kerby and Ruppenicker, 1992) than those at more proximal positions on any given mainstem position. No significant main effect or main effect by year interactions existed for first position sympodial bolls. Glyphosate and irrigation method did not affect first position bolls. Plants not treated with MC had an average of 0.6 more bolls on the first sympodial position than MC-treated plants ($p = 0.0001$; Table 3). A significant interaction was observed between MC over years for second and outer position bolls as well as for total bolls per plant. Plants treated with MC had 0.9 more bolls set on the second position in 2003 ($p = 0.0023$), while MC did not affect second position bolls in 2001 or 2002. Although irrigation did not affect first position boll counts, plants under SDI had an average of 0.4 more second position bolls than those under OSI ($p = 0.0020$; data not shown). Outer sympodial positions are set on positions further out than the second including third and fourth sympodial positions. In 2003, there were 0.6 more bolls ($p = 0.0480$) set on outer positions on plants not treated with MC, however, in 2001 and 2002 no MC effect was detected. Plants produced 2.3 more bolls when

MC was not applied in 2003 (*p* = 0.0012). Since MC did not affect yield but did cause plants to produce fewer bolls in 2003, these data suggest that non-treated cotton required more yield contributing bolls to attain similar yield that year. Plants with more bolls may have reached maturity later, since they were probably set over a longer period of time. Regardless of MC use, cotton under SDI had 0.9 more harvestable bolls per plant than those under OSI (*p* = 0.0011; data not shown).

Cotton plants have the ability to fill space in row middles and especially between plants when a poor plant stand is established by increasing resource allocation to monopodial branches, much like was observed with outer sympodial positions. There were no main effect or main effect by year interactions for bolls set on monopodial branches. An average of 1.1 to 1.3 bolls per plant were located on monopodial branches in this study. Plants treated with MC had 0.2 more monopodial bolls than plants not treated with MC (*p* = 0.0346; data not shown). Irrigation and glyphosate did not affect monopodial boll production.

Uniform crop maturity is a goal for producers because it simplifies harvest preparation by improving harvest-aid performance. The northeastern region of the cotton belt is prone to periods of cool weather during early fall when harvest-aids are applied. Cotton metabolism is driven by the accumulation of heat units, thus delayed crop development decreases the effectiveness of plant hormone based harvest aid tools. In this study, crop maturity data are based on the percent of first position sympodial bolls that were open during plant mapping. A significant three-way interaction was observed between glyphosate, irrigation, and years for boll maturity. In 2002, cotton under OSI that was treated with non-precision PD glyphosate had 11% fewer open first-position sympodial bolls than cotton sprayed with glyphosate POST (*p* = 0.0009; Table 4). Glyphosate did not affect maturity in OSI cotton in either 2001 or 2003. Cotton under SDI was 24% less mature (p = 0.0031) when sprayed with non-precision PD glyphosate in 2001 compared to glyphosate POST. However, this was not observed in either 2002 or 2003. Plants treated with MC had 53% open first position sympodial bolls, while plants without MC were only 46% mature at the time of plant mapping when pooled over years (p = 0.0056; data not shown).

Since cotton initiates fruit over a long period of time and is exposed to variable sources of stress, it does not retain every fruit set. Cotton will abort small fruit when introduced to stress, postponing reproductive activity for more favorable environments. Each fruit set and subsequently aborted is a waste of resources, which could have contributed to overall yield in a purely non-stressed environment. Irrigation supplies moisture necessary to alleviate drought stress which causes plant stress, however, water supplied to cotton after drought stress may also cause fruit abortion if plants revert to vegetative growth. Data for total aborted sites and percent fruit retention were only recorded in 2002 and 2003. There were no significant main effect or main effect by year interactions for percent open first-position sympodial bolls. Cotton irrigated with SDI aborted an average of 1.3 more fruit than did OSI in this test (p = 0.0316; data not shown). Use of MC caused 4.1 fewer aborted sites per plant than plants without MC and increased fruit retention from 39 to 44% (p = 0.0001; data not shown). Glyphosate did not affect any plant mapping parameters, except for the interaction of irrigation method and years on maturity.

Some irregular results were found with this study regarding anticipated results of MC use. Through regulation of vegetative growth, MC can generally prepare plants to be more productive under stressful conditions, which was proven by its higher fruit retention and fewer boll abortions. Such results show that the positive results from MC treatments are highly variable and closely related to the environment in which the crop is grown, as previously indicated by Lege et al. (1996). In this study, considering the delivery of equal seasonal amounts of water between irrigation systems, SDI seemed to be a better supply of water since plants exhibited taller growth, produced more bolls, and had a high yield difference in one of 3 years. There were no yield interactions between irrigation, MC, and glyphosate suggesting that both SDI and OSI delivered sufficient water to avoid the stress of non-precision PD glyphosate application. Both irrigation systems also allow cotton not managed with MC to have equal yield, although the oversized plants may be undesirable considering harvest-aid activity, facility of machine harvest, and the possibility of late-season conditions promoting boll rot (*Phytophthora* sp.). Studies comparing these irrigation systems against proven rain-fed production practices need to be evaluated on an economic basis to determine which system is consistently more profitable for cotton producers in the northern cotton belt of the United States.

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Table 1. Interaction of irrigation method and glyphosate application timing and method by year for lint yields in Lewiston-Woodville, NC in 2001 to 2003.[v]

	Lint yield			
	Irrigation method		Glyphosate[w]	
Year	OSI	SDI	4 POST	8 PD
	kg ha-^{1}			
2001	1360	1600[x]	1470	1490
2002	1820	1900	1940[y]	1780
2003	1010[z]	910	940	980

[v] Abbreviations: OSI, overhead sprinkler irrigation; SDI, sub-surface drip irrigation; 4 POST, four-leaf post emergence over-the-top; 8 PD, eight-leaf non-precision post-directed.

[w] Glyphosate applications made at 0.84 kg ae ha^{-1}.

[x] This value is significantly greater than OSI in 2001 according to Fisher's Protected LSD at α=0.05.

[y] This value is significantly greater than 8 PD in 2002 according to Fisher's Protected LSD at α=0.05.

[z] This value is significantly greater than SDI in 2003 according to Fisher's Protected LSD at α=0.10.

Table 2. Interaction of mepiquat chloride and years on plant height, height to node ratio, and total nodes in 2001 to 2003 in Lewiston-Woodville, NC.[y]

	Plant height		Height to node ratio		Nodes	
Year	MC	None	MC	None	MC	None
	cm				no. plant^{-1}	
2001	65	90[z]	5.2	6.4[z]	12.6	14.0[z]
2002	92	100	5.7	6.0	16.2	16.7
2003	76	112[z]	4.9	6.4[z]	15.4	17.6[z]

[y] Mepiquat chloride was applied as recommended by the modified early bloom method as described in 2004 Cotton Information (Edmisten, 2004). Plant height and node count data were recorded 12, 27, and 15 September in 2001, 2002, and 2003 respectively. These data are the average of six plants per plot.

[z] This value is significantly greater than MC in the same year according to Fisher's Protected LSD at $\alpha=0.05$.

Table 3. Interaction of mepiquat chloride and years on first, second, and outer position sympodial bolls and total mature bolls per plant in 2001 to 2003 in Lewiston-Woodville, NC.[u]

	Sympodial positions							
	First		Second		Outer[v]		Total bolls[w]	
Year	MC	None	MC	None	MC	None	MC	None
	no. plant^{-1}							
2001	4.8	5.3[y]	1.8	1.8	0.3	0.1	6.8	7.1
2002	4.7	5.3[y]	2.1[z]	1.8	0.3	0.4	7.1	7.5
2003	5.3	6.0[y]	2.3	3.2[y]	0.6	1.2[y]	8.1	10.4[y]

[u] Plant mapping was conducted on 12, 27, and 15 September in 2001, 2002, and 2003 respectively. These data are the average of six plants per plot.

[v] Outer includes all bolls set on third, fourth, and positions further out on sympodial branches.

[w] Total bolls includes all bolls retained on sympodial branches.

[x] Mepiquat chloride (MC) was applied as recommended by the modified early bloom method as described in 2004 Cotton Information (Edmisten, 2004).

[y] This value is significantly greater than MC in the same year according to Fisher's Protected LSD at $\alpha=0.05$.

[z] This value is significantly greater than no MC in the same year according to Fisher's Protected LSD at $\alpha=0.05$.

Table 4. Three-way interaction of irrigation method, glyphosate, and years on cotton maturity in 2001 to 2003 in Lewiston-Woodville, NC.[v,w]

	Overhead Sprinkler[x]		Sub-surface drip	
Year	4 POST	8 PD	4 POST	8 PD
	percent open first-position bolls			
2001	36	36	50[z]	26
2002	89[y]	78	80	70
2003	39	39	20	31

[v] Maturity was recorded as the percent 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.

[w] Glyphosate applications made at 0.84 kg ae ha^{-1}.

[x] Abbreviations: 4 POST, 4-leaf post emergence over-the-top; 8 PD, 8-leaf non-precision post-directed.

[y] This value is significantly greater than 8 PD in 2002 according to Fisher's Protected LSD at α=0.05.

[z] This value is significantly greater than 8 PD in 2001 according to Fisher's Protected LSD at α=0.05.

CHAPTER III

Comparison of Weed Control and Net Economic Return between Conventional and Glyphosate Resistant Cotton Weed Management Systems

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Funded by Cotton Incorporated® and the North Carolina Cotton Producers Association.

Abbreviations: acid equivalent (ae); active ingredient (ai) glyphosate-resistant (GR), over-the-top (OT), pre-plant incorporated (PPI); pre-emergence (PRE); post-emergence (POST); post-emergence directed (PD).

Nomenclature: Fluometuron, 1,1-dimethyl-3-(a,a,a-trifluoro-m-tolyl) urea; glyphosate, N-(phosphonomethyl) glycine; metolachlor, *S*-metolachlor; MSMA, monosodium acid methanearsonate; pendimethalin, (N-(1-ethylpropyl)-3, 4-dimethyl-2,6-dinitrobenzenamine); prometryn, 2,4-bis(isopropylamino)-6-(methylthio)s-triazine; pyrithiobac, sodium 2-chloro-6-[(4,6-dimethoxypyrimidin-2-yl)thio] benzoate; broadleaf signalgrass; *Brachiaria platyphylla* (Griseb.) Nash # BRAPP; carpetweed, *Mollugo verticillata* (L.) # MOLVE; common cocklebur, *Xanthium strumarium* (L.); common lambsquarters, *Chenopodium album* (L.) # CHEAL; common ragweed, *Ambrosia artemisiifolia* (L.); eclipta, *Eclipta prostrate* (L.) # ECLAL; entireleaf morningglory, *Ipomoea hederacea* (L.) # IPOHG; goosegrass, *Eleusine indica* (L,) Gaertn. # ELEIN; large crabgrass, *Digitaria sanguinalis* (L.) Scop. # DIGSA; pink

purslane, *Portulaca pilosa* # PORPI; pitted morningglory, *Ipomoea lacunosa* (L.) # IPOLA; slender amaranth, *Amaranthus palmeri* (S.Wats.) # AMAPA; smooth pigweed, *Amaranthus hybridis* (L.) # AMACH; slender pigweed, *Amaranthus viridis* (L.) # AMAVI; sicklepod, *Senna obtusifolia* (L.) # CASOB; tall morningglory, *Ipomoea purpurea* (L.) Roth # PHBPU.

Comparison of Weed Control and Net Economic Return between Conventional and Glyphosate Resistant Cotton Weed Management Systems

ABSTRACT

Glyphosate resistant cotton (*Gossypium hirsutum* L.) was used in four trials during 2001 and 2002 in North Carolina. Glyphosate, conventional, and combinations of glyphosate with conventional herbicide programs were evaluated for weed control, yield, lint quality, and net returns. Cotton injury of 9% was caused by pyrithiobac PRE in two of four trials. Pyrithiobac and MSMA POST caused a maximum of 14% injury. A maximum of 33% biomass reduction was caused by weed interference with cotton in low-input programs. Control of pigweed and grass species was adequate in programs consisting of conventional PRE followed by POST herbicides, glyphosate with conventional PRE, and glyphosate applied at one- and four-leaf. Morningglory sp. control was best when pyrithiobac was included in PRE and POST or when glyphosate was applied sequentially. Herbicide programs with PRE and POST conventional compounds had up to 1.1% less lint turnout than programs with one or fewer conventional applications. In 3 of 4 trials, programs consisting of only a conventional PRE or one glyphosate application produced less cotton, which was reflected by net return in Goldsboro. At Rocky Mount, broadleaf weed pressure was light, and programs with pendimethalin and fluometuron PRE returned more profit when not followed by pyrithiobac POST. Higher costs of conventional programs offset the profit margin compared to those achieved in glyphosate systems. Herbicide programs had no affect on lint quality.

