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Evaluation of Volatility and Physical Drift of 2,4-D, Dicamba, and Triclopyr Formulations

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EVALUATION OF VOLATILITY AND PHYSICAL DRIFT OF 2,4-D, DICAMBA, AND TRICLOPYR FORMULATIONS

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ABSTRACT

Availability of dicamba- and 2,4-D-resistant crops will provide alternative weed management options, but the risk of off-target movement of herbicides to sensitive crops is of concern. Soybean [*Glycine max* (L.) Merr.] treated with diglycolamine (DGA) salt of dicamba at 4.4 g ae/ha (1/128 of the recommended use rate of 560 g/ha) at V3/V4 (two to three trifoliate) was injured 39% 14 days after treatment (DAT) and injury was 97% with 280 g/ha (1/2 of use rate). For application at R1 (first flower), injury 14 DAT was 23% at 1.1 g/ha (1/512 of use rate) and was 68% at 70 g/ha (1/8 of use rate). Soybean yield for dicamba at 4.4 g/ha was reduced 4% when applied at V3/V4 and 10% at R1; for 17.5 g/ha (1/32 of use rate), yield was reduced 16% at V3/V4 and 36% at R1. Research was also conducted to evaluate volatility of various formulations of 2,4-D applied at 1,120 and 2,240 g ae/ha; dicamba applied at 560 and 1,120 g/ha; and triclopyr applied at 1,680 and 3,360 g ae/ha. Herbicides were applied to tilled soil and potted cotton (*Gossypium hirsutum* L.) and tomato (*Solanum lycopersicum* L.) plants were placed in treated strips. Injury was visually rated using four criteria (leaf cupping/crinkling/ drooping; leaf rolling/strapping; stem epinasty; and stem swelling/cracking) and a severity scale of 0 to 5 (0= no injury and 5= severe). A weighted factor assigned to each injury criterion provided an estimate of total injury on a 0 to 100% scale. Only leaf cupping/crinkling/drooping injury was observed for cotton and total injury 14 DAT was no more than 11% for the 1x rates of the herbicides and formulations. Total injury for tomato for the 1x rates of 2,4-D isooctyl ester was 36% 14 DAT and injury was attributed primarily to stem epinasty and stem swelling/cracking. For the 2,4-D dimethylamine (DMA) and acid formulations and for the dicamba DMA, DGA, and acid formulations, total injury for tomato was equivalent and was as

high as 24% for the 1x rates. Injury to tomato with triclopyr butoxyethyl ester was 2.1 times that of triclopyr acid.

CHAPTER 1
INTRODUCTION

The agricultural industry in Louisiana has a significant impact on the state with regard to employment, state legislature policy, and the economy. Over the past few decades commodity prices have risen to record levels and remained at those levels with relative consistency. Row crop acreage has increased and the industry's contribution to the state economy has grown. In 2013, the agricultural industry had an estimated value to the economy of $6.9 billion with plant enterprises consisting of 61% of that (Anonymous 2013). Soybean [*Glycine max* (L.) Merr.] production was valued at $773.4 million with nearly 1.5 billion kg of seed produced on 445,574 ha on 2,394 farms. Cotton (*Gossypium hirsutum* L.) was valued at $147.8 million with 85 million kg of lint harvested across 50,349 ha on 287 farms in 2013. In 2014, there were 546,326 and 72,844 ha planted to soybean and cotton, respectively (USDA 2014a; USDA 2014b). This increase from 2013 can be attributed primarily to promising market futures and increases in production are expected to continue in the future.

In the early 1990s in the mid-South, weed-infested fields planted to cotton, soybean, and corn (*Zea mays* L.) were relatively common. Although numerous herbicides were labeled for use in each crop, it was not economical to control all weeds present in fields because of low commodity prices and high herbicide costs. The introduction of glyphosate-resistant soybean in the mid-1990's offered economic advantages and allowed growers to effectively manage problem weeds that had limited production in the past. Roundup Ready® technology (Monsanto Company, St. Louis, MO 63167) was introduced in soybean in 1996, cotton in 1997, and corn in 1998 that allowed for the use of the non-selective herbicide glyphosate. In many cases, growers were able to effectively manage problem weeds that had limited production in the past. However, where glyphosate was used over several crop cycles, shifts in weed populations in fields were observed. Although glyphosate was effectively removing certain weeds, others less sensitive to the herbicide were becoming more prevalent and causing significant yield losses. This problem was addressed by applying additional glyphosate or tank-mixing glyphosate with other herbicides. Long-term use of glyphosate also selected for glyphosate-resistant weeds (Heap 2014). In Tennessee, Mississippi, and Arkansas, glyphosate-resistant marestail [*Conyza Canadensis* (L.) Cronquist] was identified in 2001 and 2003 (Heap 2014). Glyphosate-resistant Palmer amaranth (*Amaranthus palmeri* S. Wats) was reported in 2005 in Georgia, in 2006 in Arkansas and Tennessee, and in 2008 in Mississippi. Glyphosate-resistant Italian ryegrass [*Lolium perenne* L. spp. *multiflorum* (Lam) Husnot] was reported in Mississippi in 2005 and in Arkansas in 2007. Johnsongrass [*Sorghum halepense* (L.) Pers.] resistance to glyphosate was reported in Arkansas in 2007. In Louisiana, glyphosate-resistant Palmer amaranth and johnsongrass were identified in 2010 and Italian ryegrass in 2014.

Due to the increased prevalence of glyphosate-resistant weeds across the mid-South, companies are currently developing crop cultivars with resistance to additional modes of action. Two novel weed management alternatives are currently under investigation for use in soybean and cotton. Monsanto is developing the Roundup Ready® Xtend Crop System (Monsanto Company, St. Louis, MO 63167) (Seifert-Higgins and Arnevik 2012). This new technology will allow for use of both dicamba and glyphosate in soybean and dicamba, glyphosate, and glufosinate in cotton. Roundup® Xtend, a premix of glyphosate and the diglycolamine (DGA) salt of dicamba with a polybasic polymer added to reduce dicamba volatility, will be available for application before planting and in season over-the-top. The DGA salt of dicamba with the polybasic polymer will also be sold separately to allow growers flexibility in use and in selection of glyphosate formulations. Dicamba as a BAPMA [N,N-Bis-(aminopropyl)methylamine], a tridentate amine salt that provides binding of dicamba residues to suppress volatilization (Xu et al. 2012) will also be available for use in Roundup Ready® Xtend Crop System (BASF Corporation, Research Triangle Park, NC 27709). Due to concerns with volatility and off-target movement issues, dicamba formulations in-crop other than the DGA and tridentate salt formulations will not be allowed for use in the technology.

The Enlist™ Weed Control System with Colex-D™ Technology (Dow AgroSciences LLC, Indianapolis, IN 46268), also a double-traited seed product, will allow for use of 2,4-D, glyphosate, and glufosinate in cotton and soybean (Braxton et al. 2010). Enlist Duo™, the premix that will be marketed for use in the technology, will contain glyphosate and 2,4-D choline, a quaternary ammonium salt with reduced volatility. The 2,4-D choline salt will also be marketed as a stand-alone product. Only the 2,4-D choline salt formulation will be allowed for in-crop use in the technology. Both the Monsanto and Dow AgroSciences technologies, with a tentative release date of 2015, will offer management options for glyphosate-resistant weeds. As was experienced with glyphosate-resistant crops and extensive use of glyphosate (Banks and Shroeder 2002; Ellis et al. 2003), problems are expected due to off-target movement of dicamba and 2,4-D. Soybeans are sensitive to dicamba (Al-Khatib and Peterson 1999; Johnson et al. 2012) and cotton to 2,4-D (Banks and Shroeder 2002).

Monsanto, BASF, and Dow claim to have developed low volatile dicamba and 2,4-D herbicide formulations that will reduce the potential for off-target movement. Also, an acid formulation of 2,4-D without the distinctive phenoxy odor and with reduced volatility has been developed (Helena Chemical Company, Memphis, TN 38017). This formulation contains surfactants that solubilize 2,4-D acid to make a water-miscible liquid formulation. Acid formulations of dicamba and triclopyr have also been developed by Helena Chemical Company.

