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WEED SCIENCE

Glyphosate/MSMA Mixtures in Glyphosate-Resistant Cotton (*Gossypium hirsutum*)

A. Stanley Culpepper*, Theodore M. Webster, Alan C. York, Ronnie M. Barentine, and Benjamin G. Mullinix, Jr.

ABSTRACT

Yellow nutsedge (*Cyperus esculentus* L.) and purple nutsedge (*Cyperus rotundus* L.) are troublesome weeds of cotton (*Gossypium hirsutum* L.) in the southeastern United States. Glyphosate and MSMA applied in combination may be more effective in controlling these weeds than either herbicide alone. In field experiments, glyphosate at 0.2, 0.4, 0.6 and 0.8 kg acid equivalent (a.e.) ha^{-1} and MSMA at 0.6, 1.1, and 2.2 kg a.i. ha^{-1} were applied alone and in combination as topical treatments to yellow nutsedge (plants 10 to 20 cm tall) in glyphosate-resistant cotton (3- to 4-leaf stage). When each herbicide was applied alone, yellow nutsedge control increased as the herbicide rate increased. Yellow nutsedge was controlled by glyphosate at 0.4 and 0.8 kg ha^{-1} at 46 and 71%, respectively, and by MSMA at 1.1 and 2.2 kg ha^{-1} at 40 and 90%, respectively. Regression analysis indicated that control of yellow nutsedge with glyphosate in the field and greenhouse improved as the concentration of MSMA increased. Purple nutsedge control with glyphosate was improved with the addition of MSMA, but only when glyphosate was applied at less than 0.6 kg ha^{-1}. Glyphosate was more effective in controlling purple nutsedge than yellow nutsedge, but MSMA was more effective in controlling yellow nutsedge than purple nutsedge. Glyphosate did not cause visible injury to cotton, but MSMA treatments alone and in combination with glyphosate caused stunting and stem reddening. Greater injury occurred from the combination of glyphosate and MSMA than from either herbicide alone, and injury increased as the concentration of glyphosate or MSMA in the mixtures increased. Further research is needed to evaluate strategies to reduce injury and to measure yield response.

A.S. Culpepper, Department of Crop and Soil Sciences, University of Georgia, P. O. Box 1209, Tifton, GA 31793; T.M. Webster, Crop Protection and Management Research Unit, USDA/ARS, P. O. Box 748, Tifton, GA 31793; A. C. York, Department of Crop Science, North Carolina State University, Box 7620, Raleigh, NC 27695-7620; R.M. Baratine, Pulaski Extension Service, University of Georgia, P. O. Box 240, Hawkinsville, GA 31036; B.G. Millinix, Jr., Experimental Statistics, University of Georgia, P. O. Box 748, Tifton, GA 31793-0748
*Corresponding author: stanley@arches.uga.edu

Glyphosate-resistant cotton (*Gossypium hirsutum* L.) cultivars have quickly become the standard technology planted by growers across the Southeast (USDA-ERS, 2003). Widespread use of this technology is due, in part, to the potential to reduce or eliminate soil-applied herbicides, along with reducing total herbicide use (Culpepper and York, 1998 and 1999; Smith and Branson, 2000), to greater flexibility in crop rotations (Rogers et al., 1986; York, 1993), to the capability to control previously uncontrollable weeds in cotton (Byrd, 1995), to the ability to produce more hectares of cotton with less labor and time requirements (Smith et al., 2003), and to the availability of additional herbicide chemistry to use in resistance management programs (Shaw, 1995).

Glyphosate is a highly effective herbicide that controls a broad spectrum of annual and perennial grass and broadleaf weeds (Franz et al., 1997; Wilcut et al., 1996). Several weed species, including yellow nutsedge (*Cyperus esculentus* L.) and purple nutsedge (*Cyperus rotundus* L.), are difficult to manage with a single application of glyphosate (Bariuan et al., 1999; Fischer and Harvey, 2002; Nelson and Renner, 2002). Unfortunately, these nutsedge species are among the most common weeds infesting cotton throughout the Southeast (Webster, 2001). An estimated 0.49 million hectares of cotton in Georgia and North Carolina were infested with these nutsedge species during the 2001 growing season (Byrd, 2002).