INTRODUCTION

Roundup Ready® or GR cotton (*Gossypium hirsutum* L.) was commercially released in 1997 (Faircloth, et al., 2001; Pline, et al., 2001). This technology has been overwhelming accepted by producers leading to more than two-thirds of the 2003 United States cotton crop and more than 95% of the 2003 North Carolina crop being planted with Roundup Ready® seed (Ihrig et al., 2003) (USDA-AMS, 2003). Since very few conventional cultivars are still planted, the use of herbicides other than glyphosate in cotton production has declined and has changed weed management for most growers. According to USDA-NASS, glyphosate use increased from 20% of North Carolina cotton hectarage in 1997 to 80% in 2001, while pyrithiobac, MSMA, and fluometuron each declined during that period from 28 to 13%, 50 to 30%, and 80 to 40%, respectively. Pendimethalin use remained constant at nearly 40% during this period. Glyphosate is a member of the glycine herbicide family and non-selectively controls a broad-spectrum of economically significant grass and broadleaf weed pests (Ellis and Griffin, 2002). The GR weed management system is an effective alternative to conventional methods, requiring less herbicide and fewer applications to produce the same yield and net economic return (Culpepper and York, 1998).

Understanding of incomplete reproductive tolerance to glyphosate in GR cotton has improved in recent years, providing solutions to improve management, giving growers more confidence with the GR system (Pline et al., 2002; Viator et al., 2003). The label (Anonymous, 1999) for GR cotton allows 2 OT applications of glyphosate prior to the four-leaf stage. Sequential OT applications must be at least 10 days apart and have 2 or more nodes of incremental growth. In addition to OT applications, precision PD or hooded applications are recommended after the four-leaf stage, since glyphosate contact to green tissue may result in yield damage. Choosing the GR system does not rule out using conventional herbicides at any time in the growing season to improve or broaden the spectrum of weed control. Using conventional chemistry will strengthen a glyphosate system and can improve control of target species which glyphosate may be less effective in controlling. Soil applied PPI or PRE herbicides may be useful when only one OT application of glyphosate can be made before the four-leaf stage due to weather conditions, equipment breakdown, or other reasons not allowing a grower to cover all of their cotton fields in a timely manner. In efforts to prevent glyphosate resistance in existing weed populations, the North Carolina Extension service recommends using a conventional herbicide with the glyphosate system either as a PRE or PD application. Further benefit from conventional herbicides may also be realized by providing residual control not offered by standard glyphosate systems.

Conventional weed control usually consists of soil-applied herbicides, a limited number of compounds applied OT, and PD compounds which usually provide residual control. Good early cotton growth is essential for reaching a height differential to make safe PD applications (Shankle et al., 1996). If soil-applied herbicides do not provide adequate control, early-season weed competition will result before the height differential is reached, therefore most growers favor using OT herbicides on small cotton (Culpepper and York, 1999; Jennings et al., 1999). Pyrithiobac and MSMA are two of the few conventional herbicides labeled for OT applications in cotton, however their potential for causing chlorosis and stunted growth and can affect yield (Baldwin, et al., 1997; Jennings et al., 1999; Jordan et al., 1993; Keeling et al., 1993; Shankle et al., 1996). In contrast, glyphosate does not have the same potential for stunting early foliar cotton growth like pyrithiobac or MSMA, which may promote earlier canopy closure, reducing weed germination and competition in interrow spaces. Pyrithiobac controls many broadleaf weeds, however it is not effective on some economically significant weeds like sicklepod and tall morningglory and usually requires other soil-applied and PD herbicides for sufficient control (Culpepper and York, 1999; Kendig, 1997).

Glyphosate-resistant technology is associated with an upfront cost for technology fees, which may seem less attractive than conventional systems. However, herbicides used in conventional systems cost more than glyphosate used to achieve similar control. In an attempt to reduce input costs, many growers have taken advantage of the precision offered by vacuum planters and have experimented with decreased seeding rates. This practice has encouraged seed retailers to convert pricing of technology fees from cost per kg to cost per ha planted.

Previous research comparing the cost effectiveness between conventional and glyphosate programs has concluded that one application of glyphosate returned less than conventional programs, and glyphosate applied 3 to 4 weeks after planting was similar in weed control, cotton yield, and net returns to conventional programs (Culpepper and York, 1998). Three glyphosate applications were not more effective than two, and soil-applied herbicides did not enhance systems with two glyphosate applications or glyphosate followed by cyanazine plus MSMA (Culpepper and York, 1998).

The objectives of this study are to compare profit potential between variable weed management systems considering technology fees, herbicide costs and rates, application cost, and the resulting cotton yield and quality. Conclusions will include comparisons of weed control between glyphosate and conventional herbicide programs, and programs including combinations of glyphosate and conventional herbicides in variable weed pressure situations.

MATERIALS AND METHODS

Field trials were conducted in Clayton and in Goldsboro, North Carolina in 2001 and in Clayton and in Rocky Mount, North Carolina in 2002. Trials in Clayton and Rocky Mount were planted on conventional beds and the trial in Goldsboro was planted flat. Soil type in Clayton was a Norfolk loamy sand (Fine-loamy, kaolinitic, thermic Typic Kandiudults), in Goldsboro was a Wickham loamy sand (Fine-loamy, mixed, semiactive, thermic Typic Hapludults), and in Rocky Mount was an Aycock very fine sandy loam (Fine-silty, siliceous, subactive, thermic Typic Paleudults). Row spacing in Rocky Mount was 91 cm and the other trials were spaced at 97 cm. All trials were in a randomized complete block design with 16 treatments and had four treatment replications. Plots were four row by 9.1 m long. Cotton cultivar ‘SG 125 BG/GR’ was planted 3 May in Clayton and 15 May in Goldsboro in 2001, ‘SG 215 BG/GR’ was planted 2 May in Clayton, and ‘ST 4892 BG/GR’ was planted 10 May in Rocky Mount in 2002. Management decisions and inputs other than weed control were made according to North Carolina Extension recommendations (Crozier, 2004; Edmisten, 2004a; Edmisten, 2004b; Koenning, 2004; Spears, 2004).

Treatments consisted of one untreated and 15 herbicide programs with either conventional PRE herbicides followed by conventional POST herbicides, conventional PRE herbicides followed by glyphosate, and glyphosate applied POST at one- and four-leaf cotton growth stages. The eight conventional herbicide programs consisted of pendimethalin and fluometuron or pendimethalin, fluometuron, and pyrithiobac PRE each followed by either

MSMA, pyrithiobac, pyrithiobac and MSMA, or no POST. Four four-leaf POST glyphosate programs were preceded by a conventional PRE of pendimethalin, pendimethalin and fluometuron at half (0.5X) and full (1X) rates, or no PRE. The three remaining standard glyphosate programs were applied POST at one- and four-leaf stages, with either metolachlor, pyrithiobac, or no tank-mixture at four-leaf. All programs were followed by a PD tank-mixture at lay-by of prometryn and MSMA. Herbicides were applied at the following rates: pendimethalin, 1.1 kg ai ha^{-1}; fluometuron, 0.7 (0.5X) or 1.4 (1X) kg ai ha^{-1}; pyrithiobac, 35.8 g ai ha^{-1} PRE, 71.5 g ai ha^{-1} POST, and 35.8 g ai ha^{-1} POST with glyphosate; glyphosate, 0.56 kg ae ha^{-1} one-leaf POST, 1.12 kg ae ha^{-1} four-leaf POST when preceded by a PRE or no glyphosate, and 0.84 kg ae ha^{-1} when preceded by glyphosate; metolachlor, 1.4 kg ai ha^{-1}, MSMA, 0.93 kg ai ha^{-1} POST and 2.2 kg ai ha^{-1} PD; and prometryn, 1.12 kg ai ha^{-1}. All conventional POST and PD applications included 0.25% by volume non-ionic surfactant.

All herbicide applications were made with a CO_2-pressurized backpack sprayer delivering 140 L ha^{-1} aqueous solution. Pre-emergence herbicides were applied directly after planting. Early and late POST applications were made when cotton was at one- and four-leaf growth stages, respectively. Cotton had 7 to 11 nodes when PD applications were made. Estimations of weed control and cotton injury due to herbicide or weed competition were recorded by visual ratings prior to late POST, prior to lay-by, and after lay-by on a 0 to 100% scale compared to species present in untreated plots within respective experimental blocks.

Weed species present and their size at each application are listed in Tables 1 and 2. Species present in Clayton 2001 were pigweed (60% smooth pigweed and 40% slender amaranth), entireleaf morningglory, goosegrass, pink purslane, and eclipta. Weed populations in Goldsboro 2001 were morningglory (35% tall morningglory, 20% pitted morningglory, and 45% entireleaf morningglory), pigweed (85% palmer amaranth and 15% smooth pigweed), broadleaf signalgrass, and sicklepod. Clayton had pigweed (90% tall morningglory and 10% entireleaf morningglory), palmer amaranth, large crabgrass, common lambsquarters, common ragweed, and common cocklebur in 2002. Rocky Mount weed populations consisted of morningglory (26% tall morningglory, 36% entireleaf morningglory, and 38% pitted morningglory), slender amaranth, large crabgrass, common lambsquarters, and common ragweed.

The middle two plot rows were machine harvested with a spindle picker, and seedcotton sub-samples were taken from each plot for high volume instrument analysis (Cotton Incorporated HVI Laboratory, Cary, NC) (Sasser, 1981). The only trial that had light enough weed pressure to harvest untreated plots was Clayton 2001, therefore the data for this trial were analyzed with and without the untreated plots for comparisons of yield and lint quality against the herbicide programs.

Costs for each herbicide program were calculated based on 2002 retail prices in North Carolina for seed, technology fees, application cost, and herbicides. Net return was figured subtracting the total herbicide program cost from the gross value of the crop considering base loan value for cotton produced in North Carolina in 2002. Seedcotton yield, percent lint turnout, and HVI data were analyzed to obtain crop value for each herbicide program (2002 Crop Loan Valuation Program, Larry Falconer – Texas Cooperative Extension). Although Roundup Ready®/Bollgard® seed was used in all trials, the Roundup Ready® technology fee was not included as a cost in herbicide programs when glyphosate was not applied to make a valid comparison between conventional and GR herbicide systems. This method was used to eliminate variable genetic yield potential present between cultivars. The assumptions used in cost comparisons are as follows: seeding rate was 13.1 seed linear m^{-1}; 22.7 kg seed with Bollgard® technology fee cost $163.20 and with Roundup Ready® and Bollgard® technology fee cost $209, ginning cost was $0.22 kg^{-1}, seed value of 0.9 metric $ton^{-1}$was $85.00, picking and moduling costs for 100 kg seedcotton were $154.00, and base loan value of lint was $1.1737 kg^{-1}. Retail herbicide and surfactant costs used are: pendimethalin, $12.67 kg^{-1}ai; fluometuron, $19.25 kg^{-1} ai; prometryn, $15.40 kg^{-1} ai; MSMA, $5.30 kg^{-1} ai; non-ionic surfactant, $5.28 $liter^{-1}$; pyrithiobac, $828.24 kg^{-1} ai; glyphosate, $23.78 kg^{-1} ae; and metolachlor, $21.08 kg^{-1} ai. Visual rating data were stabilized via arcsine transformation and analyzed in SAS under the general linear model. Means were separated using Fisher's Protected LSD at α=0.05. Orthogonal contrasts were made grouping like treatments in order to draw more basic conclusions from the data. Descriptions of contrasts made are in the table footnotes for which data they represent.

RESULTS AND DISCUSSION

There were no species by herbicide program interactions for weed control results, so data are reported pooled by species prior to POST, prior to lay-by, and after lay-by.

Response to Conventional PRE: Control prior to POST in conventional herbicide programs with pendimethalin and fluometuron (1X) either with or without pyrithiobac controlled 98-100% of pigweed species and common lambsquarters and 70 to 80% of morningglory species (Table 3). Pigweed and common lambsquarters control was reduced to 91 to 94% with pendimethalin and fluometuron (0.5X) and only 73 to 74% with pendimethalin alone. Morningglory species control dropped to 16% with pendimethalin alone and pendimethalin with fluometuron (0.5X) marginally improved control to 38%. Sicklepod control was only 68% with pendimethalin and fluometuron (1X), while adding pyrithiobac to this combination improved control to 91% (data not shown). Common ragweed control was 90 to 99% with any combination of pendimethalin, fluometuron, and pyrithiobac, however only 3% with pendimethalin alone (data not shown). Control of common cocklebur was poor with only 49 to 58% with pendimethalin and fluometuron (1X) either with or without pyrithiobac and was 6 and 20% respectively for pendimethalin alone and pendimethalin and fluometuron (0.5X) (data not shown). Pendimethalin and fluometuron (1X) provided 98% control of grasses regardless of whether pyrithiobac was included. Grass control dropped to 94% with pendimethalin and fluometuron (0.5X) and to 73% with pendimethalin alone . Complete control of carpetweed was achieved with all PRE programs (data not shown).