Synthetic auxins are classified in the O[(4)] HRAC/WSSA Herbicide Mechanism of Action Group that mimics the endogenous auxin indole acetic acid(IAA) (Senseman 2007a). The true mechanism of action is not well understood and the molecular binding site has not been identified. At low concentrations these compounds can stimulate protein biosynthesis and at higher concentrations, cell division and growth is inhibited, usually in the meristematic regions. These compounds primarily affect cell wall plasticity and nucleic acid metabolism. Synthetic auxins provide excellent control of most broadleaf weeds.

2,4-D [(2,4-dichlorophenoxy)acetic acid] is a member of the phenoxy chemical family (Senseman 2007b). Research was initiated on the compound during World War II under wartime secrecy. This chemical has a water solubility of 900 mg/L for the acid, 100 mg/L for the butoxyethyl ester (BEE), 796 mg/L for the dimethylamine salt (DMA), and 0.0324 mg/L for the icooctyl ester. Ester formulations resist washing from leaves and penetrate foliage more rapidly than salt formulations, but once inside the plant, all forms are converted to the acid. The vapor pressure of 2,4-D acid is 4.5×10^{-3} Pa (25 C), but volatility differs depending on the formulation. Losses of salt formulations are said to be minor with amine salts considered to be the least volatile. Among the ester formulations, isooctyl and butoxyethyl forms are considered low-volatile. 2,4-D is used in pastures and rangelands, turf, and in some horticulture crops and aquatic situations. It may be applied POST in small grains and corn at rates of 0.28 to 0.56 kg/ha. In soybean, it may be applied preplant at 0.42 to 1.12 kg/ha. Weedone® LV4 EC (Nufarm Inc., Burr Ridge, IL 60527) and Weedar® 64 (Nufarm Inc., Burr Ridge, IL 60527) are some of the trade names under which 2,4-D is sold.

Dicamba (3,6-dichloro-2-methoxybenzoic acid) is in the benzoic acid chemical family and was discovered by S. B. Richter in 1958 (Senseman 2007c). It has a vapor pressure of 4.5 x

10^{-3} Pa (25 C) and water solubility of 4,500 mg/L for the acid, 720,000 mg/L for the DMA, and 400,000 mg/L for the sodium salt. Dicamba penetrates plant tissue slightly less rapidly than 2,4-D, and among formulations, the DMA penetrates foliage more rapidly than other formulations. It may be applied before planting, PRE, and POST in corn and small grains at rates of 0.28 to 0.56 kg/ha, as well as POST in fallow, pastures and rangelands, and turf. Dicamba is sold under many trade names including Banvel® Herbicide (Arysta LifeScience North America LLC, Cary, NC 27513) and Clarity® herbicide (BASF Corporation, Research Triangle Park, NC 27709).

Triclopyr {[(3,5,6-trichloro-2-pyridinyl)oxy]acetic acid} is a member of the pyridinecarboxylic acid chemical family and was first reported in 1975 (Senseman 2007d). Its vapor pressure is 1.6 x 10^{-4} Pa (25 C), and its water solubility is 430 mg/L for the acid, 23 mg/L for the BEE, and 2,100,000 mg/L for the triethylamine salt. Triclopyr readily penetrates plant foliage, however, leaf adsorption of the BEE formulation is considered to be particularly rapid. Triclopyr is used in rights-of-ways, pastures and rangelands, and turf. It may be applied POST in rice (*Oryza sativa* L.) at 0.28 to 0.42 kg/ha. Garlon® 4 Ultra Specialty Herbicide (Dow AgroSciences, Indianapolis, IN 46268), Remedy® Ultra Specialty Herbicide (Dow AgroSciences, Indianapolis, IN 46268), and Grandstand® R Herbicide (Dow AgroSciences, Indianapolis, IN 46268) are some labeled trade names of triclopyr.

Off-target movement of herbicides can occur through physical drift of the liquid spray solution or through volatilization and subsequent vapor drift of the chemical. Volatilization is the conversion of a substance from a liquid or solid to a gas state. All chemicals have a finite vapor pressure and the higher the vapor pressure, the greater the volatility. Environmental factors, such as high temperature and relative humidity conditions can facilitate herbicide volatility (Egan and Mortenson 2012). For most herbicides, the vapor pressure is such that volatility is of little consequence. For other herbicides, however, volatility can result in significant off-target movement. Losses from volatilization of dicamba as an unformulated acid of 29% during 7 d at 35C (Burnside and Lavy 1966) and 58% in 4 d at 30C (Baur et al. 1973) have been reported.

Behrens and Luechen (1979) reported 92% of the acid dicamba had volatilized at 12 h compared with 43% for the DMA salt. In a field study where potted soybean was placed in corn treated with dicamba, significant soybean injury from volatility of the DMA salt was observed for 3 d after application to corn. Symptoms caused by dicamba vapors were observed on soybean placed up to 60 m downwind of treated corn. Use of less volatile dicamba formulations, diethanolamine and tallow amine salts, did not eliminate dicamba symptoms on soybean. Volatility ceased when treated corn received rainfall of 1mm or more.

Egan and Mortensen (2012) in a field study detected vapor drift of dicamba DMA salt at a mean concentration of 0.56 g/ha (1/1,000th of the applied rate of 560 g/ha) 21 m away from the treated plot. The extent and severity of vapor drift for the DMA salt was positively correlated with air temperature and relative humidity at time of application. Vapor drift for the DGA formulation was reduced compared with the DMA but was not eliminated.

The effect of 2,4-D on cotton is well documented (Bovey and Meyer 1981). In an attempt to quantify volatility and to model herbicide rate versus injury, extreme variability in plant response to 2,4-D, dicamba, and triclopyr was observed for data collected before 14 DAT (Scumibato et al. 2004). For the field study, injury to cotton from volatilization was greater for 2,4-D DMA than for dicamba DGA salts, but both herbicides were less volatile than triclopyr BEE.

Although with auxin herbicides symptomology is easily recognized, subsequent yield loss would be dependent on the herbicide rate, specific crop, and weather conditions prior to and following application. All herbicides are susceptible to off-target movement through physical drift of the liquid spray solution. Herbicide drift is most often the result of improper application (Wauchope et al. 1982). Wind speed, spray pressure, and nozzle height above the intended target are primary contributors to herbicide drift (Hatterman-Valenti et al. 1995). An applicator must consider these conditions in order to minimize spray drift. Maybank et al. (1978) reported that between 1 to 8% of the spray solution with ground sprayers can physically drift beyond the spray swath. Wolf et al. (1992) reported drift from unshielded sprayers as high as 16%. Herbicide application by airplane can increase the risk associated with off-target movement (Martin and Green 1995). Droplet size can influence drift, especially when herbicides are applied by air as ultralow-volume sprays where spray droplets are less than 105 microns in size (Hanks 1995). However, droplet size can be altered through nozzle selection and use of drift retardants specifically designed to reduce spray drift (Bouse et al. 1976).

Glyphosate herbicide is formulated as isopropylamine, ammonia, and potassium salts and is essentially non-volatile. However, off-target movement of glyphosate is common resulting in yield losses in grass crops. Off-target movement of herbicide during application can be somewhere between 1/10 and 1/100 of the applied rate (Wolf et al. 1992). Research has addressed sub-lethal rates of herbicides in drift studies (Al-Khatib and Peterson 1999; Bailey and Kapusta 1993; Snipes et al. 1991, 1992). In susceptible crops, response can be quite severe when herbicide drift occurs at sub-lethal rates. Based on yield reduction, rice and corn can be classified as equally sensitive to glyphosate (Ellis et al. 2003). For both crops, early glyphosate application (2- to 3-leaf rice and 6-leaf corn) reduced yield more than the later application (panicle differentiation in rice and 1 week prior to corn tasseling). Glyphosate at 140 g/ha or 12.5% of the labeled use rate, realistic of what could be expected from herbicide drift (Wolf et al. 1992), reduced rice yield in 2 of 3 years 99 and 67% when applied early and 54 and 29% when applied late. In corn, yield following 140 g/ha glyphosate was reduced an average of 78% over 3 years when applied early and 33% when applied late. Height reduction and foliage discoloration of both rice and corn associated with the lower glyphosate rates in some cases was minimal, but the negative effect on yield was significant (Ellis et al. 2003). Injury and height reduction occurred in most cases when glyphosate was applied at 140 g/ha to 2- to 3-trifoliate soybean and 2- to 3-leaf cotton but both crops recovered rapidly from herbicide injury and yields were not reduced (Ellis and Griffin 2002).