Multiple applications of glyphosate effectively control nutsedge species (Swann, 2000), but glyphosate applied once usually only suppresses nutsedge species (Fischer and Harvey, 2002; Nelson and Renner, 2002; Swann, 2000). Topical applications of glyphosate may be applied twice to glyphosate-resistant cotton prior to the fifth-leaf stage, but growers are often limited to a single topical application because of the size of their operation and constraints of labor and time. Since commercial release of glyphosate-resistant cotton in 1997, estimated nutsedge infestations have increased by 18 and 30% in North Carolina and Georgia, respectively (Byrd, 2002), indicating that current glyphosate programs may be less effective on nutsedge species than previous conventional weed management systems.

Growers have the option of a topical application of MSMA for nutsedge control during the early season in several southeastern states, including Georgia and North Carolina. Topical applications of MSMA can cause significant cotton injury (Byrd and York, 1987), so rates for topical application are lower than rates for directed applications (York and Culpepper, 2003). MSMA at rates registered for topical application only suppress nutsedge (Bridges et al., 2002).

Since single topical applications of glyphosate or MSMA to glyphosate-resistant cotton do not adequately control nutsedge, questions have arisen concerning the efficacy of combinations of glyphosate and MSMA. Little research has been published to assist growers and their advisors in determining the value of glyphosate plus MSMA combinations for control of nutsedge species in glyphosate-resistant cotton; therefore, field and greenhouse studies were conducted in Georgia and North Carolina to evaluate combinations of glyphosate and MSMA applied topically for control of yellow and purple nutsedge in glyphosate-resistant cotton.

MATERIALS AND METHODS

Field experiments. The experiments were conducted in Hawkinsville, Georgia, in 1999 and Tifton, Georgia, in 1999 and 2000. The soil at both locations was a Tifton loamy sand (fine-loamy, kaolinitic, thermic Plinthic Kandiudults) with organic matter ranging from 0.7 to 1.2% and pH ranging from 5.5 to 6.1. Glyphosate-resistant cotton cultivars Deltapine 458 B/RR and Sure-Grow 125 B/RR (Delta and Pine Land Co.; Scott, MS) were planted using a vacuum planter spacing seed 10 cm apart into 76-cm rows in conventionally prepared seedbeds at Tifton and Hawkinsville, respectively, between 5 and 29 May.

The experimental design was a randomized complete block with a factorial arrangement of treatments and replicated three times. Herbicide treatments included glyphosate isopropylamine salt (Roundup ULTRA; Monsanto Co., St. Louis, MO) at 0, 0.2, 0.4, 0.6, and 0.8 kg ha^{-1} and MSMA (MSMA Plus H.C.; Helena Chemical Co., Collierville, TN) at 0, 0.6, 1.1, and 2.2 kg ha^{-1}. MSMA Plus H.C. contains a pre-formulated surfactant and is labeled for topical applications to cotton in several southeastern states. Pendimethalin (Prowl 3.3 EC; BASF Corp., Research Triangle Park, NC) at 0.9 kg ai ha^{-1} was applied pre-emergence to all treatments. Cultural practices, including fertilization, insect management, and plant growth management, were standard for Georgia (Jost et al., 2003).

Glyphosate and MSMA alone and in combination were applied topically when cotton was in the 3- to 4-leaf stage. Natural populations of yellow nutsedge were present at each location with densities ranging from 8 to 32 plants m^{-2}. Yellow nutsedge was treated at 10 to 20 cm tall with 4 to 7 leaves. Herbicide treatments were applied using a CO_2-pressurized backpack sprayer equipped with flat-fan nozzles calibrated to deliver 140 L ha^{-1} at 4.8 km ha^{-1}. Crop injury was estimated visually at 10, 20, and 40 days after treatment (DAT), and weed control was evaluated at 20 DAT using a scale of 0 to 100, where 0 = no injury or control and 100 = cotton death or complete weed control (Frans et al., 1986). Cotton yield was not determined.

Greenhouse experiments. These experiments were conducted once in Raleigh, NC, in 1999 and once in Tifton, GA, in 2001. The experimental design was a randomized complete block with treatments replicated four times. Treatments included all combinations of glyphosate at 0, 0.2, 0.4, 0.6, and 0.8 kg ha^{-1} and MSMA at 0, 0.6, 1.1, and 2.2 kg ha^{-1} applied to yellow nutsedge and purple nutsedge.