Response to POST: Herbicide programs including glyphosate gave nearly perfect control of pigweed species, grasses, and sicklepod prior to lay-by (Table 4) (Askew and

Wilcut, 1999). Pigweed species control was 3% better in conventional systems when PRE was followed by POST, compared to a PRE alone. The program with no PRE and POST four-leaf glyphosate had 2% less control than other glyphosate programs with a PRE. This may be due to either large grass size or other weeds present at the time of application limiting grass coverage (Askew and Wilcut, 1999). Glyphosate programs controlled 2% more pigweed species and improved grass control by 4% over conventional programs including both PRE and POST herbicides. Grass control before lay-by in conventional systems with pendimethalin and fluometuron PRE was 3% better when followed by POST herbicides, however when pyrithiobac was included PRE, the POST herbicides did not improve control. In conventional systems with PRE and POST herbicides, a 2% advantage in grass control was gained by including pyrithiobac PRE. Pendimethalin and fluometuron PRE followed by pyrithiobac and MSMA gave 2% better grass control when followed by pyrithiobac alone. Two POST applications of glyphosate provided 9% better morningglory species control than glyphosate systems with a PRE and conventional systems with a PRE followed by POST. One application of glyphosate gave 15% less morningglory control than two applications. Conventional systems with a PRE followed by POST controlled 91% of morningglory species, while PRE alone dropped severely to 57%. Of the conventional PREs followed by glyphosate, pendimethalin and fluometuron (1X) was 13, 6, and10% respectively better than pendimethalin alone, pendimethalin and fluometuron (0.5X), and no PRE. Regardless of PRE, pyrithiobac POST controlled 87 to 94% of morningglory species and pyrithiobac plus MSMA POST boosted the performance to 96 to 98%. Conventional systems with pyrithiobac PRE controlled 85 to 98% of sicklepod, while those without pyrithiobac PRE provided only 51 to 88% control. Of the conventional programs without pyrithiobac PRE, pyrithiobac plus MSMA gave 88% control, while MSMA and pyrithiobac alone were 71% and 58% effective on sicklepod before lay-by. Wilcut and Hinton (1997) and Jennings and York (1998) had similar results of improved sicklepod control when pyrithiobac plus MSMA followed fluometuron PRE, but poor sicklepod control was achieved with pyrithiobac alone. Eclipta, pink purslane, carpetweed, sicklepod, common lambsquarters, and common ragweed were controlled 98 to 100% by all herbicide programs before lay-by (data not shown). Common cocklebur control was only 38 to 40% with programs consisting of a PRE alone, and 95% or better with all other programs before lay-by (data not shown).

Response after lay-by: Carpetweed, eclipta, pink purslane, common lambsquarters, and common ragweed were no longer present in treated plots after lay-by. Common cocklebur control was at least 96% by all programs (data not shown). Late season control of pigweed and morningglory species in conventional programs without a POST application was 87 to 88% and 74 to 83% respectively and all other programs controlled 95 to 100% of pigweed species (Table 4). One application of glyphosate regardless of pendimethalin PRE controlled 89 to 91% of morningglory species, while glyphosate programs with fluometuron PRE or two glyphosate applications controlled 96 to 99% of morningglory species populations. Conventional PRE followed by pyrithiobac POST resulted in 4 to 6% greater control compared to conventional PRE followed by MSMA. Over 90% of grasses were controlled with any herbicide program, with the poorest treatments having 91 to 93% control. One application of glyphosate controlled 89% of sicklepod and pendimethalin plus fluometuron PRE controlled 93%, while all other programs accomplished 97 to 100% control after lay-by. Sicklepod rated after lay-by were newly emerged seedlings.

Cotton response to herbicides: Pyrithiobac applied to the soil caused noticeable injury to cotton in Goldsboro and Clayton in 2002 while neither pendimethalin or fluometuron injury was recorded (Table 3). Cotton injury data before lay-by are pooled over location within year, due to a year by injury interaction. Glyphosate programs in 2001 only caused injury when tank-mixed POST applications were made. Pyrithiobac added to glyphosate caused 3% injury while metolachlor injury to cotton was 1% (Table 5) (Askew and Wilcut, 1999). These tank-mixes were similar in 2002 with pyrithiobac responsible for 7% and metolachlor 3% of cotton injury. Injury before lay-by in Clayton in 2002, was from POST applications of MSMA and biomass reduction from poor weed control in glyphosate programs with only one application or a single appliation preceded by pendimethalin alone. Injury in Rocky Mount was from glyphosate programs without a PRE, and biomass reduction from early weed competition. No symptoms of herbicide injury to cotton were noted in Rocky Mount. The greatest amount of injury prior to lay-by was a 33% biomass reduction due to early weed competition in 2002, when only one application of glyphosate was made at the four-leaf stage. Programs with pyrithiobac PRE had more injury before lay-by than those with only pendimethalin and fluometuron. Pyrithiobac POST caused 3 to 7% and 8 to 9% injury in 2001 and 2002, respectively. Injury was increased 2 to 6% when MSMA and pyrithiobac were tank-mixed in either year. MSMA injury before lay-by was 1 to 4% in 2001 and ranged between 7 and 9% in 2002. Late-season cotton injury data were pooled over all trials. Cotton had recovered from most injury symptoms previously caused by pyrithiobac and/or MSMA with a maximum of 3% injury remaining for these programs. Reduced cotton plant biomass of 1-4% was noted in herbicide programs with a PRE and no POST and 2% for the program with no PRE and only one application of glyphosate.

Effect on yield, lint turnout, and quality: Yield responses were not the same in all trials, so yield and net returns are reported separately. All herbicide programs in Clayton in 2001 performed similarly (Table 6) and out-yielded plots with no herbicide by 940 kg ha^{-1} lint (data not shown). One glyphosate application at four-leaf yielded 340 to 930 kg ha^{-1} lint less than all other programs in Goldsboro (Askew and Wilcut, 1999). Pendimethalin and fluometuron at half and full rates followed by glyphosate improved yield by 350 to 450 kg ha^{-1} over pendimethalin alone followed by glyphosate in Goldsboro. A preceding study reported that glyphosate systems benefited from soil-applied herbicides in one year of a two-year study (Askew et al., 2002). Conventional programs including only PRE herbicides produced less cotton than conventional programs including PRE and POST applied material by 140 to 380 kg ha^{-1} in Goldsboro (Askew et al., 2002). Injury from conventional POST herbicides that stunted growth may cause delayed maturity and adversely affect yield (Guthrie, 1989; York, 1983). Glyphosate programs yielded better in Clayton in 2002 and Rocky Mount when a PRE or two POST applications were included compared to conventional systems with PRE and POST applications by 100 and 50 kg ha^{-1}, respectively. Yield for pendimethalin and fluometuron PRE was improved by 150 kg ha^{-1} by a POST application of pyrithiobac in Clayton in 2002.

Herbicide programs did not affect lint quality. Data were pooled over trials and micronaire reading ranged from 3.7 to 4.0, fiber length was 26.9 to 27.3 mm, length uniformity index was 82.1 to 82.6%, and fiber strength was 250 to 257 kN m kg^{-1} (data not shown).

Glyphosate programs had higher percent lint turnout in Clayton in 2001 and 2002 and Rocky Mount when a PRE or two POST applications were included compared to conventional systems with PRE and POST applications by 0.8, 0.7, and 1.0%, respectively (Table 7). A delay in maturity caused by herbicide stunting can reduce lint turnout. Conventional programs in 2002 with no POST had 1.1% higher lint turnout than conventional programs with PRE and POST herbicides.

Net return: These return values assume that all other input costs involved with producing this crop remain constant between herbicide programs, and do not account for them, nor claim to represent them. These data are intended to show gross crop value considering yield and quality less herbicide program costs. Costs used are only relevant to the herbicide program and their associated estimated application costs. All remaining input costs should be subtracted from the gross crop value in order to show profit per acre.

Economic returns followed the trends of weed control and yield (Askew et al., 2002). All herbicide programs returned an average of \$588 more ha^{-1} than the untreated (data not shown) in Clayton in 2001. The light weed pressure in Clayton in 2001 made it possible for the cheaper herbicide program of pendimethalin and fluometuron PRE to return an average of \$91 more ha^{-1} than programs consisting of pendimethalin and fluometuron PRE followed by POST herbicides (Table 8). A similar response was found in Rocky Mount, with pendimethalin and fluometuron PRE returning \$42 more ha^{-1} than pendimethalin and fluometuron followed by pyrithiobac and \$116 more ha^{-1} when followed by pyrithiobac plus MSMA. Conventional programs in Rocky Mount with pyrithiobac PRE, profited \$49 more ha^{-1} than when this PRE was followed by any POST. One application of glyphosate at four-leaf POST returned an average of \$230 ha^{-1} less than all other herbicide programs in Goldsboro, which is a reflection of yield loss due mainly to poor morningglory control. Pendimethalin and fluometuron (1X) PRE followed by glyphosate at four-leaf POST returned \$158, and \$53 ha^{-1} more than conventional programs with pyrithiobac PRE and POST. The same program also returned \$146 ha^{-1} more than either conventional program with no POST and the glyphosate program with no fluometuron PRE. Conventional and glyphosate systems gave similar returns when the PRE included both pendimethalin and fluometuron and the glyphosate programs included a PRE or two POST applications. In Goldsboro, the two glyphosate programs with fluometuron PRE, which cost an average of \$240 ha^{-1} returned \$96 ha^{-1} more than conventional programs with pyrithiobac PRE followed by any POST costing an average of \$275 ha^{-1}. In Clayton and Rocky Mount in 2002, all glyphosate programs with a PRE or 2 POST applications returned an average of \$42 and \$27, respectively ha^{-1} more than conventional programs with a PRE followed by POST. Overall, glyphosate systems returned more because they cost less and did not cause any cotton injury.

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Table 1. Population density and growth stage of weeds at early postemergence (POST), late POST, and layby herbicide applications for Clayton and Goldsboro in 2001.

	Clayton				Goldsboro			
Weed		Weed size				Weed size		
species[w]	Weed density	Early POST	Late POST	Layby	Weed density	Early POST	Late POST	Layby
	— Plant m^{-2} —	Leaves plant^{-1}			— Plant m^{-2} —	Leaves plant^{-1}		
Pigweed	17	cot-2	7-8	4-6	115	1-4	3-20	3-20
Morningglory	2	cot-3	4-5	7-15	36	cot-2	cot-15	cot-19
Grasses	16	3	4-6	3lf-4till	102	1-3	3lf-6till	3-12till
Sicklepod	–[z]	–	–	–	20	cot-1	1-8	cot-11
Carpetweed	8	–	7-9	8-10	–	–	–	–
Eclipta	6	–	–	–	–	–	–	–
Purselane	4	–	4	4	–	–	–	–

[w] Weed species Clayton: pigweed, 60% smooth pigweed and 40% slender amaranth; entireleaf morningglory, goosegrass, eclipta, and pink purselane. Goldsboro: pigweed, 85% palmer amaranth and 15% smooth pigweed; morning glory, 35% tall morningglory, 20% pitted morningglory, and 45% entireleaf morningglory; broadleaf signalgrass, and sicklepod.

[x] Cotton was at cotyledon, 4-leaf, and 8-leaf stages for ealry POST, late POST, and layby herbicide applications.

[y] Abbreviations: cot, cotyledon; lf, leaf; till, tiller.

[z] Species not present at time of evaluation.

Table 2. Population density and growth stage of weeds at early postemergence (POST), late POST, and layby herbicide applications for Clayton and Rocky Mount in 2002.

Weed species[w]	Clayton				Rocky Mount			
		Weed size[x,y]				Weed size		
	Weed density	Early POST	Late POST	Layby	Weed density	Early POST	Late POST	Layby
	— Plant m^{-2} —	Leaves $plant^{-1}$			— Plant m^{-2} —	Leaves $plant^{-1}$		
Pigweed	58.0	2	6-16	cot-35	0.1	2-3	cot-19	
Morningglory	1.6	cot-4	2-15	cot-20	2.1	cot-2	cot-18	3-35
Grasses	15.0	1-2	3-5	1-6lf, 5till	33.0	1-3	1-3	14-35
Lambsquarters	3.3	2	4-8	1-35	24.0	4-6	cot-9	4-30
Ragweed	0.4	2-3	2-3	–[z]	0.1	–	–	–
Cocklebur	0.3	2	6-8	8-12	–	–	–	–

[w] Weed species Clayton: pigweed, palmer amaranth; morningglory, 90% tall morningglory and 10% entireleaf morningglory, large crabgrass, common lambsquarters, common ragweed, and common cocklebur. Rocky Mount: pigweed, slender amaranth; morning glory, 26% tall morningglroy, 36% entireleaf morningglory, and 38% pitted morningglory; large crabgrass, common lambsquarters, and cotmmon ragweed.

[x] Cotton was at cotyledon, 4-leaf, and 8-leaf stages for ealry POST, late POST, and layby herbicide applications.

[y] Abbreviations: cot, cotyledon; lf, leaf; till, tiller

[z] Species not present at time of evaluation.

Table 3. Weed control and cotton injury ratings as affected by preemergence herbicides.[w] Ratings taken prior to POST applications for evaluation of PRE herbicide activity.