In dicamba-resistant soybean, dicamba applications will be made preplant, at planting, and POST (Seifert-Higgins and Arnevik 2012). The flexibility in application timing during the growing season will increase the opportunity for off-target movement to adjacent fields. Al-Khatib and Peterson (1999) reported that soybean at V3/V4 (two to three trifoliate) treated with dicamba at rates of 5.6 to 187 g/ha (1/100 to 1/3 of the use rate of 560 g/ha) was injured an average of 12 to 66% 7 d after treatment (DAT) and by 14 DAT, injury was 30 to 92%. Severe shoot and petiole epinasty, swollen petioles, leaf cupping, and leaf curling were observed 7 DAT. Dicamba at 5.6 g/ha reduced soybean height 15%, but yield was reduced only 2%. Soybean yield was reduced 45% with dicamba at 56 g/ha. Johnson et al. (2012) reported soybean injury 7 DAT for dicamba applied at 3 g/ha to 20- to 30-cm soybean (pre-bloom) of 8 to 21% and injury was 37 to 80% at 41 g/ha. Soybean yield was reduced 1 to 20% with dicamba at 3 g/ha and 13 to 85% with 41 g/ha. Variability among experiments for visual estimates of injury led to the conclusion that injury from dicamba was only a moderate indicator of yield response. In two experiments Andersen et al. (2004) reported 30 and 40% soybean injury 7 d after a V3 application of dicamba at 5.6 g/ha and 80% injury at 56 g/ha. Soybean yield was reduced 14 and 34% with dicamba at 5.6 g/ha and 72 and 83% with 56 g/ha.

Research has also addressed soybean injury with dicamba applied during reproductive growth stages. Wax et al. (1969) reported yield reduction of 23% when dicamba at 4.4 g/ha was applied at mid-bloom and a 75% yield reduction for application at 35 g/ha. In research conducted over 2 yr with dicamba applied at early bloom, Auch and Arnold (1978) reported that 11 g/ha dicamba reduced soybean yield 34 and 42%; 56 g/ha reduced yield 36 and 67%. Weidenhamer et al. (1989) in a one year study conducted using two soybean cultivars reported no yield reduction when both cultivars were exposed to dicamba at mid-bloom at 5 g/ha and for one of the cultivars treated with 40 g/ha.

In direct comparisons of soybean response to dicamba applied at vegetative and reproductive growth stages, Auch and Arnold (1978) reported an 8% yield increase for application of dicamba at 11 g/ha at V2/V3 and a 9% yield decrease for early-bloom application. Wax et al. (1969) reported greater yield loss for application of dicamba at 4.4 g/ha at mid-bloom (23%) compared with V4 application (4%). In other research, soybean yield was either greater for application of dicamba at 5 g/ha applied at mid-bloom compared with pre-bloom (Weidenhamer et al. 1989), or yield was equivalent for application of 5.6 g/ha at V3 and R2 growth stages (Kelley et al. 2005).

The ability of soybean to recover from significant injury when exposed to low rates of dicamba without suffering yield loss will be important to grower education and acceptance of the dicamba-tolerant crop technology. Future use of 2,4-D and dicamba in herbicide-resistant crops should offer viable weed management alternatives. In the mid-South with high temperature and relative humidity conditions, serious concerns exist as to crop injury resulting from 2,4-D and dicamba volatility, physical drift, and sprayer contamination. Research has not been conducted under the unique climatic conditions of the mid-South to evaluate the effect of off-target movement of these auxin herbicides on crops or to evaluate differences in volatility as related to the various herbicide formulations.

Literature Cited

Al-Khatib, K. and D. Peterson. 1999. Soybean (Glycine max) response to simulated drift from selected sulfonylurea herbicides, dicamba, glyphosate, and glufosinate. Weed Technol. 13:264-270.

Andersen, S. M., S. A. Clay, L. J. Wrage, and D. Matthees. 2004. Soybean foliage residues of dicamba and 2,4-D and correlations to application rates and yield. Agron. J. 96:750-760.

Anonymous. 2013. Agriculture: Backbone of Louisiana's Economy. Web page: http://www.lsuagcenter.com/agsummary. Accessed 22 June 2014.

Auch, D. E. and W. E. Arnold. 1978. Dicamba use and injury on soybeans (*Glycine max*) in South Dakota. Weed Sci. 26:471-475.

Bailey, J. A. and G. Kapusta. 1993. Soybean (Glycine max) tolerance to simulated drift of nicosulfuron and primisulfuron. Weed Technol. 7:740-745.

Banks, P. A. and J. Shroeder. 2002. Carrier volume affects herbicide activity in simulated spray drift studies. Weed Technol. 16:833-837.

Baur, J. R., R. W. Bovey, and H. G. McCall. 1973. Thermal and ultraviolet loss of herbicides. Arch. Environ. Contam. Toxicol. 1:289-302

Behrens, R. and W. E. Lueschen. 1979. Dicamba volatility. Weed Sci. 27:486-493.

Braxton, L. B., C. Cui, M. A. Peterson, J. S. Richburg, D. M. Simpson, and T. M. Wright. 2010. Dow Agrosciences herbicide tolerance traits (DHT) in cotton. Page 35 in Proceedings of the Beltwide Cotton Conference, New Orleans, LA, Jaunuary 4-7, 2010. Memphis, TN: National Cotton Council of America.

Bouse, L. F., J. B. Carlton, and M. G. 1976. Spray recovery from nozzles designed to reduce drift. Weed Sci. 24:361-365.

Bovey, R. W. and R. E. Meyer. 1981. Effects of 2,4,5-T, triclopyr, and 3,6-dichoropicolinic acid on crop seedlings. Weed Sci. 29:256-261.

Burnside, O. C. and T. L. Lavy. 1966. Dissipation of dicamba. Weeds 14:211-214.

Egan, J. F. and D. A. Mortensen. 2012. Quantifying vapor drift of dicamba herbicides applied to soybean. Environ. Toxicol. Chem. 31:1023-1031.

Ellis, J. M. and J. L. Griffin. 2002. Soybean (*Glycine max*) and cotton (*Gossypium hirsutum*) response to simulated drift of glyphosate and glufosinate. Weed Technol. 16:580-586.

Ellis, J. M., J. L. Griffin, S.D. Linscombe, and E. P. Webster. 2003. Rice (*Oryza sativa*) and corn (*Zea mays*) response to simulated drift of glyphosate and glufosinate. Weed Technol. 17:452-460.

Hanks, J. E. 1995. Effect of drift retardant adjuvants on spray droplet size of water and paraffinic oil applied at ultralow volume. Weed Technol. 9:380-384.

Hatterman-Valenti, H., M. D. K. Owen, and N. E. Christians. 1995. Comparison of spray drift during postemergence herbicide applications to turfgrass. Weed Technol. 9:321-325.

Heap, I. M. 2014. International survey of herbicide resistant weeds. Available at www.weedscience.org. Accessed June 26, 2014.

Johnson, V. A., L. R. Fisher, D. L. Jordan, K. E. Edmisten, A. M. Stewart, and A. C. York. 2012. Cotton, peanut, and soybean response to sublethal rates of dicamba, glufosinate, and 2,4-D. Weed Technol. 26:195-206.

Kelley, K. B., L. M. Wax, A. G. Hager, and D. E. Riechers. 2005. Soybean response to plant growth regulator herbicides is affected by other postemergence herbicides. Weed Sci. 53:101-112.

Martin, J. R. and J. D. Green. 1995. Herbicide drift - A growing concern in Kentucky. Proc. South. Weed Sci. Soc. 48:204.

Maybank, J., K. Yoshida, and R. Grover. 1978. Spray drift from agricultural pesticide applications. Air Pollut. Control Assoc. J. 28:1009-1014.

Sciumbato, A. S., J. M. Chandler, S. A. Senseman, R. W. Bovey, and K. L. Smith. 2004. Determining exposure to auxin-like herbicides. II. Practical application to quantify volatility. Weed Technol. 18:1135-1142.