Six tubers of each nutsedge species were planted in separate 15-cm round pots containing commercial greenhouse potting media (Metro-Mix 220; Scotts-Sierra Horticultural Products Co., Marysville, OH). At initial nutsedge emergence, all pots were thinned to five plants per pot in 1999 and two plants per pot in 2001. Plants were grown with day/night temperatures of 33/17 °C and were subsurface-irrigated as needed. Sunlight was supplemented with metal halide lamps (300 μmol m^{-2} s^{-1} photosynthetic photon flux) for 14 hours daily. All pots received 10 ml of a 13 g L^{-1} commercial greenhouse fertilizer (Peters Professional 20-20-20; Scotts-Sierra Horticultural Products Co., Marysville, OH) solution. Herbicides were applied using a spray chamber equipped with a single even-spray, flat-fan nozzle calibrated to deliver 160 L ha^{-1} at 200 kPa and 2.4 km h^{-1}. Nutsedge control was estimated visually 20 DAT using the scale described previously.

Statistical analysis. Data for weed response and cotton injury were subjected to analysis of variance. The treatment by location (field experiment) and treatment by trial (greenhouse experiment) interactions were not significant, so data were pooled. The relationship between dependent variables (cotton injury and nutsedge control) and rate of glyphosate for each glyphosate plus MSMA mixture was fit to a linear model using Proc MIXED (SAS Version 8.02; SAS Institute, Cary, NC). A quadratic regression model was used when an *F*-test indicated a significant improvement in fit compared with the linear model. Differences among parameter estimates (mean-intercept and slope) of linear regression were evaluated using a *t*-test (Glantz and Slinker, 2001).

RESULTS AND DISCUSSION

Nutsedge control. In the field experiments, control of yellow nutsedge increased as the rate of MSMA or glyphosate increased when each herbicide was applied alone (Figure 1). Glyphosate at 0.4 and 0.8 kg ha^{-1} controlled yellow nutsedge at 46 and 71%, respectively. Yellow nutsedge is often only suppressed by a single application of glyphosate (Fischer and Harvey, 2002; Hoss et al., 2003; Nelson and Renner, 2002; Nelson et al., 2002), and previous research indicated that multiple glyphosate applications were required for adequate control of yellow nutsedge (Fischer and Harvey, 2002; Swann, 2000). Control of yellow nutsedge by MSMA at 1.1 and 2.2 kg ha^{-1} was 40 and 90%, respectively. Previous research indicated that MSMA at rates labeled for topical application ($\leq$1.1 kg ha^{-1}) to cotton will not adequately control yellow nutsedge (Swann, 2000), but directed application of MSMA at 2.2 kg ha^{-1} is often more effective than glyphosate for control of yellow nutsedge (Swann, 2000).

The estimated y-intercept of the regression (effect of MSMA rate in the mixture in controlling yellow nutsedge) and the slope of the regression (effect of glyphosate rate in the mixture in controlling yellow nutsedge) were used to evaluate yellow nutsedge control by the MSMA and glyphosate mixtures. Yellow nutsedge control was significantly higher with MSMA at 2.2 kg ha^{-1} than with MSMA at 1.1 kg ha^{-1} (t = 8.77), but there was no difference between MSMA at 0.6 and 1.1 kg ha^{-1} (t = 1.68). When glyphosate was applied alone, the slope was greater than when MSMA at 0.6 kg/ha was mixed with glyphosate (t = 2.8). Yellow nutsedge control from glyphosate at 0.8 kg ha^{-1} and from glyphosate at 0.8 kg ha^{-1} plus MSMA at 0.6 kg ha^{-1} was similar (71 and 75%, respectively) (Figure 1). The slopes were not different between glyphosate mixed with MSMA at 0.6 and at 1.1 kg ha^{-1} (t = 0.1). The addition of glyphosate to MSMA at 2.2 kg ha^{-1} alone did not improve control of yellow nutsedge, because of the high level of yellow nutsedge control attributed to MSMA at this rate.