	Weed species				
PRE herbicides[x,y]	**Pigweed sp.**	**Morningglory sp.**	**Grass sp.**	**Lambsquarters**	**Injury**
	%				
Pend	**74 d[z]**	**16 c**	**73 c**	**73 c**	**0.0 b**
Pend/fluo (0.5X)	**91 c**	**38 b**	**92 b**	**94 b**	**0.5 b**
Pend/fluo	**98 b**	**70 a**	**98 a**	**98 a**	**0.5 b**
Pend/fluo/pyrith	**100 a**	**80 a**	**98 a**	**100 a**	**8.7 a**

[w] Ratings taken prior to POST herbicide applications respectively on 10, 6, 3 June and 29 May in Clayton 2001, Goldsboro, Clayton 2002, and Rocky Mount. Pigweed, morningglory, and grass species pooled over trials. Common lambsquarters pooled over Clayton 2002 and Rocky Mount. Cotton injury is pooled over Goldsboro and Clayton 2002. There was no cotton injury from PRE herbicides present in Clayton 2001 or Rocky Mount

[x] Abbreviations: fluo, fluometuron; pend, pendimethalin; PRE, preemergence; pyrith, pyrithiobac.

[y] Pendimethalin, 1.1 kg ha^{-1}; fluometuron, 0.68(0.5X) or 1.35 kg ha^{-1}; pyrithiobac, 35.76 g ha^{-1}

[z] Means followed by the same letter within a column are not statistically different according to Fisher's Protected LSD at a=0.05.

Table 4. Weed control ratings before and after layby as affected by herbicide programs for pigweed, morningglory, grasses, and sicklepod for 2001 and 2002 in Clayton, Goldsboro, and Rocky Mount, NC.[r]

Herbicide	Herbicides[s,t]			Weed species							
				Pigweed		Morningglory		Grass		Sicklepod	
program	PRE	Conv. POST	Glyphosate	POST[w,x]	Layby	POST[w,z]	Layby	POST[x,y]	Layby	POST	Layby
				%							
1	None	None	None	–[u]	–	–	–	–	–	–	–
2	Pend/fluo	None	None	94 c[v]	87 e	49 g	74 g	92 e	91 e	51 g	93 c
3	Pend/fluo	MSMA	None	95 c	95 d	81 e	94 de	95 cd	95 cd	71 ef	99 ab
4	Pend/fluo	Pyrith	None	99 ab	97 bcd	87 cd	99 ab	94 de	96 c	58 fg	97 bc
5	Pend/fluo	Pyrith/MSMA	None	97 b	97 bcd	98 ab	100 a	96 c	96 c	88 cd	100 a
6	Pend/fluo/pyrith	None	None	95 c	88 e	65 f	83 f	97 c	92 e	85 de	99 ab
7	Pend/fluo/pyrith	MSMA	None	99 ab	99 ab	87 cd	95 cd	97 c	96 c	91 bcd	99 ab
8	Pend/fluo/pyrith	Pyrith	None	99 ab	98 abc	94 bc	99 ab	97 c	97 bc	95 bcd	98 ab
9	Pend/fluo/pyrith	Pyrith/MSMA	None	99 ab	99 ab	96 ab	99 ab	97 c	97 bc	99 ab	99 ab
10	Pend	None	4-leaf	100 a	100 a	80 e	91 de	100 a	98 b	100 a	98 ab
11	Pend/fluo (0.5X)	None	4-leaf	100 a	100 a	87 cd	97 abc	100 a	99 ab	100 a	99 ab
12	Pend/fluo	None	4-leaf	100 a	100 a	93 bc	96 bc	100 a	100 a	100 a	100 a
13	None	None	4-leaf	99 ab	97 bcd	83 de	89 e	98 b	93 de	98 abc	89 c
14	None	None	Cot/4-leaf	100 a	100 a	98 ab	97 abc	99 ab	94 cd	100 a	98 ab
15	None	Metolachlor	Cot/4-leaf	100 a	100 a	98 ab	99 ab	100 a	100 a	100 a	99 ab
16	None	Pyrith	Cot/4-leaf	100 a	100 a	99 a	99 ab	99 ab	97 bc	100 a	100 a

[r] Pigweed, morningglory, and grass control data are pooled over all four trials. Sicklepod was only present in Goldsboro.

[s] Abbreviations: Conv. POST, herbicides other than glyphosate applied broadcast postemergence to cotton at 4-leaf stage; Cot/4-leaf, cotton at cotyledon and 4-leaf stages; fluo, fluometuron; pend, pendimethalin; PRE, preemergence; pyrith, pyrithiobac.

[t] Pendimethalin, 1.1 kg ha^{-1}; fluometuron, 0.68(0.5X) or 1.35 kg ha^{-1}; pyrithiobac, 35.76 g ha^{-1} PRE, 71.5 g ha^{-1} POST, and 35.76 g ha^{-1} POST with glyphosate; glyphosate cot POST, 0.56 kg ha^{-1}, 4-leaf POST 1.12 kg ha^{-1} when preceded by a PRE or no glyphosate, and 0.84 kg ha^{-1} when preceded by glyphosate; metolachlor, 1.4 kg ha^{-1}, MSMA, 0.93 kg ha^{-1} POST.

[u] Data from untreated plots were not included in analysis.

[v] Means followed by the same letter within a column are not statistically different according to Fisher's Protected LSD at α=0.05.

[w] Programs 2 and 6 gave 3% and 34% poorer control, respecitvely for pigweed and morningglory species than 3,4,5,7,8, and 9.

[x] Programs 10,11,12,14,15, and 16 gave 2% and 4% better control, respecitvely for pigweed and grass species than 3,4,5,7,8, and 9.

[y] Programs 7,8, and 9 provided 2% better grass species control than 3,4, and 5.

[z] Programs 14,15, and 16 provided 9% better morningglory species control than 3,4,5,7,8,9,10,11, and 12.

Table 5. Visual injury rating of cotton plants from herbicide application or lack of weed control causing biomass reduction.[v]

Herbicide program	Herbicides[w,x] PRE	Conv. POST	Glyphosate	Cotton Injury Before Layby 2001	2002	After Layby
				%		
1	None	None	None	–[y]	–	–
2	Pend/fluo	None	None	0 f[z]	0 d	1 bc
3	Pend/fluo	MSMA	None	1 e	7 c	1 bc
4	Pend/fluo	Pyrith	None	3 d	8 c	2 ab
5	Pend/fluo	Pyrith/MSMA	None	5 bc	14 b	3 a
6	Pend/fluo/pyrith	None	None	1 e	1 d	4 a
7	Pend/fluo/pyrith	MSMA	None	4 cd	9 c	0 c
8	Pend/fluo/pyrith	Pyrith	None	7 b	9 c	2 ab
9	Pend/fluo/pyrith	Pyrith/MSMA	None	10 a	12 bc	3 a
10	Pend	None	4-leaf	0 f	8 c	1 bc
11	Pend/fluo (0.5X)	None	4-leaf	0 f	1 d	0 c
12	Pend/fluo	None	4-leaf	0 f	0 d	0 c
13	None	None	4-leaf	0 f	33 a	2 ab
14	None	None	Cot/4-leaf	0 f	2 d	0 c
15	None	Metolachlor	Cot/4-leaf	1 e	3 cd	0 c
16	None	Pyrith	Cot/4-leaf	3 d	7 c	1 bc

[v] Rating data recorded before layby are pooled over Clayton and Goldsboro in 2001 and Clayton and Rocky Mount in 2002. Ratings after layby are pooled over Clayton in 2001, Goldsboro, and Rocky Mount. No injury or biomass reduction was evident in Clayton 2002 after layby.

[w] Abbreviations: Conv. POST, herbicides other than glyphosate applied broadcast postemergence to cotton at 4-leaf stage; Cot/4-leaf, cotton at cotyledon and 4-leaf stages; fluo, fluometuron; pend, pendimethalin; PRE, preemergence; pyrith, pyrithiobac.

[x] Pendimethalin, 1.1 kg ha^{-1}; fluometuron, 0.68(0.5X) or 1.35 kg ha^{-1}; pyrithiobac, 35.76 g ha^{-1} PRE, 71.5 g ha^{-1} POST, and 35.76 g ha^{-1} POST with glyphosate; glyphosate cot POST, 0.56 kg ha^{-1}, 4-leaf POST 1.12 kg ha^{-1} when preceded by a PRE or no glyphosate, and 0.84 kg ha^{-1} when preceded by glyphosate; metolachlor, 1.4 kg ha^{-1}, MSMA, 0.93 kg ha^{-1} POST; All POST applications without glyphosate included 0.25% by volume non-ionic surfactant.

[y] Data from untreated plots were not included in analysis.

[z] Means followed by the same letter within a column are not statistically different according to Fisher's Protected LSD at α=0.05.

Table 6. Lint yield as affected by herbicide program for 2001 and 2002 in Clayton, Goldsboro, and Rocky Mount, NC.

Herbicide	Herbicides[r,s]			Lint Yield			
				2001		2002	
program	PRE	Conv. POST	Glyphosate	Clayton[x]	Goldsboro[v,w,x,y]	Clayton[z]	Rocky Mount[z]
				kg ha^{-1}			
1	None	None	None	–[t]	–	–	–
2	Pend/fluo	None	None	1740 a[u]	1120 f	560 d	690 a
3	Pend/fluo	MSMA	None	1540 a	1500 abc	600 cd	710 a
4	Pend/fluo	Pyrith	None	1570 a	1470 bc	710 abc	660 a
5	Pend/fluo	Pyrith/MSMA	None	1680 a	1480 bc	650 cd	670 a
6	Pend/fluo/pyrith	None	None	1550 a	1220 ef	660 bcd	750 a
7	Pend/fluo/pyrith	MSMA	None	1700 a	1450 bcd	650 cd	650 a
8	Pend/fluo/pyrith	Pyrith	None	1580 a	1360 cde	700 abcd	710 a
9	Pend/fluo/pyrith	Pyrith/MSMA	None	1660 a	1380 cde	640 cd	680 a
10	Pend	None	4-leaf	1600 a	1250 def	690 abcd	720 a
11	Pend/fluo (0.5X)	None	4-leaf	1680 a	1600 ab	810 a	750 a
12	Pend/fluo	None	4-leaf	1660 a	1710 a	720 abc	750 a
13	None	None	4-leaf	1630 a	780 g	660 bcd	720 a
14	None	None	Cot/4-leaf	1570 a	1590 ab	800 ab	730 a
15	None	Metolachlor	Cot/4-leaf	1750 a	1510 abc	800 ab	750 a
16	None	Pyrith	Cot/4-leaf	1700 a	1450 bcd	720 abc	680 a

[r] Abbreviations: Conv. POST, herbicides other than glyphosate applied broadcast postemergence to cotton at 4-leaf stage; Cot/4-leaf, cotton at cotyledon and 4-leaf stages; fluo, fluometuron; pend, pendimethalin; PRE, preemergence; pyrith, pyrithiobac.

[s] Pendimethalin, 1.1 kg ha^{-1}; fluometuron, 0.68(0.5X) or 1.35 kg ha^{-1}; pyrithiobac, 35.76 g ha^{-1} PRE, 71.5 g ha^{-1} POST, and 35.76 g ha^{-1} POST with glyphosate; glyphosate cot POST, 0.56 kg ha^{-1}, 4-leaf POST 1.12 kg ha^{-1} when preceded by a PRE or no glyphosate, and 0.84 kg ha^{-1} when preceded by glyphosate; metolachlor, 1.4 kg ha^{-1}, MSMA, 0.93 kg ha^{-1} POST.

[t] Data from untreated plots were not included in analysis.

[u] Means followed by the same letter within a column are not statistically different according to Fisher's Protected LSD at α=0.05.

[v] Herbicide program 2 yielded 370 kg ha^{-1} less than 3,4, and 5 combined in Goldsboro.

wHerbicide program 6 yielded 180 kg ha^{-1} less than 7,8, and 9 combined in Goldsboro.

[x] Herbicide programs 7,8, and 9 combined yielded 120 kg ha^{-1} less than 14, 15, and 16 combined in Goldsboro.

[y] Programs 11 and 12 combined yielded 140, 170, and 260 kg ha^{-1}, respectively more than 3,4, and 5; 7,8,and 9; and 14, 15, and 16 combined in Goldsboro.

[z] Programs 10,11,12,14,15, and 16 yielded 100 and 50 kg ha^{-1} more than programs 3,4,5,7,8, and 9 in Clayton 2002 and Rocky Mount, respectively.

Table 7. Percent lint turnout as affected by herbicide program for 2001 and 2002 in Clayton, Goldsboro, and Rocky Mount, NC.