Seifert-Higgins, S. and C. L. Arnevik. 2012. Development of weed management recommendations for dicamba tolerant soybeans. Proc. So. Weed Sci. Soc. 65:266.

Senseman, S. A., ed. 2007a. Herbicide Handbook. 9th ed. Lawrence, KS: Weed Science Society of America. Pp. 15.

Senseman, S. A., ed. 2007b. Herbicide Handbook. 9th ed. Lawrence, KS: Weed Science Society of America. Pp. 322-328.

Senseman, S. A., ed. 2007c. Herbicide Handbook. 9th ed. Lawrence, KS: Weed Science Society of America. Pp. 335-338.

Senseman, S. A., ed. 2007d. Herbicide Handbook. 9th ed. Lawrence, KS: Weed Science Society Of America. Pp. 359-361.

Snipes, C. E., J. E. Street, and T. C. Mueller. 1991. Cotton (*Gossypium hirsutum*) response to simulated triclopyr drift. Weed Technol. 5:493-498.

Snipes, C. E., J. E. Street, and T. C. Mueller. 1992. Cotton (*Gossypium hirsutum*) injury from simulated quinclorac drift. Weed Sci. 40:106-109.

[USDA] United State Department of Agriculture. 2014a. 2014 Acreage, Yield, Production and Price for Cotton. Available at http://www.nass.usda.gov/Quick_Stats/Lite/result.php?96BB8E72-B76F-37EE-A63B-4F1E5040EE5C. Accessed 22 June 2014.

[USDA] United State Department of Agriculture. 2014b. 2014 Acreage, Yield, Production and Price for Soybeans. Available at http://www.nass.usda.gov/Quick_Stats/Lite/result.php? 9165C776-F8E4-38F3-9682-8E6A181D91CE. Accessed 22 June 2014.

Wauchope, R. D., E. P. Richard, and H. R. Hurst. 1982. Effects of simulated MSMA drift on rice (*Oryza sativa*). II. Arsenic residues in foliage and grain and relationships between arsenic residues, rice toxicity symptoms, and yields. Weed Sci. 30:405-410.

Wax, L. M., L. A. Knuth, and F. W. Slife. 1969. Response of soybeans to 2,4-D, dicamba, and picloram. Weed Sci. 17:388-393.

Weidenhamer, J. D., G. B. Triplett, Jr., and F. E. Sobotka. 1989. Dicamba injury to soybean. Agron. J. 81:637-643.

Wolf, T. M., R. Grover, K. Wallace, S. R. Shewchuk, and J. Maybank. 1992. Effect of protective shields on drift and deposition characteristics of field sprayers. In The Role of Application Factors in the Effectiveness and Drift of Herbicides. Agric. Canada, Regina, SK. pp. 29-52.

Xu, W., T. M. Cannan, C. W. Finch, G. Schnabel, S. J. Bowe, and C. L. Brommer. 2012. Advancements in dicamba formulation. Proc. Weed Sci. Soc. Am. Web page: http://wssaabstracts.com/public/9/proceedings.html. Accessed 22 June 2014.

CHAPTER 2
SOYBEAN RESPONSE TO DICAMBA APPLIED AT VEGETATIVE AND REPRODUCTIVE GROWTH STAGES

Introduction

Introduction of glyphosate-resistant soybean in the mid-1990's offered economic advantages and allowed growers to effectively manage problem weeds that had limited production in the past. Long-term use of glyphosate, however, selected for glyphosate-resistant weeds (Heap 2012). Dicamba is a synthetic auxin herbicide currently used in corn (*Zea mays* L.), small grains, and pastures for control of broadleaf weeds. Advances in technology have led to the development of dicamba-resistant soybean (Seifert-Higgins and Arnevik 2012). Cultivars with both glyphosate- and dicamba-resistance traits, expected to be available in 2015, will provide a viable weed management option. There is concern, however, for the potential off-target movement of dicamba and injury to sensitive crops. Behrens and Lueschen (1979) reported significant injury to soybean from volatility of the dimethylamine (DMA) salt of dicamba up to 3 d following application to corn. Egan and Mortensen (2012) detected vapor drift of dicamba DMA salt at a mean concentration of 0.56 g ae/ha (1/1000th of the applied rate of 560 g/ha) 21 m away from the treated plot. The extent and severity of vapor drift for the DMA salt was positively correlated with air temperature at time of application.

All herbicides are prone to off-target movement as spray particle drift. Maybank et al. (1978) reported that between 1 to 8% of the spray solution with ground sprayers can physically drift beyond the spray swath. Wolf et al. (1992) reported drift from unshielded sprayers as high as 16%. Wind speed, spray pressure, and nozzle height above the intended target are primary contributors to herbicide drift (Hatterman-Valenti et al. 1995). In dicamba-resistant soybean, dicamba applications will be made preplant, at planting, and POST (Seifert-Higgins and Arnevik

2012). The flexibility in application timing during the growing season will increase the opportunity for off-target movement to adjacent fields. Al-Khatib and Peterson (1999) reported that soybean at V3/V4 (two to three trifoliate) treated with dicamba at rates of 5.6 to 187 g/ha (1/100 to 1/3 of the use rate of 560 g/ha) was injured an average of 12 to 66% 7 d after treatment (DAT) and by 14 DAT, injury was 30 to 92%. Severe shoot and petiole epinasty, swollen petioles, leaf cupping, and leaf curling were observed 7 DAT. Dicamba at 5.6 g/ha reduced soybean height 15%, but yield was reduced only 2%. Soybean yield was reduced 45% with dicamba at 56 g/ha.

Johnson et al. (2012) reported soybean injury 7 DAT for dicamba applied at 3 g/ha to 20- to 30-cm soybean (pre-bloom) of 8 to 21% and injury was 37 to 80% at 41 g/ha. Soybean yield was reduced 1 to 20% with dicamba at 3 g/ha and 13 to 85% with 41 g/ha. Variability among experiments for visual estimates of injury led to the conclusion that injury from dicamba was only a moderate indicator of yield response. In two experiments Andersen et al. (2004) reported 30 and 40% soybean injury 7 d after a V3 application of dicamba at 5.6 g/ha and 80% injury at 56 g/ha. Soybean yield was reduced 14 and 34% with dicamba at 5.6 g/ha and 72 and 83% with 56 g/ha.

Research has also addressed soybean injury with dicamba applied during reproductive growth stages. Wax et al. (1969) reported yield reduction of 23% when dicamba at 4.4 g/ha was applied at mid-bloom at 4.4 g/ha and a 75% yield reduction for application at 35 g/ha. In research conducted over 2 yr with dicamba applied at early bloom, Auch and Arnold (1978) reported that 11 g/ha dicamba in two years reduced soybean yield 34 and 42%; 56 g/ha reduced yield 36 and 67%. Weidenhamer et al. (1989) in a one year study conducted using two soybean cultivars reported no yield reduction when both cultivars were exposed to dicamba at mid-bloom at 5.0 g/ha and for one of the cultivars treated with 40 g/ha.

In direct comparisons of soybean response to dicamba applied at vegetative and reproductive growth stages, Auch and Arnold (1978) reported an 8% yield increase for application of dicamba at 11 g ha^{-1} at V2/V3 and a 9% yield decrease for early-bloom application. Wax et al. (1969) reported greater yield loss for application of dicamba at 4.4 g/ha at mid-bloom (23%) compared with V4 application (4%). In other research, soybean yield was either greater for application of dicamba at 5 g/ha applied at mid-bloom compared with pre-bloom (Weidenhamer et al. 1989), or yield was equivalent for application of 5.6 g/ha at V3 and R2 growth stages (Kelley et al. 2005).

Future use of dicamba in dicamba-resistant soybean should offer a viable weed management alternative for the mid-South. Serious concerns, however, exist as to soybean injury resulting from dicamba volatility, physical drift, and sprayer contamination. Data comparing soybean treated with dicamba at vegetative and reproductive growth stages is limited and inconsistent. Research has not been conducted to evaluate soybean injury from dicamba in the mid-South where hot and humid conditions could greatly affect response. The objective of this research was to evaluate soybean injury and yield of soybean exposed to sub-lethal rates of dicamba at vegetative and reproductive growth stages.