In greenhouse studies, yellow nutsedge control from both glyphosate and MSMA confirmed the trends observed in the field (Figure 2). These

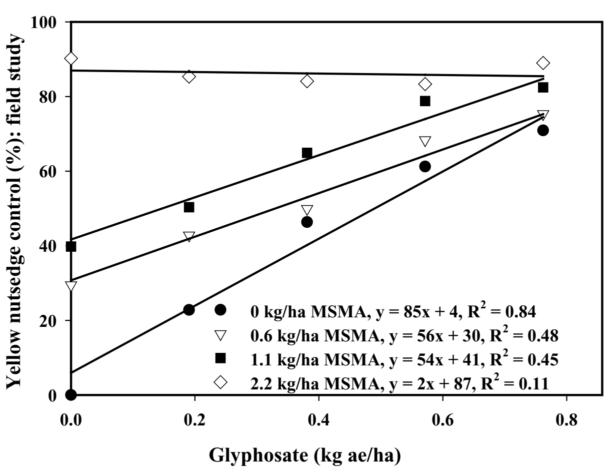

Figure 1. **Yellow nutsedge control at 20 d after treatment by glyphosate plus MSMA combinations in the field experiment. Linear regression was significant for all rates of MSMA (P < 0.0001), except MSMA at 2.2 kg ha^{-1} (P = 0.69).**

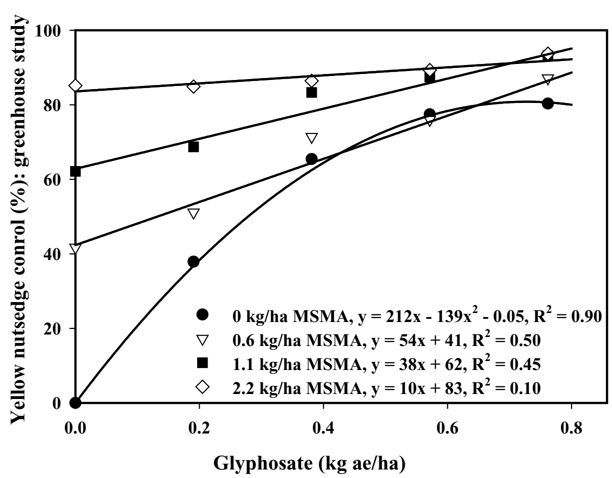

Figure 2. **Yellow nutsedge control at 20 d after treatment by glyphosate plus MSMA combinations in the greenhouse experiment. Linear regression was significant for all rates of MSMA (P ≤0.0007), except MSMA at 2.2 kg ha^{-1} (P = 0.66). Quadratic regression had a significantly better fit than the linear regression for 0 kg ha^{-1} MSMA (P < 0.0001).**

trends included 1) similar yellow nutsedge control by glyphosate at rates >0.4 kg ha^{-1} with or without MSMA at 0.6 kg ha^{-1}; 2) similar slopes for MSMA at 0.6 and 1.1 kg ha^{-1} (t = 1.2); and 3) a high level of yellow nutsedge control from MSMA at 2.2 kg ha^{-1} regardless of the rate of glyphosate. In the field, control of yellow nutsedge by glyphosate without MSMA increased as the rate of glyphosate increased, but in the greenhouse, control was not increased by glyphosate above 0.6 kg ha^{-1}.

When applied alone, control of purple nutsedge increased as the rate of MSMA increased (Figure 3). Control of purple nutsedge by MSMA at 1.1 and 2.2 kg ha^{-1} was 42 and 73%, respectively. Purple nutsedge control with MSMA at 1.1 and 2.2 kg ha^{-1} increased as the rate of glyphosate increased. Control with MSMA at 0.6 kg ha^{-1} and glyphosate without MSMA fit a quadratic relationship that increased for rates of glyphosate upto 0.6 kg ha^{-1}. Purple nutsedge was controlled at 77 and 96% by glyphosate at 0.4 and 0.8 kg ha^{-1}, respectively. Wills and McWhorter (1987) determined that regrowth of purple nutsedge shoot biomass following treatment with MSMA at 1.1 kg ha^{-1} was 61% of the non-treated control. MSMA at 2.0 kg ha^{-1} reduced purple nutsedge shoot numbers 85% at 6 wk after treatment (Zandstra et al., 1974), which was similar to the reduction observed in this study. Unlike yellow nutsedge, the addition of glyphosate at 0.8 kg ha^{-1} to MSMA at 2.2 kg ha^{-1} improved purple nutsedge control by 23% compared with MSMA applied at 2.2 kg ha^{-1} (Figure 3).