Herbicide	Herbicides[u,v]			Lint turnout			
				2001		2002	
program	PRE	Conv. POST	Glyphosate	Clayton[y]	Goldsboro	Clayton[y,z]	Rocky Mount[y,z]
				%			
1	None	None	None	–[w]	–	–	–
2	Pend/fluo	None	None	41.0 cde[x]	40.9 a	40.8 d	44.0 ab
3	Pend/fluo	MSMA	None	41.2 bcde	39.2 a	41.5 abcd	42.5 def
4	Pend/fluo	Pyrith	None	40.9 de	39.5 a	41.0 bcd	42.5 def
5	Pend/fluo	Pyrith/MSMA	None	41.3 abcde	38.6 a	40.4 d	41.9 f
6	Pend/fluo/pyrith	None	None	40.6 de	40.1 a	42.6 a	43.8 abc
7	Pend/fluo/pyrith	MSMA	None	41.7 abcd	39.7 a	40.9 cd	42.2 ef
8	Pend/fluo/pyrith	Pyrith	None	40.7 de	39.0 a	41.7 abcd	42.6 cdef
9	Pend/fluo/pyrith	Pyrith/MSMA	None	40.5 e	38.1 a	40.5 d	42.1 ef
10	Pend	None	4-leaf	42.2 ab	39.0 a	42.3 a	43.0 bcdef
11	Pend/fluo (0.5X)	None	4-leaf	41.6 abcde	39.1 a	42.2 ab	43.6 abcd
12	Pend/fluo	None	4-leaf	42.1 abc	39.9 a	40.9 d	43.2 abcde
13	None	None	4-leaf	42.4 a	38.9 a	40.5 d	44.4 a
14	None	None	Cot/4-leaf	42.1 abc	38.9 a	41.6 abcd	43.3 abcde
15	None	Metolachlor	Cot/4-leaf	41.6 abcde	39.3 a	42.2 abc	43.4 abcd
16	None	Pyrith	Cot/4-leaf	41.5 abcde	39.2 a	40.8 d	43.1 bcdef

[u] Abbreviations: Conv. POST, herbicides other than glyphosate applied broadcast postemergence to cotton at 4-leaf stage; Cot/4-leaf, cotton at cotyledon and 4-leaf stages; fluo, fluometuron; pend, pendimethalin; PRE, preemergence; pyrith, pyrithiobac.

[v] Pendimethalin, 1.1 kg ha^{-1}; fluometuron, 0.68(0.5X) or 1.35 kg ha^{-1}; pyrithiobac, 35.76 g ha^{-1} PRE, 71.5 g ha^{-1} POST, and 35.76 g ha^{-1} POST with glyphosate; glyphosate cot POST, 0.56 kg ha^{-1}, 4-leaf POST 1.12 kg ha^{-1} when preceded by a PRE or no glyphosate, and 0.84 kg ha^{-1} when preceded by glyphosate; metolachlor, 1.4 kg ha^{-1}, MSMA, 0.93 kg ha^{-1} POST; All POST applications without glyphosate included 0.25% by volume non-ionic surfactant.

[w] Data from untreated plots were not included in analysis.

[x] Means followed by the same letter within a column are not statistically different according to Fisher's Protected LSD at α=0.05.

[y] Programs 10,11,12,14,15, and 16 had 0.8, 0.7, and 1.0% better lint turnout than programs 3,4,5,7,8, and 9 for 2001 and 2002 in Clayton and Rocky Mount, respectively.

[z] Programs 2 and 6 had 1.1% higher lint turnout than 3,4,5,7,8, and 9 combined in 2002.

Table 8. Herbicide program input costs and net returns for 2001 and 2002 in Clayton, Goldsboro, and Rocky Mount, NC.[s]

					Net Return			
Herbicide	Herbicides[t,u]				2001		2002	
program	PRE	Conv. POST	Glyphosate	Input cost	Clayton[x]	Goldsboro	Clayton[z]	Rocky Mount[y,z]
					$ ha^{-1}			
1	None	None	None	92	–[v]	–	–	–
2	Pend/fluo	None	None	188	652 a[w]	343 b	96 cd	136 a
3	Pend/fluo	MSMA	None	207	558 a	430 ab	101 cd	124 abc
4	Pend/fluo	Pyrith	None	262	554 a	445 ab	114 abcd	94 cd
5	Pend/fluo	Pyrith/MSMA	None	267	571 a	403 ab	91 cd	20 cd
6	Pend/fluo/pyrith	None	None	218	554 a	434 b	119 abcd	141 a
7	Pend/fluo/pyrith	MSMA	None	237	618 a	410 ab	104 bcd	96 cd
8	Pend/fluo/pyrith	Pyrith	None	291	536 a	358 b	96 cd	101 bcd
9	Pend/fluo/pyrith	Pyrith/MSMA	None	296	578 a	331 b	82 d	79 d
10	Pend	None	4-leaf	220	568 a	346 b	131 abcd	124 abc
11	Pend/fluo (0.5X)	None	4-leaf	233	613 a	435 ab	158 a	133 ab
12	Pend/fluo	None	4-leaf	246	598 a	489 a	116 abcd	128 abc
13	None	None	4-leaf	194	608 a	171 c	133 abc	136 a
14	None	None	Cot/4-leaf	211	571 a	427 ab	163 a	133 ab
15	None	Metolachlor	Cot/4-leaf	241	633 a	440 ab	158 ab	126 abc
16	None	Pyrith	Cot/4-leaf	241	618 a	408 ab	126 abcd	111 abcd

[s] Inputs include costs for seed, technology fees, and herbicides. Net return is the total crop value less input costs for herbicide program.

[t] Abbreviations: Conv. POST, herbicides other than glyphosate applied broadcast postemergence to cotton at 4-leaf stage; Cot/4-leaf, cotton at cotyledon and 4-leaf stages; fluo, fluometuron; pend, pendimethalin; PRE, preemergence; pyrith, pyrithiobac.

[u] Pendimethalin, 1.1 kg ha^{-1}; fluometuron, 0.68(0.5X) or 1.35 kg ha^{-1}; pyrithiobac, 35.76 g ha^{-1} PRE, 71.5 g ha^{-1} POST, and 35.76 g ha^{-1} POST with glyphosate; glyphosate cot POST, 0.56 kg ha^{-1}, 4-leaf POST 1.12 kg ha^{-1} when preceded by a PRE or no glyphosate, and 0.84 kg ha^{-1} when preceded by glyphosate; metolachlor, 1.4 kg ha^{-1}, MSMA, 0.93 kg ha^{-1} POST; All POST applications without glyphosate included 0.25% by volume non-ionic surfactant.

[v] Data from untreated plots were not included in analysis.

[w] Means followed by the same letter within a column are not statistically different according to Fisher's Protected LSD at α=0.05.

[x] Herbicide program 2 returned $91 ha^{-1} more than 3,4, and 5 combined in Clayton 2001.

[y] Herbicide program 6 returned $49 ha^{-1} more than 7,8, and 9 combined in Rocky Mount.

[z] Programs 10,11,12,14,15, and 16 returned $42 and $27 ha^{-1} more than programs 3,4,5,7,8, and 9 in Clayton 2002 and Rocky Mount, respectively.

CHAPTER IV

Economic Comparison of Conventional and Transgenic Management Systems in Cotton (*Gossypium hirsutum*)[1]

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Abstract: The rapid adoption of glyphosate-resistant (GR) and insect-resistant (Bollgard) cotton lines has profoundly altered cotton pest management and associated inputs. Weed management with GR cotton has simplified application methods compared to previous methods of directing herbicides under small cotton to avoid injury. Glyphosate is effective against most weed pests in cotton, is available in many formulations, and is less costly compared to other herbicides required to control the same spectrum of species in cotton. The 1996 commercialization of Bollgard (BG) cotton lines has allowed cotton procucers to greatly reduce the number of insecticide applications for several key caterpillar pests. Because a technology fee is assessed for transgenic lines and because these cultivars represent new germplasm, questions about the relative costs and returns of pest management with various transgenic and non-transgenic lines must be answered. Field trials were conducted in 2002 and 2003 in Clayton and Goldsboro, North Carolina. Nine common commercial cultivars were selected for testing under transgenic and conventional pest management systems. Glyphosate systems provided excellent control of all weed species, while conventional herbicides gave acceptable control in most cases. Palmer amaranth biotypes resistant to pyrithiobac were present in Goldsboro, causing severe yield loss. Stacked (Bollgard + GR) gene cultivars returned more profit than those with

glyphosate resistance alone. Glyphosate systems had better yields and returned more profit than conventional systems of the same cultivar.

Nomenclature: Clethodim, (*E*)-2-[1-[(3-chloro-2-propenyl)oxy]imino]propyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one; fluometuron, 1,1-dimethyl-3-(*a*,*a*,*a*-trifluoro-m-tolyl) urea; glyphosate, *N*-(phosphonomethyl) glycine; MSMA, monosodium acid methanearsonate; pendimethalin, (*N*-(1-ethylpropyl)-3, 4-dimethyl-2,6-dinitrobenzenamine); prometryn, 2,4-bis(isopropylamino)-6-(methylthio)*s*-triazine; pyrithiobac, sodium 2-chloro-6-[(4,6-dimethoxypyrimidin-2-yl)thio] benzoate; lambda-cyhalothrin, [1α(*S**),3α(Z)]-(±)-cyano-(3-phenoxyphenyl)methyl-3-(2-chloro-3,3,3-trifluoro-1-propenyl)-2,2-dimethylcyclopropanecarboxylate; broadleaf signalgrass; *Brachiaria platyphylla* (Griseb.) Nash #[3] BRAPP; common lambsquarters, *Chenopodium album* L. # CHEAL; common ragweed, *Ambrosia artemisiifolia* L. # AMBEL; cutleaf groundcherry, *Physalis angulata* L. # PHYAN; entireleaf morningglory, *Ipomoea hederacea* L. # IPOHG; fall panicum, *Panicum dichotomiflorum* Michx. # PANDI; goosegrass, *Eleusine indica* L. Gaertn. # ELEIN; ivyleaf morningglory, *Ipomoea hederacea* L. Jacq. # IPOHE; jimsonweed, *Datura stramonium* L. # DATST; johnsongrass, *Sorghum halepense* (L.) Pers. # SORHA; large crabgrass, *Digitaria sanguinalis* (L.) Scop. # DIGSA; Palmer amaranth, *Amaranthus palmeri* S.Wats. # AMAPA; pitted morningglory, *Ipomoea lacunosa* L. # IPOLA; smooth pigweed, *Amaranthus hybridis* (L.) # AMACH; sicklepod, *Senna obtusifolia* (L.) # CASOB; tall morningglory, *Ipomoea purpurea* (L.) Roth # PHBPU; cotton, *Gossypium hirsutum* (L.) ‘DP 436 RR’, ‘DP 451 B/RR’, ‘FM 958’, FM 989RR’, ‘PM 1218 BG/RR’, PSC 355’, ‘ST 474’, ‘ST 4793R’, ‘ST 4892BR’;

Additional index words: transgenic cotton, glyphosate-resistant cotton, BT cotton, herbicide resistance, economics.

Abbreviations: glyphosate-resistant (GR), over-the-top (OT), pre-emergence (PRE); post-emergence (POST); post-directed (PD), Bollgard (BG), stacked (BG/GR).

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[3] Letters following this symbol are a WSSA-approved computer code from *Composite List of Weeds*, Revised 1989. Available only on computer disk from WSSA. 810 East 10th Street, Lawrence, KS 66044-8897.

INTRODUCTION

When making cultivar selections for the growing season, cotton producers have to make a larger decision than just which plant growth characteristics and yield potential are best. Many cotton cultivars are available with transgenic traits, such as resistance to non-selective herbicides and improved insect control, which simplifies management and often reduces overall inputs. Producing an acceptable cotton crop requires chemical weed control because seedling cotton is unable to compete with the rapid growth characteristics of broadleaf and grass weed species (Rout and Satapathy 1998). Pigweed and morningglory species are the most damaging weeds in North Carolina cotton, each accounting for about 35% of the total yield loss due to weeds in 2002 (Byrd 2002). Due to the broad spectrum of weed species that are competitive with cotton, using an herbicide-resistant cotton cultivar and the respective non-selective herbicide is desirable. Cotton is currently available which is tolerant to the herbicides bromoxynil, glufosinate, or glyphosate (Culpepper and York, 1999). The GR weed management system is an effective alternative to conventional methods, requiring less herbicide and fewer applications to produce the same yield and net economic return as non-transgenic systems (Culpepper and York 1998). The commercial release of GR cotton was in 1997 (Faircloth et al. 2001; Pline, et al. 2001). Glyphosate is a member of the glycine herbicide family and non-selectively controls a broad-spectrum of economically significant grass and broadleaf weed pests (Ellis and Griffin 2002).