Materials and Methods

Experiments to evaluate soybean response to dicamba were conducted at the LSU AgCenter, Central Research Station, Ben Hur Research Farm in Baton Rouge, LA, in 2008, 2009, and 2010; at the Northeast Research Station in St. Joseph, LA, in 2009 and 2010; and at the Dean Lee Research and Extension Center in Alexandria, LA, in 2010. For experiments conducted at each location, soil type and soil classification along with soil pH and organic matter, soybean cultivar and maturity group, and planting and harvest date information are provided in Table 2.1. Soybean was planted at a seeding rate of around 300,000 seed/ha. In each experiment, glyphosate (Roundup WeatherMax, Monsanto Co., St. Louis, MO 63167) was applied twice at 870 g/ha when weeds were 5 to 8 cm tall and around 2 weeks later to eliminate weed competition.

Because of the number of dicamba rates being evaluated, the concern for cross contamination between/among plots, and the field size required, separate experiments for dicamba application at V3/V4 (two to three fully expanded trifoliates) and R1 (first flower) were conducted each year and each location. Experiments (V3/V4 and R1) at each location, however, were conducted in either adjacent fields or within the same field separated by a large buffer area and soybean cultivar and planting date were the same (Table 2.1). The DGA salt formulation of dicamba (Clarity® herbicide, BASF Corporation, Research Triangle Park, NC 27709) was used. For the V3/V4 experiments, dicamba was applied at 4.4, 8.8, 17.5, 35, 70, 140, and 280 g/ha (1/128 to ½ of the manufacturer's use rate of 560 g/ha). For the R1 experiments, dicamba was applied at 1.1, 2.2, 4.4, 8.8, 17.5, 35, and 70 g/ha (1/512 to 1/8 of use rate). A nontreated control was included in both studies for comparison. The original plan was to evaluate the same rates in both experiments. After seeing the severe injury with the higher dicamba rates and the minimal injury at the lower rates following the V3/V4 application in the first year in 2008, the decision was made for the R1 application to eliminate the two highest rates (140 and 280 g/ha) and to add two lower rates (1.1 and 2.2 g/ha).

Specific application dates for each experiment along with rainfall received 2 wk before dicamba application (WBA), 0 to 2 wk after application (WAA), and 2 to 4 WAA are shown in

Table 2.1. Soil type and soil classification, soybean cultivar and maturity group (MG), and planting and harvest date information for dicamba experiments conducted in Baton Rouge, St. Joseph, and Alexandria, LA.

Location	Year	Soil type/classification; pH / organic matter (OM) percent	Cultivar/ Maturity Group[a]	Plantin g date	Harvest date	
					V3/V4 application	R1 application
Baton Rouge	2008	Mhoon silt loam (fine-silty, mixed, nonacid, thermic Typic Fluvaquent); pH 6.3 / OM 1.9	DPL 5808 RR / MG 5	May 20	Sep 29	Sep 29
	2009	Mhoon silt loam; pH 6.3 / OM 1.9	AsGrow 5803 / MG 5	May 12	Oct 13	Oct 13
	2010	Mhoon silt loam; pH 6.3 / OM 1.9	AsGrow 5606 / MG 5	May 25	Oct 18	Oct 18
St. Joseph	2009	Mhoon silt loam ; pH 6.8 / OM 0.5	DKB 46-51 / MG 4	May 19	--	Sep 30
	2010	Mhoon silt loam; pH 6.8 / OM 0.5	TV 49R19/ MG 4	May 25	Oct 8	Oct 8
Alexandria	2010	Coushatta silt loam (fine-silty, mixed, superactive, thermic Fluventic Entrudepts); pH 7.8 / OM 2.3	Pioneer 95Y20 / MG 5	May 24	Oct 7	Oct 14

[a]Maturity group 4 cultivars are considered to be indeterminate and MG 5 cultivars are considered to be determinate.

Table 2.2. Ranges in maximum temperature and relative humidity 2 WBA, 0 to 2 WAA, and 2 to 4 WAA are provided in Tables 2.3 and 2.4, respectively. For all experiments, dicamba treatments were applied using a CO_2-pressurized backpack sprayer calibrated to deliver 140 L/ha spray volume at 170 to 270 kPa. Sprayers were fitted with 110 degree XR flat-fan nozzles (TeeJet Technologies, Springfield, IL 62703) and wind speed at application was no more than 4.8 km/h. Treated areas consisted of either two rows spaced 76 cm apart or 3 rows spaced 38 cm apart. Nontreated border areas between plots were 152 cm wide. Cross contamination between adjacent treated plots based on visible injury was not apparent. The experimental design for each experiment was a randomized complete block with four replications.

Soybean injury ratings were made 7 and 14 DAT using a scale of 0 (no injury) to 100% (plant death). Injury included leaf cupping and crinkling, stem and leaf petiole epinasty, terminal chlorosis/death, stem swelling, and stem cracking. To document the ability of soybean to recover from dicamba injury, canopy height was determined 28 DAT and mature height was determined just prior to harvest. Soybean was combine-harvested in late September/October (Table 2.1) and yields were adjusted to 13% moisture.

Data were subjected to the Mixed Procedure in SAS (SAS Institute Inc., Cary NC 27513). Years, locations, replications (nested within years and location), and all interactions containing these effects were considered random (Carmer et al. 1989). Herbicide rate was considered a fixed effect. Considering year and location as random effects permits inferences about treatments to be made over a range of environments (Carmer et al. 1989). Based on ANOVA, significant herbicide rate effects ($P < 0.05$) were observed for all parameters measured in both V3/V4 and R1 studies. Data for all of the parameters (injury ratings, canopy height, mature height, and yield) were not collected for all six experiments conducted. For the V3/V4

Table 2.2. Rainfall received 2 weeks before dicamba application (WBA), 0 to 2 weeks after application (WAA), and 2 to 4 WAA for experiments conducted in Baton Rouge, St. Joseph, and Alexandria, LA.

Location	Year	Application timing	Application date	Rainfall		
				2 WBA	0 to 2 WAA	2 to 4 WAA
				------------------cm--------------------		
Baton Rouge	2008	V3/V4	June 16	1.2	4.5	4.2
	2009	V3/V4	June 1	1.6	0.1	3.0
	2010	V3/V4	June 21	0.5	5.1	4.6
St. Joseph	2009	V3/V4	June 15	0.5	0.0	5.4
	2010	V3/V4	June 18	1.8	0.4	3.9
Alexandria	2010	V3/V4	June 16	11.4	3.5	6.6
Baton Rouge	2008	R1	July 17	4.2	5.8	6.8
	2009	R1	June 26	0.0	6.5	2.5
	2010	R1	July 9	4.5	3.9	5.9
St. Joseph	2009	R1	June 29	0.00	5.4	8.6
	2010	R1	July 16	1.8	5.8	5.5
Alexandria	2010	R1	July 8	10.0	2.0	2.6

application, data for soybean injury 7 and 14 DAT represented six experiments (Baton Rouge in 2008, 2009, and 2010; St. Joseph in 2009 and 2010; Alexandria in 2010); data for canopy height 28 DAT and yield represented five experiments (Baton Rouge in 2008, 2009, and 2010; St. Joseph in 2010; Alexandria in 2010); and data for mature height represented two experiments (Baton Rouge in 2010; Alexandria in 2010). For the R1 application, data for soybean injury 7 DAT and yield represented six experiments (Baton Rouge in 2008, 2009, and 2010; St. Joseph in 2009 and 2010; Alexandria in 2010); data for injury 14 DAT and canopy height 28 DAT

Table 2.3. Range in maximum temperature 2 weeks before dicamba application (WBA), 0 to 2 weeks after application (WAA), and 2 to 4 WAA for experiments conducted in Baton Rouge, St. Joseph, and Alexandria, LA.