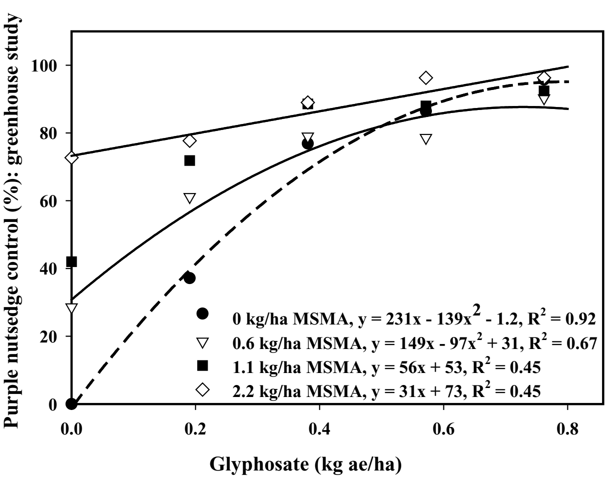

Figure 3. **Purple nutsedge control at 20 d after treatment by glyphosate plus MSMA combinations in the greenhouse experiment. Linear regression was significant for all rates of MSMA (*P* < 0.0001). Quadratic regression had a significantly better fit than the linear regression for 0 kg ha-1 MSMA and 0.6 kg ha^{-1} MSMA (*P* < 0.0001).**

Cotton injury. Applications of glyphosate alone did not injure cotton at 10 DAT, but MSMA at 1.1 and 2.2 kg ha^{-1} injured cotton by 10 and 20%, respectively (Figure 4). Byrd and York (1987) also noted minor injury (<5%) 14 d after topical application of MSMA at 1.1 kg ha^{-1} to cotton in the 2- to 4-leaf stage. When glyphosate was mixed with MSMA, there was a linear increase in cotton injury at 10 DAT relative to MSMA alone. While there were differences (t > 2.7) in cotton injury associated with the different rates of MSMA alone, the effect of glyphosate in the mixtures on cotton injury were not detected (t < 1.7). Maximum cotton injury at 10 DAT was 33% from glyphosate at 0.8 kg ha^{-1} + MSMA at 2.2 kg ha^{-1} (Figure 4). Trends in cotton injury at 20 DAT were similar to those observed at 10 DAT, but less severe (Figure 5). Cotton injury

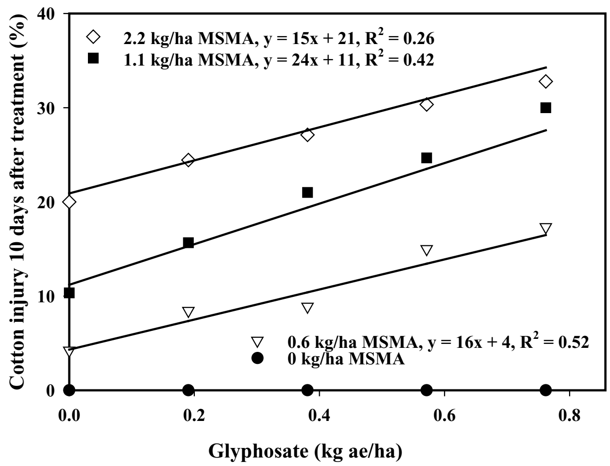

Figure 4. **Cotton injury 10 d after treatment with glyphosate plus MSMA combinations. Linear regression was significant for all rates of MSMA (*P* < 0.0001), except MSMA at 0 kg ha^{-1}.**

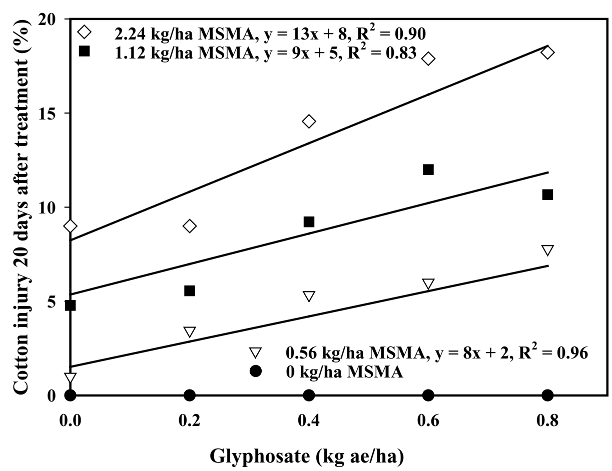

Figure 5. **Cotton injury 20 d after treatment with glyphosate plus MSMA combinations. Linear regression was significant for all rates of MSMA (*P* < 0.0001), except MSMA at 0 kg ha^{-1}.**

was not visible at any location by 40 DAT (data not shown). One potential explanation for the synergistic cotton injury from the glyphosate + MSMA mixtures at 10 and 20 DAT could be related to the amount of adjuvant included in commercial formulations of both glyphosate and MSMA.