Glyphosate-resistant cotton has been overwhelming accepted by producers, leading to more than two-thirds of the 2003 United States cotton crop and more than 95% of the 2003 North Carolina crop being planted with GR seed (Ihrig et al. 2003; USDA-AMS 2003). Despite these figures, considerable interest remains to compare the economics between GR and conventional herbicide systems in cotton. There are advantages and restrictions with the decision to use either system, and the rapid transition to transgenic systems has left questions regarding how well cotton will perform under either system. Conventional weed control usually consists of soil-applied herbicides, a limited number of post-emergence (POST) compounds, and post-directed (PD) compounds, such as prometryn, which usually provide residual control. Good early cotton growth is essential for reaching a height differential between cotton plants and weed targets to keep PD applications with conventional herbicides safe (Shankle et al. 1996). If the soil-applied herbicides do not provide adequate control, early season weed competition will result before the height differential is reached, therefore most growers favor using POST herbicides on small cotton (Culpepper and York 1999; Jennings et al. 1999). Pyrithiobac and MSMA are two of the few conventional herbicides labeled for POST applications in non-transgenic cotton. However, they have potential for causing chlorosis resulting in stunted growth which may result in yield loss (Baldwin et al. 1997; Jennings et al. 1999; Jordan et al. 1993; Keeling et al. 1993; Shankle et al. 1996). Glyphosate does not have the same potential for stunting early foliar cotton growth of GR cotton like pyrithiobac or MSMA. Avoiding early stunting will promote canopy closure, reducing weed germination and competition in row middles. Pyrithiobac controls many broadleaf weeds, however it is not effective on some economically significant weeds like sicklepod and tall morningglory and usually requires additional soil-applied or PD herbicides for sufficient control (Culpepper and York 1999; Kendig 1997). Systems including the soil-applied combination of fluometuron and pendimethalin, versus glyphosate alone, have proven to be more effective in controlling grass species when weed pressure was severe enough to interfere with cotton growth before the first glyphosate application was made (Culpepper and York 1999). However, other results were that soil-applied herbicides did not enhance systems with two glyphosate applications or glyphosate followed by cyanazine plus MSMA (Culpepper and York 1998).

The label for glyphosate application to GR cotton restricts use to two POST applications prior to the four-leaf stage, and requires that a sequential POST application be at least 10 d after the first one with at least two nodes of incremental growth (Anonymous 1999). Soil-applied herbicides provide a protective advantage over a glyphosate system when weather conditions, equipment breakdown, or other common unforeseeable events do not allow a grower to cover all cotton hectarage before the four-leaf stage.

Additional commercially available transgenic traits cause the plant to produce a *Bacillus thuringiensis* endotoxin that is insecticidal to feeding lepidopteran larvae (Pitts et al. 2003). This technology was released in commercial cotton in 1996 under the trade name Bollgard® (BG) (Pitts et al. 2003). When GR and BG transgenic traits are combined in a commercial cultivar, it is known as a stacked (BG/GR) cultivar. Benefits of BG/GR over GR traits alone are variable across the cotton belt depending on typical lepidopteran pest pressure and decisions with weed management. Each transgenic option is associated with it's own technology fee, thus growers in regions with low lepidopteran pressure have trouble warranting the initial purchase of the BG/GR biotechnology package. It is a challenge for seed companies to combine the best plant yield and quality characteristics with the most applicable transgenic traits and carry sufficient inventory of each cultivar and transgenic option combinations to suit the market needs. In regions such as the northeastern part of the cotton belt, including North Carolina, South Carolina, and Virginia, where lepidopteran pest pressure can be lower than other regions, the technology fee for BG in BG/GR cultivars has been discounted 25% (J. Lewis, Monsanto Company, personal communication).

Growers choosing non-transgenic cultivars do not face the up-front technology fees, but may be more challenged to manage weed and insect pests later in the season. In previous studies comparing the economics between glyphosate and conventional herbicide systems in cotton, one application of glyphosate returned less than conventional programs, and glyphosate applied 3 to 4 wk after planting was similar in weed control, cotton yield, and net returns to the conventional herbicide programs (Culpepper and York, 1998). It was also noted that three glyphosate applications were not more effective than two (Culpepper and York, 1998).

The concern remains that cultivars with transgenic traits do not have the quality or yield potential equal to their non-transgenic parents. Transgenic cultivars are not direct decedents from leading commercial cultivars. Rather, they are a product of backcrossing a non-commercial cultivar bearing the desirable trait into a commercial line. It is genetically impossible to achieve the same yield potential as the original commercial parent, since the progeny will carry some yield traits from the transgenic parent, which may or may not be equal to the potential of the non-transgenic parent. In comparisons made in equal environments, such as the North Carolina official cultivar trials, transgenic siblings of FM 989 and DP 5415 produced 58 to 147 kg/ha more lint than their non-transgenic parents in 45 comparisons over 2001 and 2002 (Bowman 2002, 2003). In 11 trials during 1999 to 2001, ST 4793R averaged 40 kg/ha less lint than it's non-transgenic parent line ST 474 (Bowman, 2002). The remaining 32 comparisons of the ST 474 family in 1999 to 2002 showed a yield advantage of 36 to 160 kg/ha for the transgenic cultivars grown in the same environments (Bowman 2002, 2003). In order to include cultivars with more than one type of herbicide resistance or those that are non-transgenic, official cultivar trials are usually managed with conventional herbicides. Some make the argument that transgenic cultivar evaluation should only be made within the herbicide system for which it was designed (May and Culpepper, 2002). This theory detracts from the conclusions drawn in official cultivar trials.

The objectives of this study were to compare the overall difference in returned profit between non-transgenic and transgenic management systems in cotton considering technology fees, herbicide and insecticide costs, and effect on weed control and the resulting cotton yield and quality. Secondary objectives include comparing GR and BG/GR cotton in conventional and glyphosate herbicide systems and BG and non-BG cotton with and without insecticide.

MATERIALS AND METHODS

Field trials were conducted in 2002 and 2003 in Clayton, North Carolina on a Norfolk loamy sand (Fine-loamy, kaolinitic, thermic Typic Kandiudults) and in Goldsboro, North Carolina on a Wickham loamy sand (Fine-loamy, mixed, semiactive, thermic Typic Hapludults). Trials were planted between 2 May and 9 May each year. Three each of non-transgenic, GR, and BG/GR cultivars were selected representing a respective average of 31, 33, and 52% of cotton cultivars planted in North Carolina during 2001 to 2003 (USDA-AMS, 2003). The non-transgenic cultivars included FM 958, PSC 355, and ST 474; GR cultivars were DP 436 R, FM 989 R, and ST 4793R; and cultivars with BG/GR genes were DP 451 B/RR, PM 1218 BG/GR, and ST 4892BR. Plots were four rows wide with the selected cultivars planted in the middle two rows and a common GR cultivar planted in the border rows. Cotton was planted flat on 97 cm wide rows in all trials except Clayton in 2003 where rows were on beds. Treatments were replicated three times and arranged in a randomized complete block design with plot lengths of 8.5 to 10.7 m depending on location. Management decisions and cultural inputs other than weed and insect control, were made according to North Carolina Extension recommendations (Crozier 2003; Edmisten 2003a; Edmisten 2003b; Koenning 2003; Spears 2003).

Conventional and glyphosate-based herbicide programs were used as a main treatment factor. Each of the nine cultivars were treated with the conventional herbicide program and each of the six transgenic cultivars were included in a glyphosate program. The conventional herbicide program consisted of 1.1 kg ai/ha fluometuron plus 1.1 kg ai/ha pendimethalin PRE, followed by 72 g ai/ha pyrithiobac plus 0.8 kg ai/ha MSMA POST, followed by 0.14 kg ai/ha clethodim POST with 1% v/v crop oil concentrate, followed by 1.1 kg ai/ha prometryn plus 1.9 kg ai/ha MSMA PD with 0.25% v/v non-ionic surfactant. Glyphosate in the form of isopropylamine salt was applied at 0.6 kg ae/ha POST, followed by 0.8 kg ae/ha POST, and 0.8 kg ae/ha PD for all treatments in the glyphosate program. Due to dry conditions and poor activity from soil-applied herbicides, an additional PD application of MSMA was required in the conventional program to control morningglory escapes in Clayton in 2002.

Six additional treatments used FM 958, DP 436 R, and PM 1218 BG/GR. Each of these cultivars was used with the conventional herbicide lacking MSMA POST. These cultivars were also included in treatments consisting of the full conventional herbicide program, however no insecticide was used. FM 958 was also used as an untreated check.

Comparisons for bollworm [*Helicoverpa zea* (Boddie)] control were based on two scouting methods. Cotton was scouted weekly from the middle of July through August. Non-BG cotton, including GR cotton, thresholds for triggering insecticide application were 10 eggs or three live bollworms counted per 100 cotton terminals. Thresholds for BG cotton were 3% bollworms at least 32 mm long either on or around bolls or bloom tags.

Lambda-cyhalothrin at 45 g ai/ha delivered in 75 L/ha water was applied when bollworm thresholds were reached. Bollgard cotton was treated once and non-BG cotton was treated twice per season in all trials except for Goldsboro 2003, which required one more application in each system.

All herbicide applications were made with a CO_2-pressurized backpack sprayer delivering 140 L/ha aqueous solution. Preemergence herbicides were applied directly after planting. First and second POST applications were made when cotton had one and four true leaves, respectively. Clethodim POST was applied for additional grass control to conventional plots at the five- to eight-leaf stage. Cotton had 10 to 14 nodes when PD applications were made. Estimation of weed control and cotton injury due to herbicide or weed competition were recorded by visual ratings on a scale of 0 to 100% prior to lay-by, after lay-by, and late in the season.

Weed species present and their size at each application are listed in Table 1. Tall morningglory was present in all trials and Palmer amaranth and broadleaf signalgrass were present in all trials except Clayton in 2002, which had smooth pigweed and common ragweed. All trials except Clayton in 2003 had entireleaf morningglory, and goosegrass was present in all trials except Goldsboro in 2003. Large crabgrass was present each year in Clayton, pitted morningglory was present in Goldsboro, and common lambsquarters was only present in 2002 at each location. Additional species present in 2003 were fall panicum in Clayton and ivyleaf morningglory, seedling johnsongrass, sicklepod, jimsonweed, and cutleaf groundcherry in Goldsboro in 2002. The middle two plot rows were machine harvested with a spindle picker, and sub-samples of seedcotton were taken from each plot for high volume instrument (HVI) analysis. No yield or quality data were taken for non-treated checks, because no significant cotton was produced in these plots and weed growth was inhibitive to machine harvest. In Goldsboro, Palmer amaranth control without MSMA POST in the conventional herbicide system was so poor that yield was not recorded in 2002 for these three treatments. Seedcotton samples were hand-picked for HVI in these plots. In 2003, Palmer amaranth escapes were removed by hand from the plots in Goldsboro prior to harvest in order to facilitate machine harvest.

Costs for each herbicide program were calculated based on 2002 retail prices in North Carolina for seed, technology fees, herbicides, insecticide, and application. Net return was figured subtracting the total herbicide and insecticide program costs from the gross value of the crop considering base loan value for cotton produced in North Carolina in 2002. Seedcotton yield, percent lint turnout, and HVI data were analyzed to obtain crop value for each herbicide program (2002 Crop Loan Valuation Program, Larry Falconer – Texas Cooperative Extension). Required lint quality input data for the Crop Loan Valuation program include: percent lint turnout, color, leaf grade, micronaire, fiber length, fiber strength, and fiber length uniformity. The assumptions used in cost comparisons are as follows: seeding rate was 13.1 seed/m; non-transgenic seed cost \$58 to \$65/22.7 kg, GR seed including technology fee cost \$105 to \$112/22.7 kg, and BG/GR seed including technology fee cost 192 to \$209/22.7 kg; ginning cost \$0.22/kg, seed value of 0.9 metric/ton was \$85.00, picking and moduling costs for 100 kg seedcotton were \$154.00, each application cost \$12.35/ha, and the base loan value of lint was \$1.17/kg. Retail herbicide, insecticide, and surfactant costs used were: pendimethalin, \$12.67/kg ai; fluometuron, \$19.25/kg ai; prometryn, \$15.40/kg ai; MSMA, \$5.30/kg ai; pyrithiobac, \$828.24/kg ai; glyphosate, \$23.78/kg ae; clethodim, \$187.00/kg ai, lambda-cyhalothrin,

$364.90/kg ai, non-ionic surfactant, $5.28/liter, and crop oil concentrate $2.38/liter. Visual rating data were stabilized via arcsine transformation for statistical analysis in SAS and subject to the general linear model. Non-transformed means are reported in tables. Means were separated using Fisher's Protected LSD at α=0.05 or 0.10. Orthogonal contrasts were used to compare management systems with the same cultivar.

RESULTS AND DISCUSSION

No significant weed species by herbicide program interactions existed for control ratings, so data are pooled by species over locations and years when possible.

Response to Conventional PRE and Early Glyphosate. Weed control ratings were taken prior to the second POST application of glyphosate in 2002, and prior to any glyphosate applications in 2003. Soil-applied herbicides controlled 17 to 32% of morningglory, 87 to 89% of grasses, and 80 to 92% of seedling pigweed in all trials. Early control of pigweed, annual grasses, and morningglory species was similar between conventional and glyphosate systems in 2002 (data not shown). In Clayton in 2002, common ragweed and common lambsquarters were controlled completely by soil-applied herbicides and 96% and 84% control from the first glyphosate application, respectively. Common lambsquarters was controlled by soil-applied herbicides and one application of glyphosate in Goldsboro in 2002. One glyphosate application also controlled 99% of common cocklebur, while fluometuron plus pendimethalin had 17% escapes in Goldsboro in 2002. Sicklepod control was similar between herbicide systems at 77% for glyphosate and 64% for conventional.