Location	Year	Application timing	Application date	Maximum temperature range		
				2 WBA	0 to 2 WAA	2 to 4 WAA
				---------------------------C-------------------------		
Baton Rouge	2008	V3/V4	June 16	31 - 33	31 - 34	31 - 34
	2009	V3/V4	June 1	25 - 32	27 - 33	34 - 37
	2010	V3/V4	June 21	32 - 35	29 - 36	27 - 34
St. Joseph	2009	V3/V4	June 15	27 - 33	32 - 37	26 - 37
	2010	V3/V4	June 18	29 - 36	30 - 37	32 - 37
Alexandria	2010	V3/V4	June 16	28 - 36	30 - 38	29 - 36
Baton Rouge	2008	R1	July 17	31 - 35	31 - 36	27 - 34
	2009	R1	June 26	32 - 37	32 - 37	29 - 35
	2010	R1	July 9	27 - 34	30 - 34	27 - 37
St. Joseph	2009	R1	June 29	32 - 37	26 - 37	27 - 36
	2010	R1	July 16	32 - 36	32 - 37	31 - 38
Alexandria	2010	R1	July 8	29 - 36	31 - 38	32 - 41

represented five experiments (Baton Rouge in 2009 and 2010; St. Joseph in 2009 and 2010; Alexandria in 2010); and data for mature height represented three experiments (Baton Rouge in 2010; St. Joseph in 2010; and Alexandria in 2010). For both the V3/V4 and R1 studies, regression analyses were used to quantify the relationship between dicamba application rates and each dependent variable by testing for linear and quadratic functions. R^2 values were calculated.

Results and Discussion

V3/V4 Application. Two WBA of dicamba, rainfall for the six experiments totaled 0.5 to 11.4 cm. Soybean was actively growing when dicamba was applied. From the time of

Table 2.4. Range in maximum relative humidity 2 weeks before dicamba application (WBA), 0 to 2 weeks after application (WAA), and 2 to 4 WAA for experiments conducted in Baton Rouge, St. Joseph, and Alexandria, LA.

Location	Year	Application timing	Application date	Maximum relative humidity range		
				2 WBA	0 to 2 WAA	2 to 4 WAA
				-------------------------%-------------------------		
Baton Rouge	2008	V3/V4	June 16	85 - 95	87 - 95	90 - 95
	2009	V3/V4	June 1	80 - 96	86 - 95	87 - 93
	2010	V3/V4	June 21	88 - 95	91 - 95	90 - 95
St. Joseph	2009	V3/V4	June 15	88 - 94	87 - 92	80 - 95
	2010	V3/V4	June 18	87 - 95	85 - 94	84 - 95
Alexandria	2010	V3/V4	June 16	94 - 97	92 - 96	92 - 97
Baton Rouge	2008	R1	July 17	93 - 95	89 - 95	92 - 95
	2009	R1	June 26	87 - 93	84 - 94	91 - 95
	2010	R1	July 9	91 - 95	90 - 95	83 - 96
St. Joseph	2009	R1	June 29	87 - 92	80 - 95	88 - 96
	2010	R1	July 16	84 - 95	88 - 96	85 - 95
Alexandria	2010	R1	July 8	94 - 97	93 - 97	84 - 97

application to 2 WAA, rainfall of 3.5 to 5.1 cm was received for 3 experiments; for the other three experiments rainfall was no more than 0.4 cm (Table 2.2). Rainfall 2 to 4 WAA for all experiments ranged from 3.0 to 6.6 cm. Maximum temperature 2 WBA was 25 to 36C and for 0 to 4 WAA was 26 to 38C (Table 2.3). Maximum relative humidity 0 to 2 WAA ranged from 85 to 96% and from 80 to 97% 2 to 4 WAA (Table 2.4).

A significant quadratic response was observed for soybean injury, canopy height, plant height at maturity, and yield vs. dicamba rate. At 7 DAT, predicted soybean injury increased from 20 to 89% as dicamba rate increased from 4.4 to 280 g/ha (Figure 2.1). By 14 DAT,

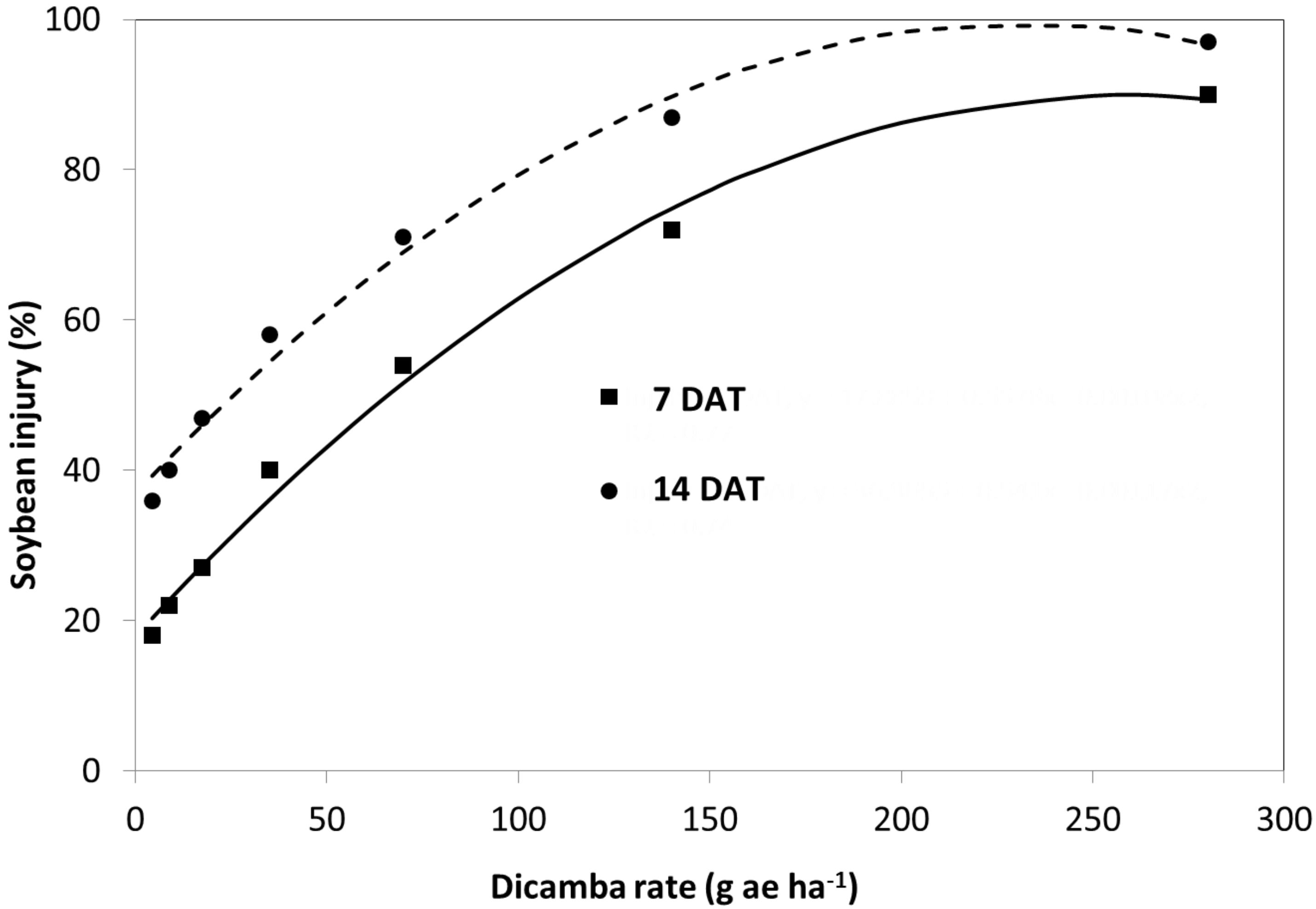

Figure 2.1. Soybean injury 7 and 14 d after treatment (DAT) at V3/V4 with dicamba applied at 4.4, 8.8, 17.5, 35, 70, 140, and 280 g/ha. Points represent observed mean values for experiments conducted in Baton Rouge in 2008, 2009, and 2010; St. Joseph in 2009 and 2010; and Alexandria, LA in 2010. Predicted response 7 DAT (solid line) is described by $y = 17.89 + 0.558x - 0.0011x^2$, $R^2 = 0.77$. Predicted response 14 DAT (dashed line) is described by $y = 36.91 + 0.541x - 0.0012x^2$, $R^2 = 0.74$.

predicted soybean injury at 4.4 to 140 g/ha had increased 15 to 19 percentage points since the earlier evaluation, but increased only 8 percentage points for 280 g/ha (Figure 2.1). Symptomology observed for dicamba consisted of chlorosis of terminals, cupping and crinkling of uppermost leaves, swollen petiole bases, and stem and leaf petiole epinasty. At the higher rates, stem swelling and cracking and necrotic terminals were observed and in some cases, plant terminals were turned down and touching the soil surface.