CONCLUSIONS

The addition of MSMA at 1.1 or 2.2 kg ha^{-1} to glyphosate increased yellow nutsedge control by $\geq$10% (Figures 1 and 2). At rates of glyphosate >0.4 kg ha^{-1}, the addition of MSMA provided no additional control of purple nutsedge (Figure 3). Results indicate that glyphosate is more effective for control of purple nutsedge than for yellow nutsedge, but MSMA is more effective for control of yellow nutsedge than purple nutsedge, which supports the findings of Swann (2000). Glyphosate applied to yellow nutsedge at 0.8 and 0.6 kg ha^{-1} resulted in <78% control in the field and greenhouse, respectively. Control of purple nutsedge in the greenhouse was <78% with glyphosate rates <0.6 kg ha^{-1}. Although mixing MSMA with glyphosate often improved nutsedge control, greater cotton injury was noted when MSMA was applied in combination with glyphosate compared with MSMA applied alone. Topical applications of the combination of glyphosate and MSMA at 2.2 kg ha^{-1} are likely to injure cotton, but directed applications to glyphosate-resistant cotton offers the potential to control both nutsedge species with a single application while avoiding injury to cotton.

LITERATURE CITED

Bariuan, J.V., K.N. Reddy, and G.D. Wills. 1999. Glyphosate injury, rainfastness, absorption, and translocation in purple nutsedge. Weed Technol. 13:111-119.

Bridges, D.C., T.L. Grey, and B.J. Brecke. 2002. Pyrithiobac and bromoxynil combinations with MSMA for improved weed control in bromoxynil-resistant cotton. J. Cotton Sci. 6:91-96. [Online]. Available at http://journal.cotton.org/2002/issue01/pdf/art10.pdf

Byrd, J.D., Jr. 1995. Herbicide-resistant crops: perspectives from an extension specialist. p. 37. *In* Proc. South. Weed Sci. Soc., Memphis, TN. 16-18 Jan. 1995. South. Weed Sci. Soc., Champaign, IL.

Byrd, J.D., Jr. 2002. Weed database:1978-2001. *In* Proc. Beltwide Cotton Conf., Atlanta, GA. 8-13 Jan. 2002. Natl. Cotton Council Am., Memphis, TN. (Unpaginated CD-ROM).

Byrd, J.D., Jr., and A.C. York. 1987. Interaction of fluometuron and MSMA with sethoxydim and fluazifop. Weed Sci. 35:270-276

Culpepper, A.S., and A.C. York. 1998. Weed management in glyphosate-tolerant cotton. J. Cotton Sci. [Online]. 2:174-185. Available at http://journal.cotton.org/1998/issue04/weed/art01/article.pdf

Culpepper, A.S., and A.C. York. 1999. Weed management and net returns with transgenic, herbicide-resistant, and non-transgenic cotton (*Gossypium hirsutum* L.). Weed Technol. 13:411-420.

Draper, N.R. and H. Smith. 1981. Applied Regression Anlaysis. 2nd ed. Wiley. New York, NY.

Fischer, D.W., and R.G. Harvey. 2002. Yellow nutsedge (*Cyperus esculentus*) and annual weed control in glyphosate-resistant field corn (*Zea mays*). Weed Technol. 16:482-487.

Frans, R.E., R. Talbert, D. Marx, and H. Crowley. 1986. Experimental design and techniques for measuring and analyzing plant responses to weed control practices. p. 29-46. *In* N. D. Camper (ed.) Research methods in weed science. South. Weed Sci. Soc., Champaign, IL.

Franz, J.E., M.K. Mao, and J.A. Sikorski. 1997. Toxicology and environmental properties of glyphosate. p. 103-141. Glyphosate: A unique global herbicide. Am. Chem. Soc. Monogr. 189. Am. Chem. Soc., Washington, DC.