Annual grass control: Near perfect grass control was achieved by both the conventional and glyphosate systems prior to lay-by in Clayton in 2002 and Goldsboro in 2003 (Table 2). Conventional herbicides had perfect control of annual grasses in Clayton in 2003 due to residual activity, and some newly emerged grass seedlings attributed to glyphosate only controlling 88%. In contrast, poor activity of soil-applied herbicides in Goldsboro in 2002 resulted in 79% grass control while glyphosate was nearly complete. Grass control was over 96% for both herbicide systems after lay-by. Glyphosate systems provided 99 to 100% grass control late in the season. The conventional programs gave 89 to 93% control of grasses in Goldsboro in 2002 and near complete control in the other trials.

Morningglory species control: Morningglory control prior to lay-by was variable between locations. Pyrithiobac plus MSMA controlled 96 to 99% of morningglory species in Goldsboro, which was better than the 86 to 94% control achieved by glyphosate (Table 3). Pyrithiobac alone performed poorly with only 48 to 77% morningglory control in Goldsboro. Glyphosate controlled morningglory 5% in Clayton in 2003 compared to pyrithiobac plus MSMA, and pyrithiobac alone was less than 50% before lay-by. Both herbicide systems provided better than 97% control of morningglory species at Clayton in 2002. Morningglory control after lay-by was 97% or better in Clayton by both herbicide systems either year. Glyphosate and pyrithiobac plus MSMA achieved nearly complete morningglory control at Goldsboro in 2002, but pyrithiobac alone only controlled 93% after lay-by. Conventional systems controlled all morningglory in Goldsboro in 2003, and glyphosate controlled 94% after lay-by. Late-season morningglory control was 96% or better for all herbicide treatments except for pyrithiobac alone in Goldsboro in 2002 which was 88%.

Pigweed species control: Pigweed species were controlled 95% or greater by either herbicide program throughout the season in Clayton (Table 4). Glyphosate controlled at least 97% of pigweed species at Goldsboro in 2002 and 2003. At any time during the season, conventional herbicides controlled pigweed species 48 to 87% in Goldsboro in both years. The presence of pyrithiobac-resistant Palmer amaranth in Goldsboro caused highly variable results for conventional herbicide performance, which are not representative of expected results such as those found in Clayton in these experiments. Coefficient of variation for visual rating of pigweed control in Goldsboro ranged from 23 to 41 for conventional plots and 3 to 9 in plots treated with glyphosate. Pigweed control ratings in Clayton had a coefficient of variation range of 0 to 14 in all herbicide treatments. Through additional testing, it was determined that both susceptible and resistant Palmer amaranth biotypes were present in Goldsboro. Previous studies have found that Palmer amaranth has variable degrees of susceptibility to pyrithiobac (Bond et al. 2002). Distribution of Palmer amaranth biotypes was variable, helping to explain the great variability in control ratings. Seed was collected from Goldsboro as well as from another site where pigweed species control was acceptable with pyrithiobac. Resistance of Palmer amaranth biotypes to pyrithiobac was verified in a replicated greenhouse trial with pyrithiobac applied at 0, 18, 36, 72, and 143.0 g ai/ha. Plants from suspected resistant seed were controlled 47% by 72 g ai/ha pyrithiobac, while susceptible plants were controlled in excess of 90% 34 DAT. This observation suggests that the resistant seed sample contained a portion of resistant and susceptible biotypes and supports the previously mentioned reasoning for erratic Palmer amaranth control in Goldsboro by pyrithiobac.

Other weed species: Glyphosate controlled 92% of sicklepod before lay-by. MSMA improved pyrithiobac control of sicklepod prior to lay-by from 54 to 73%. Sicklepod control was at least 97% with either herbicide program after lay-by and late in the season. Both herbicide programs provided complete control of common lambsquarters, common ragweed, cutleaf groundcherry, and common cocklebur (data not shown).

Cotton response to herbicides: Cotton injury was recorded after all POST herbicide applications. Soil-applied herbicides caused less than 3% injury in all trials. Pyrithiobac applied POST caused 10% injury, and MSMA plus pyrithiobac increased injury to 16%. Glyphosate injury was 2% after POST herbicides were applied. Four percent injury resulted from PD applications of prometryn plus MSMA, while no injury was recorded for PD glyphosate.

Late-season weed escapes resulted in cotton injury from weed competition in Goldsboro. Herbicide treatments including pyrithiobac plus MSMA POST caused 8% injury and pyrithiobac alone caused 18% injury. Treatments with glyphosate POST had less than 1% biomass reduction from weed competition.

Insect Damage: In North Carolina, green stink bugs [*Acrosternum hilare* (Say)], southern green stink bugs [*Nezara veridula* (L.)], and brown stinkbugs [*Euschistus servus* (Say)] collectively make up the significant cotton-damaging stink bug complex. Green stink bugs caused about 95% of the state-wide boll damage in 2002 (Bacheler 2003). Brown stink bug can commonly be a cotton pest in North Carolina, however none were observed in these tests. Stink bug damage ranged from 2 to 13% in 2002 and no damage was recorded in 2003. Cotton insect loss reports for North Carolina show 65,000 less hectares infested with stink bugs in 2003 compared to 2002 (Bacheler 2003, 2004). Cotton not treated with insecticide had 10 to 13% stink bug damage in both non-BG and BG cultivars, which was statistically different (p<.0800) than the 2 to 5% damage observed in cotton treated with insecticide for 2002.

Cotton bollworm damage ranged from 6 to 36%. Cultivars FM 958 and DP 436 R suffered 27 to 36% boll damage without insecticide, but only 11 to 14% when treated. Although less total boll damage was evident in PM 1218 BG/GR, a significant (p<.0800) improvement from 11 to 6% boll damage from bollworm was recorded when insecticide was used.

Effect on yield, lint turnout, quality, and return: Comparisons between transgenic traits and results from the cultivars used in this study and do not represent nor mean to represent all cotton cultivars in their transgenic class. Return values assume that all input costs involved with producing this crop remain constant between herbicide and insecticide programs, and do not account for them, nor claim to represent them. These data are intended to show gross crop value considering yield and quality less previously mentioned treatment input costs. Costs used are only relevant to the herbicide and insecticide programs and their associated estimated application costs. All remaining input costs should be subtracted from the gross crop value in order to estimate profit per acre. Price in $/kg lint is shown for each treatment in Tables 6 and 7. These values are a product of any premiums or discounts received from HVI testing at a base loan rate of $1.17/kg.

Lint turnout: Percent lint turnout was higher by about 0.93 percent when using glyphosate instead of conventional herbicides. This result is averaged over four trials and the six transgenic cultivars. Ginout was not affected by addition of MSMA POST to the conventional program, or by any insecticide use.

Lint quality: The base length for cotton fiber is 27 mm and discounts are taken for fiber shorter than the base (Hake et al. 1996). Micronaire is an estimation of fiber thickness, measured by surface area, which accounts for fiber perimeter and is affected by maturity and surface characteristics (Hake et al. 1996). The base ranges for micronaire are 3.5 to 3.6 and 4.3 to 4.9, with premiums given for readings between 3.7 and 4.2. To eliminate cultivar effect on herbicide and insecticide main effects on fiber quality, comparisons were made only when the same cultivar or groups of cultivars were present in each treatment. Fiber quality was not affected by insecticide use or the addition of MSMA to the conventional herbicide program. A reduction in fiber length of 0.3 mm was found when using glyphosate instead of the conventional herbicide program for all six transgenic cultivars in the test. The conventional herbicide program also improved fiber strength in GR cultivars by a difference of 6.7 kN m/kg compared to these same three cultivars treated with glyphosate.

Most differences in fiber quality were due to cultivar and are listed in Table 5. Length uniformity and fiber strength for all cultivars were above acceptable minimum values and ranged from 82.7 to 84 percent and 262 to 310 kN m/kg, respectively. FM 958 had the best fiber length of 29.5 mm, while ST 474, 4793R, 4892B/R, and PM 1218 BG/GR were all less than 27.9 mm. Cultivars with average fiber length of less than 27.9 mm are low enough to raise concern for the potential of being shorter than 27 mm and receive a discount. Micronaire reading for all cultivars was within acceptable ranges, and DP 451 B/RR was in the premium range.

Yield and Return: The six treatments used in insecticide comparisons received the full conventional herbicide program. FM 958 produced 1080 kg lint/ha with insecticide and lost 290 kg lint/ha without insecticide (Table 6). DP 436 R and PM 1218 BG/GR did not suffer significant yield loss when no insecticide was used. It is rational that PM 1218 BG/GR would not suffer significant yield damage, however it is equally expected that DP 436 R would be susceptible to the same yield loss from insect damage as FM 958. A possibility is that DP 436 R was able to compensate for insect-damaged bolls by increasing production later in the season because it has an early to medium maturity classification compared to the early maturity classification of FM 958. Another worthy idea, which may be attributable to DP 436 R not revealing a yield loss without insecticide, is that it has less yield potential than FM 958. FM 958 consistently produced 45 to 140 kg lint/ha more than DP 436 R in North Carolina official cotton cultivar trials from 1999 to 2002 (Bowman 2002, 2003). A $210/ha loss was associated with not using insecticide on FM 958 (Table 6).

Considering the conventional herbicide program, there were few distinctions, only noticed in morningglory and sicklepod control, between using MSMA plus pyrithiobac or pyrithiobac alone. The reduction in weed control by pyrithiobac without MSMA did not translate to a significant reduction in yield or return, and in fact the opposite was observed. Injury of 6% from using MSMA POST caused numerical losses of 70 to 240 kg lint/ha in yield and $140 to $340 return losses for FM 958, DP 436 R, and PM 1218 BG/GR, collectively (Table 6). Other studies report similar cotton yield when comparing cotton treated with MSMA POST to untreated cotton (Byrd and York 1987).

Using orthogonal contrasts, cultivars with transgenic traits were compared against conventional cultivars that had been treated with the full conventional herbicide program. Glyphosate-resistant cultivars yielded 180 to 210 kg/ha more lint than non-transgenic and BG/GR cultivars in Clayton in 2002. Stacked cultivars produced 350 to 420 kg/ha more lint than non-transgenic and GR cultivars at Clayton in 2003. Highly variable yield results in Goldsboro did not reveal the same results as Clayton, likely due to a non-uniform distribution of pyrithiobac-resistant biotypes of Palmer amaranth. Overall, glyphosate systems yielded 1370 kg/ha, which was 270 kg/ha more than the same cultivars under conventional herbicide systems.

When glyphosate was used, crops were worth an average of $362 more per hectare than the same cultivars in conventional herbicide systems (Table 7). Stacked cultivars returned $230/ha more than GR cultivars when treated with glyphosate; under the conventional herbicide system, this difference dropped to $168 per hectare because of higher herbicide costs. Conventional cultivars returned similarly to both BG/GR and GR cultivars under the conventional herbicide system, with non-significant numerical separation of $70 less than the BG/GR and $97 more than GR. Despite the negative impact the glyphosate system had on fiber length and strength, lint turnout was improved with glyphosate, and glyphosate systems consistently produced more cotton and returned more profit/ha than the conventional system.

The data herein support the conclusion that cultivar selection is of ultimate importance in managing for yield. Return values were most associated with high yield rather than any other factor. Quality is greatly tied to cultivar traits, and cultivar selection is key when it comes to affecting the profit potential of the crop. These data suggest that conventional cotton managed with accurate scouting and insect control will have acceptable performance. In reality, use of non-transgenic cotton cultivars in North Carolina has nearly been eliminated. According to the cultivar responses in this study, it appears there is more yield potential in the BG/GR cultivars than those with glyphosate resistance alone. The near future holds the advance of many new transgenic options for cotton growers, with improved tolerance to glyphosate, glufosinate resistance, and several variations of insecticidal proteins. Each cultivar and transgenic combination is different and will have unique potential in variable environments. It is important to plant more than one cultivar that has proven performance of acceptable yield and quality in a typical season for the region cotton will be grown in to decrease the risks involved in cotton production. The assertion has been made that high yielding cultivars often have poor lint quality characteristics. The economic results of this work suggest that the highest yielding cultivars returned the greatest profits regardless of quality discounts (Table 7).

ACKNOWLEDGEMENTS

Funded by Cotton Incorporated® and the North Carolina Cotton Producers Association. Technical support was provided by Dan Mott, Rick Seagroves, and Jamie Hinton.

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Table 1 . Population density of weeds in untreated plots and weed growth stages at herbicide application timings for Clayton and Goldsboro, NC in 2002 and 2003.[a,e]

	2002				2003			
Locations and	Weed	Weed size			Weed	Weed size		
weed species	density	POST 1	POST 2	Layby	density	POST 1	POST 2	Layby
	No./m^2	Leaves/plant			No./m^2	Leaves/plant		
Clayton								
Pigweed species[b]	215	1-4	5-8	2-37	12	3-13	4-8	6-14
Morningglory species[c]	4	cot-1	cot-20	cot-5	25	cot-7	cot-14	cot-10
Annual grasses[d]	36	1-2	3-4till	2-9;3-6till	6	5-8	1;3till	2;3till
Common ragweed	2	—[f]	—	—	—	—	—	—
Common lambsquarters	28	—	—	—	—	—	—	—
Goldsboro								
Palmer amaranth	32	2	5-20	—	56	4-10	6-15	6-20
Morningglory species[c]	5	cot-1	4-8	—	6	cot-4	4-7	4-12
Annual grasses[d]	41	2-3	3-4till	11;10till	40	2;3till	3till	2-4till
Sicklepod	1	cot	cot-3	—	—	—	—	—
Jimsonweed	2	cot	4-6	—	—	—	—	—
Common lambsquarters	2	2-3	8	—	—	—	—	—
Cutleaf groundcherry	1	—	—	—	1	2-4	—	6-8

[a] Cotton was at 1-leaf, 4-leaf, and 10 to 14-leaf stages for POST 1, POST 2, and layby herbicide applications.