In research conducted in Kansas, soybean injury when treated with dicamba at V3/V4 at 5.6, 17, 56, and 187 g/ha averaged 12 to 66% 7 DAT (Al-Khatib and Peterson 1999). By 14 DAT, soybean injury for dicamba applied at 5.6, 17, and 56 g/ha had more than doubled since the earlier rating and for dicamba at 187 g/ha, injury increased 26 percentage points. For research conducted in North Carolina where data were reported separately for each experiment, 20- to 30-cm soybean treated with dicamba was injured 7 DAT 8 to 21% for 3 g/ha, 24 to 32% for 11 g/ha, 37 to 80% for 41 g/ha, and 79 to 100% for 140 g/ha (Johnson et al. 2012). In a South Dakota study, soybean was injured 7 DAT an average of 35, 43, and 80% for dicamba at rates of 5.6, 11.2, and 56 g/ha, respectively (Andersen et al. 2004). In the present study predicted canopy height 28 DAT was 67 cm when dicamba was not applied (Figure 2.2) and height was reduced 3 to 24% for dicamba at 4.4 to 35 g/ha; 45% for 70 g/ha; and 72 and 81% for 140 and 280 g/ha, respectively.

Injury observed to soybean from dicamba applied at V3/V4 was reflected in reduced mature height and yield. For the lower rates of dicamba of 4.4 to 17.5 g/ha, predicted mature height was reduced 3 to 9% (Figure 2.3) and yield was reduced 4 to 15% (Figure 2.4). Al-Khatib and Peterson (1999) reported a 10% yield reduction with 17 g/ha dicamba and Wax et al. (1969) reported an 11% yield reduction with 17.5 g/ha. For dicamba applied at 70 g/ha in the present

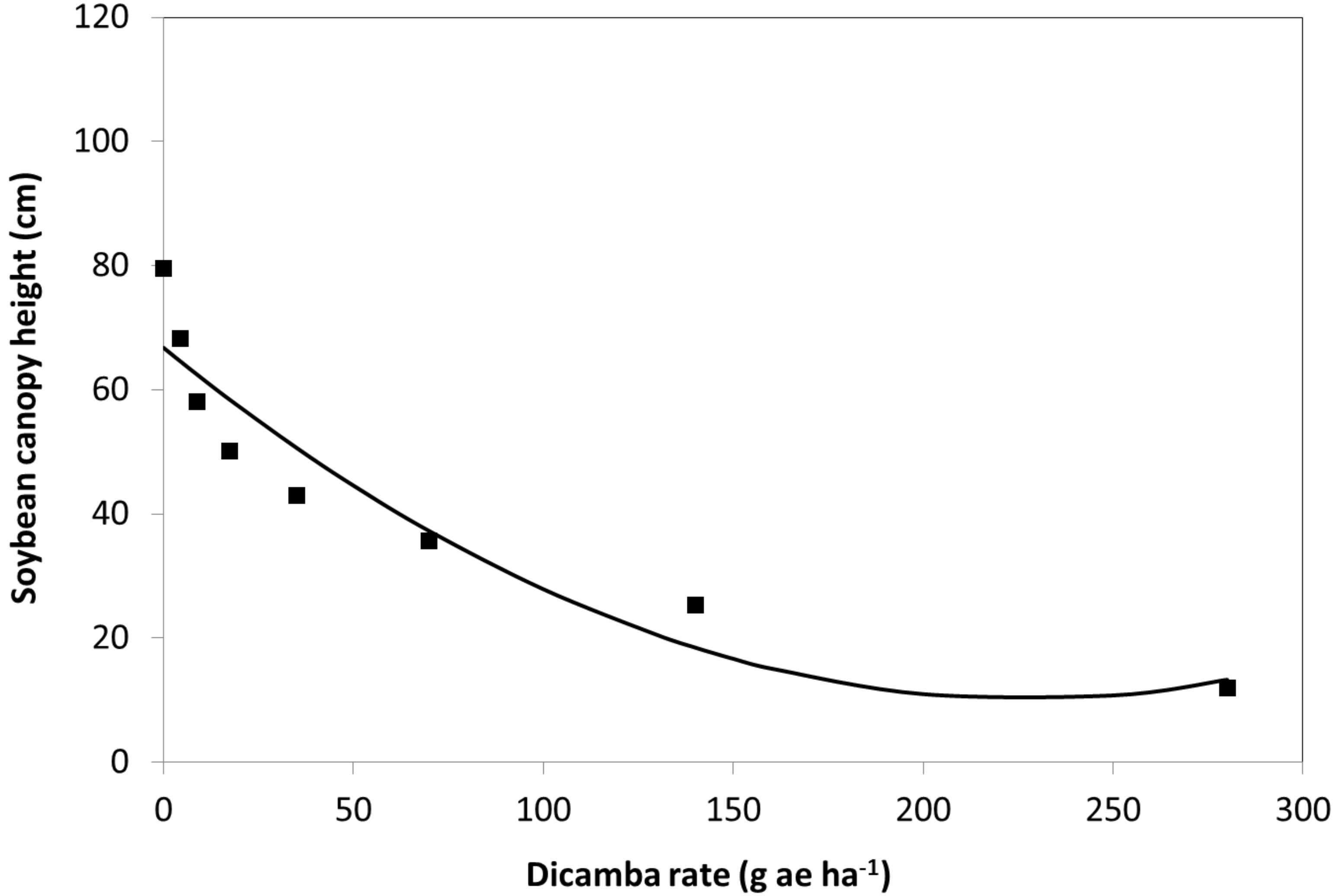

Figure 2.2. Soybean canopy height 28 d after treatment at V3/V4 with dicamba applied at 0, 4.4, 8.8, 17.5, 35, 70, 140, and 280 g/ha. Points represent observed mean values for experiments conducted in Baton Rouge in 2008, 2009, and 2010; St. Joseph in 2010; and Alexandria, LA in 2010. Predicted response is described by $y = 66.79 - 0.499x + 0.0011x^2$, $R^2 = 0.64$.