Glantz, S.A., and B.K. Slinker. 2001. Primer of Applied Regression Analysis of Variance. 2nd ed. McGraw-Hill, Medical Pub. Div., New York, NY.

Hoss, N.E., K. Al-Khatib, D.E. Peterson, and T.M. Loughin. 2003. Efficacy of glyphosate, glufosinate, and imazethapyr on selected weed species. Weed Sci. 51:110-117.

Jost, P. J., S. M. Brown, S. Culpepper, G. Harris, B. Kemerait, P. Roberts, D. Shurley,and J. Willams. 2003. Fertilization, insect management and plant development. p. 6-33. *In* 2003 Georgia cotton production guide. Publ. CSS-03-01. Univ. of Georgia Coop. Ext. Serv., Tifton, GA.

Nelson, K.A., and K.A. Renner. 2002. Yellow nutsedge (*Cyperus esculentus*) control and tuber production with glyphosate and ALS-inhibiting herbicides. Weed Technol. 16:512-519.

Nelson, K.A., K.A. Renner, and D. Penner. 2002. Yellow nutsedge (*Cyperus esculentus*) control and tuber yield with glyphosate and glufosinate. Weed Technol. 16:360-365.

Rogers, C.B., R. Talbert, and R. Frans. 1986. Effect of cotton (*Gossypium hirsutum*) herbicide carryover on subsequent crops. Weed Sci. 34:756-760.

Shaw, D.R. 1995. Herbicide-resistant crops and implications for herbicide resistant weeds. p. 38. *In* Proc. South. Weed Sci. Soc., Memphis, TN. 16-18 Jan. 1995. South. Weed Sci. Soc., Champaign, IL.

Smith, K.L., and J.W. Branson. 2000. Effectiveness of soil residual herbicides in Roundup Ready (glyphosate-tolerant) cotton programs. p. 1470-1471. *In* Proc. Beltwide Cotton Conf., San Antonio, TX. 4-8 Jan. 2000. Natl. Cotton Council Am., Memphis, TN.

Smith, N., D. Shurley, B. Givan, and C. Lacey. 2003. Cotton enterprise cost analysis. p. 3-10. *In* Crop enterprise cost analysis south Georgia – 2003. Publ. AGECON-94-010-S. Univ. of Georgia Coop. Ext. Serv., Tifton, GA.

Swann, C.W. 2000. Nutsedge management with Roundup Ready (glyphosate-tolerant) cotton. p. 1465. *In* Proc. Beltwide Cotton Conf., San Antonio, TX. 4-8 Jan. 2000. Natl. Cotton Council Am., Memphis, TN.

USDA - Economic Research Service (USDA-ERS). 2003. The extent of adoption of bioengineered crops [Online]. Available at http://www.ers.usda.gov/publications/aer810/aer810d.pdf (verified 3 May 2004).

Webster, T.M. 2001. Weed survey - southern states. p. 244-248. *In* Proc. South. Weed Sci. Soc., Biloxi, MS. 22-24 Jan. 2001. South. Weed Sci. Soc., Champaign, IL.

Wilcut, J.W., H.D. Coble, A.C. York, and D.W. Monks. 1996. The niche for herbicide-resistant crops in U.S. agriculture. p. 213-230. *In* S.O. Duke (ed.) Herbicide-resistant crops: Agricultural, environmental, economic, regulatory, and technical aspects. CRC Press, Boca Raton, FL.

Wills, G.D. and C.G. McWhorter. 1987. Effect of salt additives on activity and movement of glyphosate and MSMA in purple nutsedge. Tech. Bull.140. Miss. Agric. For. Exp. Stn., Mississippi State, MS.

York, A.C. 1993. Peanut response to fluometuron applied to a preceding cotton crop. Peanut Sci. 20:111-114.

York, A.C. and A.S. Culpepper. 2003. Weed management in cotton. p. 77-123. *In* 2003 Cotton Information. Publ. AG-417. North Carolina State Univ. Coop. Ext. Serv., Raleigh, NC.

Zandstra, B.H., C.K.H. Teo, and R.K. Nishimoto. 1974. Response of purple nutsedge to repeated applications to glyphosate. Weed Sci. 22:230-232.