[b] Pigweed species in Clayton consisted of smooth pigweed in 2002 and Palmer amaranth in 2003.

[c] Morningglory species in Clayton consisted of equal portions of tall morningglory and entireleaf morngingloy in 2002 and tall morningglory in 2003. Goldsboro had 45 percent pitted morningglory, 25 percent tall morningglory, and 30 percent entireleaf/ivyleaf morningglory in 2002 and an equal distribution of tall morningglory, pitted morningglory, and entireleaf morningglory in 2003.

[d] Annual grasses in Clayton were 60 percent large crabgrass and 40 percent goosegrass in 2002 and 35 percent broadleaf signalgrass, 35 percent goosegrass, 15 percent large crabgrass, and 15 percent fall panicum in 2003. Goldsboro annual grass composition was 80 percent broadleaf signalgrass and 10 percent each of goosegrass and seedling Johnsongrass in 2002 and all broadleaf signalgrass in 2003.

[e] Abbreviations: cot, cotyledon; till, tiller

[f] Species not present at time of evaluation.

Table 2. Annual grass control by glyphosate and pyrithiobac applied either alone or mixed with MSMA in Clayton and Goldsboro, NC in 2002 and 2003.[a,b]

Rating	Herbicide	Clayton		Goldsboro	
timing[c]	program	2002	2003	2002	2003
		%			
Before layby	Glyphosate	99 a[d]	88 b	99 a	98 b
	Pyri	99 a	100 a	74 b	100 a
	Pyri + MSMA	100 a	100 a	79 b	100 a
After layby	Glyphosate	100 a	100 a	100 a	100 a
	Pyri	99 a	100 a	96 b	100 a
	Pyri + MSMA	99 a	100 a	97 b	100 a
Late season	Glyphosate	99 a	99 a	100 a	100 a
	Pyri	99 a	99 a	89 b	99 a
	Pyri + MSMA	99 a	100 a	93 b	100 a

[a] Annual grasses in Clayton were 60 percent large crabgrass and 40 percent goosegrass in 2002 and 35 percent broadleaf signalgrass, 35 percent goosegrass, 15 percent large crabgrass, and 15 percent fall panicum in 2003. Goldsboro annual grass composition was 80 percent broadleaf signalgrass and 10 percent each of goosegrass and seedling Johnsongrass in 2002 and all broadleaf signalgrass in 2003.

[b] Abbreviations: pyri, pyrithiobac

[c] Ratings before layby were 25 and 20 June in Clayton and Goldsboro in 2002 and 24 June and 7 July for Clayton and Goldsboro in 2003. Ratings taken after layby were 1 August in 2002 and 15 July in 2003. Late season ratings were taken in the first week of September.

[d] Means followed by the same letter within a column for a rating timing are not statistically different according to Fisher's protected LSD at alpha =0.05.

Table 3. Morningglory species control by glyphosate and pyrithiobac applied alone and mixed with MSMA in Clayton and Goldsboro, NC in 2002 and 2003.[a,b]

Rating timing[c]	Herbicide program	Clayton 2002	Clayton 2003	Goldsboro 2002	Goldsboro 2003
		%			
Before layby	Glyphosate	100 a[d]	98 a	94 b	86 b
	Pyri	97 a	47 c	48 c	77 c
	Pyri + MSMA	99 a	93 b	99 a	96 a
After layby	Glyphosate	100 a	99 a	99 a	94 b
	Pyri	100 a	97 a	93 b	100 a
	Pyri + MSMA	100 a	98 a	100 a	100 a
Late season	Glyphosate	100 a	100 a	96 b	97 a
	Pyri	99 a	98 a	88 c	97 a
	Pyri + MSMA	100 a	100 a	99 a	98 a

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[a] Morningglory species in Clayton consisted of equal portions of tall morningglory and entireleaf morngin glory in 2002 and tall morningglory in 2003. Goldsboro had 45 percent pitted morningglory, 25 percent tall morningglory, and 30 percent entireleaf/ivyleaf morningglory in 2002 and an equal distribution of tall morningglory, pitted morningglory, and entireleaf morningglory in 2003.

[b] Abbreviations: pyri, pyrithiobac

[c] Ratings before layby were 25 and 20 June in Clayton and Goldsboro in 2002 and 24 June and 7 July for Clayton and Goldsboro in 2003. Ratings taken after layby were 1 August in 2002 and 15 July in 2003. Late season ratings were taken in the first week of September.

[d] Means followed by the same letter within a column for a rating timing are not statistically different according to Fisher's protected LSD at alpha =0.05.

Table 4. Pigweed species control by glyphosate and pyrithiobac applied alone and mixed with MSMA in Clayton and Goldsboro, NC in 2002 and 2003.[a,b]

Rating	Herbicide	Clayton		Goldsboro	
timing[c]	program	2002	2003	2002	2003
		%			
Before layby	Glyphosate	100 a[d]	97 a	99 a	97 a
	Pyri	100 a	100 a	78 b	83 b
	Pyri + MSMA	100 a	98 a	87 b	67 c
After layby	Glyphosate	100 a	100 a	100 a	100 a
	Pyri	100 a	99 a	52 c	84 b
	Pyri + MSMA	100 a	97 a	76 b	69 c
Late season	Glyphosate	95 a	100 a	99 a	100 a
	Pyri	100 a	100 a	48 c	86 b
	Pyri + MSMA	100 a	97 b	63 b	62 c

[a] Palmer amaranth was present in all trials except Clayton in 2002, which had smooth pigweed.

[b] Abbreviations: pyri, pyrithiobac

[c] Ratings before layby were 25 and 20 June in Clayton and Goldsboro in 2002 and 24 June and 7 July for Clayton and Goldsboro in 2003. Ratings taken after layby were 1 August in 2002 and 15 July in 2003. Late season ratings were taken in the first week of September.

[d] Means followed by the same letter within a column for a rating timing are not statistically different according to Fisher's protected LSD at alpha =0.05.

Table 5. Micronaire, fiber length, length uniformity, and fiber strength of cotton cultivars in Clayton and Goldsboro, NC in 2002 and 2003.[a]

Variety	Micronaire reading	Length mm	Uniformity index	Strength kN m/kg
FiberMax 958	4.29 b[b]	29.5 a	83.1 bc	310 a
Phytogen 355	4.58 a	28.3 bc	84.0 a	281 b
Stoneville 474	4.38 ab	27.7 cd	83.3 abc	271 cd
Deltapine 436 R	4.21 b	28.6 b	82.7 c	266 cd
Stoneville 4793R	4.41 ab	27.4 de	83.7 ab	271 cd
FiberMax 989 R	3.66 c	28.3 bc	83.3 abc	303 a
Paymaster 1218 BG/RR	4.31 b	27.0 e	83.5 ab	262 d
Deltapine 451 B/RR	4.18 b	28.6 b	82.7 c	264 cd
Stoneville 4892BR	4.34 ab	27.7 d	83.5 ab	273 bc

[a] Herbicides applied were pendimethalin plus fluometuron PRE, pyrithiobac plus MSMA POST, clethodim POST, and prometryn plus MSMA POST directed. Lambda-cyhalothrin was applied as needed for insect control.

[b] Means followed by the same letter within a column are not statistically different according to Fisher's protected LSD at alpha =0.05.

Table 6. Effect of insecticide use and conventional herbicides on cotton fiber yield in Clayton and Goldsboro, NC in 2002 and 2003.[a]

Variety	Insecticide[b]		Cost[c]	Crop value[d]	Yield	Price[e]
			$/ha		kg/ha	$/kg lint
FiberMax 958	None		100	520[f]	790[g]	1.18
FiberMax 958	As needed		123	730	1,080	1.16
Deltapine 436 R	None		108	550	870	1.17
Deltapine 436 R	As needed		131	500	870	1.17
Paymaster 1218 BG/RR	None		133	820	1,250	1.13
Paymaster 1218 BG/RR	As needed		144	690	1,100	1.16
		Herbicide[h]				
FiberMax 958		Pyri[i]	121	880	1,240	1.17
FiberMax 958		Pyri + MSMA	123	730	1,080	1.16
Deltapine 436 R		Pyri	129	640	1,040	1.17
Deltapine 436 R		Pyri + MSMA	131	500	970	1.17
Paymaster 1218 BG/RR		Pyri	142	1,030	1,410	1.16
Paymaster 1218 BG/RR		Pyri + MSMA	144	690	1,170	1.16

[a] Comparisons in this table are made within variety for response to insect control and conventional herbicide programs.

[b] Lambda-cyhalothrin at 44.9 g ai/ha was applied twice to non-BT cotton and once to BT cotton per season in Clayton each year and also in Goldsboro in 2002. Non-BT cotton was treated 3 times and BT cotton was treated twice in Goldsboro in 2003.

[c] Costs represent only those which are variable between treatments for seed, technology fees, herbicide, insecticide, and application; no fixed costs are included in these figures.Cost for each treatment with insecticide in Goldsboro 2003 were $11.64 more than the price in this table since it required one more insecticide application.

[d] Crop value represents the net return after treatment costs and accounts for premiums and discounts associated with lint quality.

[e] Price/kg lint considering lint qlulality premiums and discounts and a base loan value of $1.177/kg.

[f] This value is significantly less than the value for the same variety treated with insecticide in a single degree of freedom orthogonal contrast at $P<0.10$.

[g] This value is significantly less than the value for the same variety treated with insecticide in a single degree of freedom orthogonal contrast at $P<0.05$.

[h] Pyrithiobac applied at 71.5 g ai/ha and MSMA at 833 g ai/ha.

[i] Abbreviations: pyri, pyrithiobac.

Table 7. Treatment cost, lint yield, crop value, and average lint price of cotton treated with conventional and glyphosate herbicide programs in Clayton and Goldsboro, NC in 2002 and 2003.[a]

Variety	Herbicide[b] program	Cost[c]	Crop value[d]	Yield	Price[e]
		$/ha		kg/ha	$/kg lint
FiberMax 958	Conventional	123	730 cdef[f]	1,080 def	1.16
Phytogen 355	Conventional	123	710 def	1,130 cdef	1.13
Stoneville 474	Conventional	123	660 def	1,080 def	1.10
Deltapine 436 R	Conventional	131	500 f	970 f	1.17
Deltapine 436 R	Glyphosate	83	930 bcd	1,220 cde	1.15
FiberMax 989 R	Conventional	136	610 ef	990 ef	1.18
FiberMax 989 R	Glyphosate	88	890 bcd	1,170 cdef	1.17
Stoneville 4793R	Conventional	133	690 def	1,100 def	1.15
Stoneville 4793R	Glyphosate	85	980 abc	1,310 bcd	1.12
Deltapine 451 B/RR	Conventional	139	760 cdef	1,180 cdef	1.15
Deltapine 451 B/RR	Glyphosate	91	1,060 ab	1,360 abc	1.17
Paymaster 1218 BG/RR	Conventional	144	690 def	1,170 cdef	1.16
Paymaster 1218 BG/RR	Glyphosate	96	1,200 a	1,530 ab	1.16
Stoneville 4892BR	Conventional	144	860 bcde	1,300 bcd	1.16
Stoneville 4892BR	Glyphosate	97	1,230 a	1,600 a	1.13

[a] All treated with insecticide as needed. Costs represent only those which are variable between treatments for seed, technology fees, herbicide, insecticide, and application; no fixed costs are included in these figures.

[b] Conventional herbicide program consisted of pendimethalin plus fluometuron PRE, pyrithiobac plus MSMA POST, clethodim POST, and prometryn plus MSMA POST directed. The glyphosate program consisted of two POST applications at 1 and 4 leaf cotton stages and POST directed at the 8 leaf stage.

[c] Costs represent only those which are variable between treatments for seed, technology fees, herbicide, insecticide, and application; no fixed costs are included in these figures.Cost for each treatment with insecticide in Goldsboro 2003 were $11.64 more than the price in this table since it required one more insecticide application.

[d] Crop value represents the net return after treatment costs and accounts for premiums and discounts associated with lint quality. HVI data were analyzed in the 2002 Crop Loan Valuation Program (Larry Falconer, Texas Cooperative Extension).

[e] Price/kg lint considering lint quality premiums and discounts and a base loan value of $1.177/kg.

[f] Means within a column followed by the same letter are not significantly different according to Fisher's Protected LSD at a=0.05.