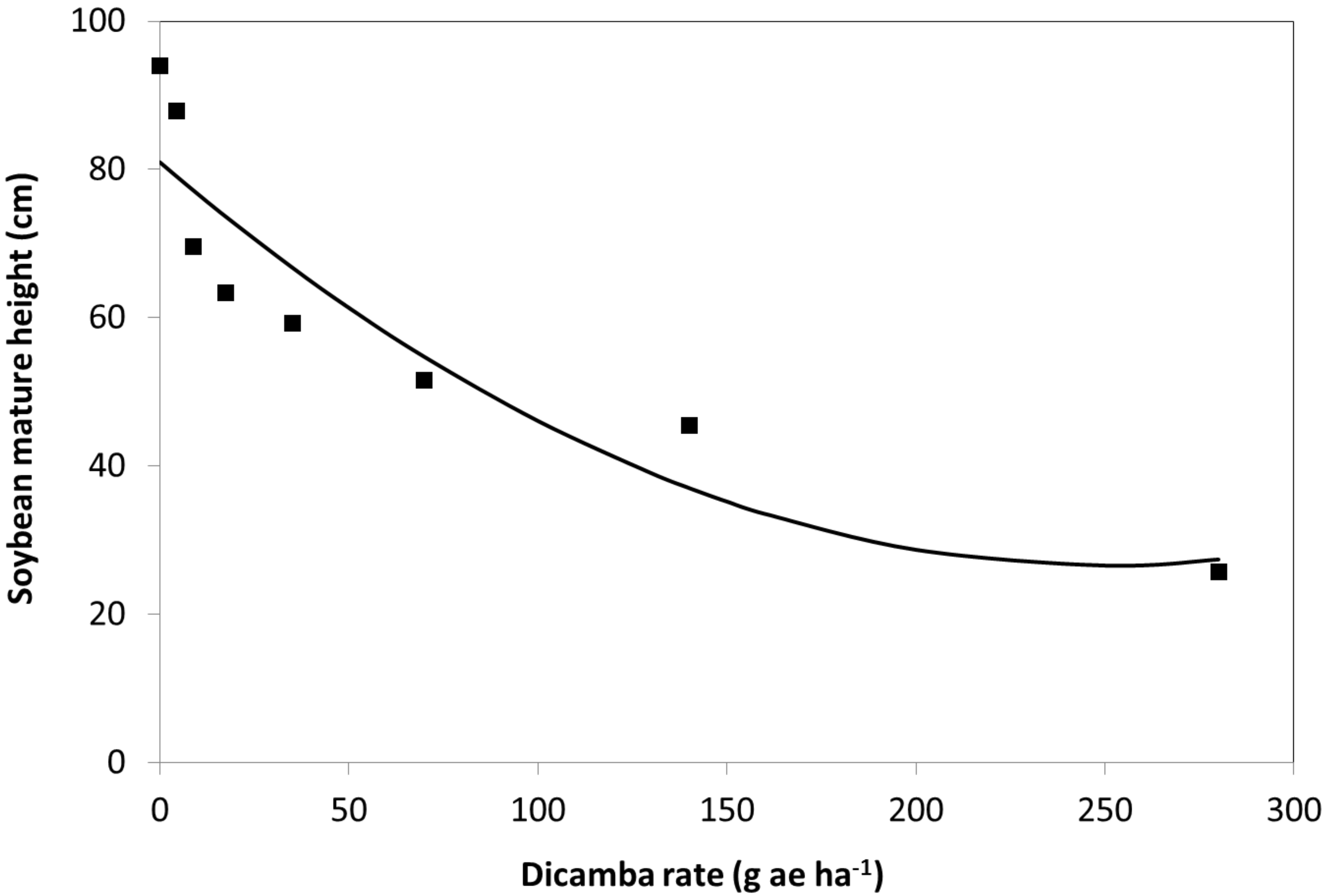

Figure 2.3. Soybean mature height after treatment at V3/V4 with dicamba applied at 0, 4.4, 8.8, 17.5, 35, 70, 140, and 280 g/ha. Points represent observed mean values for experiments conducted in Baton Rouge in 2010 and Alexandria, LA in 2010. Predicted response is described by $y = 80.99 - 0.436x + 0.00088x^2$, $R^2 = 0.42$.

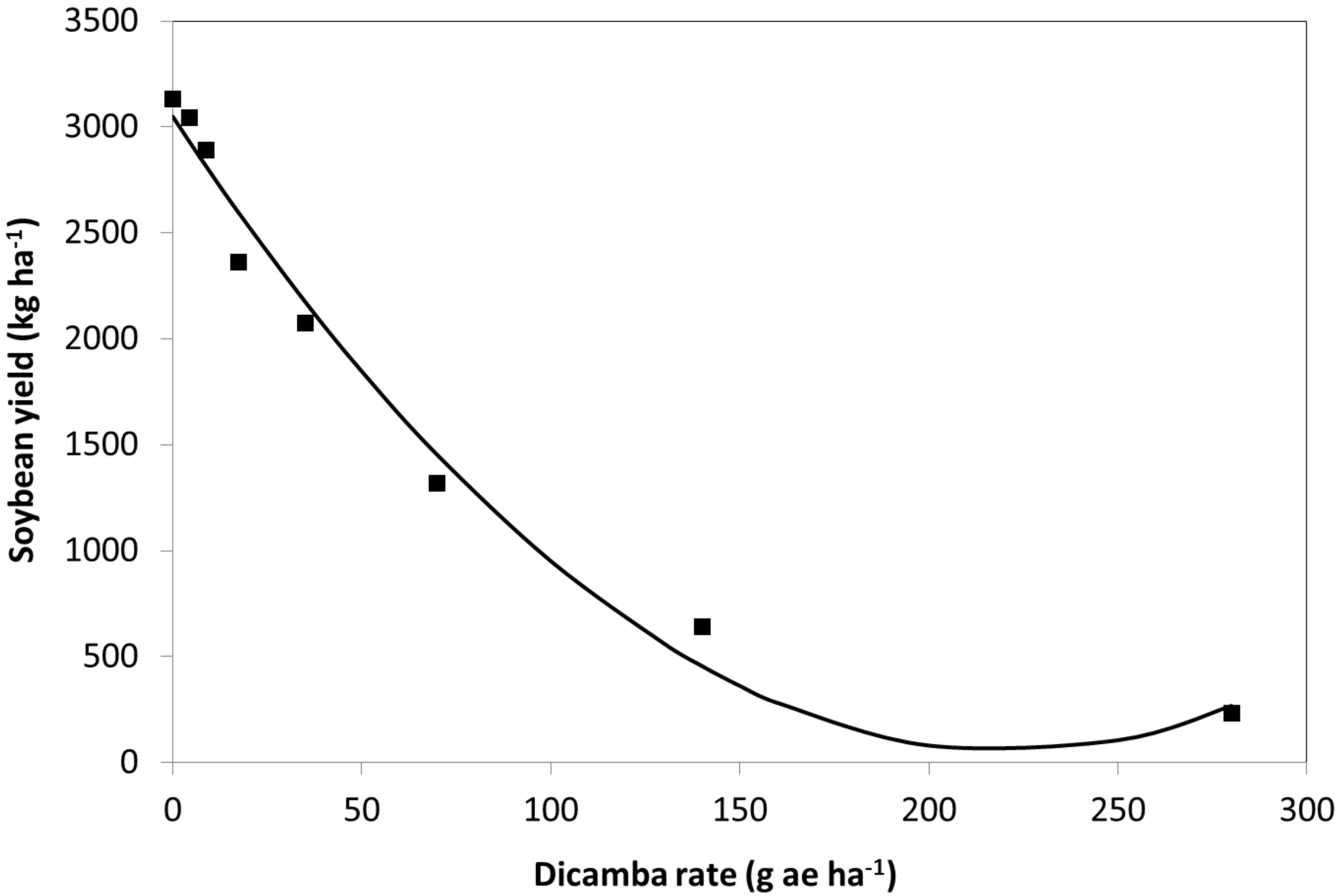

Figure 2.4. Soybean yield after treatment at V3/V4 with dicamba applied at 0, 4.4, 8.8, 17.5, 35, 70, 140, and 280 g/ha. Points represent observed mean values for experiments conducted in Baton Rouge in 2008, 2009, and 2010; St. Joseph in 2010; and Alexandria, LA in 2010. Predicted response is described by $y = 3049.43 - 27.12x + 0.0614x^2$, $R^2 = 0.77$.

study, mature height was reduced 32% and yield was reduced 52%. Al-Khatib and Peterson (1999) reported a 45% yield reduction with dicamba at 56 g/ha. Johnson et al. (2012) reported yield loss of 13 to 85% with 41 g/ha dicamba. In the present study, yield loss was 85% for 140 g/ha dicamba.

R1 Application. With the exception of two experiments, rainfall of 1.8 to 10 cm was received 2 WBA of dicamba (Table 2.2). For those two experiments, plants showed no stress (wilting) at application and rainfall in excess of 2 cm was received during the period of 0 to 2 WAA. Adequate rainfall for all experiments was received 2 to 4 WAA. During the 2 WAA period, maximum temperature ranged from 26 to 38C (Table 2.3) and maximum relative humidity ranged from 80 to 97% (Table 2.4).

A significant quadratic response was noted for soybean injury 7 DAT, canopy height, plant height at maturity, and yield vs. dicamba rate. Predicted soybean injury 7 DAT increased from 19% at 1.1 g/ha dicamba to 64% at 70 g/ha (Figure 2.5). A significant linear response was noted for soybean injury 14 DAT and the predicted increase in injury from 7 to 14 DAT for all rates was no more than 4 percentage points (Figure 2.5). Symptomology was as described previously.

Predicted soybean canopy height 28 DAT was 93 cm where dicamba was not applied (Figure 2.6). Height reduction ranged from 1 to 44% as rate increased from 1.1 to 70 g/ha. Soybean injury 14 DAT of 25% when dicamba was applied at 4.4 g/ha (Figure 2.5) was reflected in an 8% predicted mature height reduction (Figure 2.7) and a 10% predicted yield reduction (Figure 2.8). For 70 g/ha dicamba, mature height was reduced 44% and yield was reduced 73%.

Wax et al. (1969) reported that when dicamba was applied at bloom at 17.5 g/ha, soybean plant height was reduced 46% and soybean yield was reduced 52%. In the present study, mature

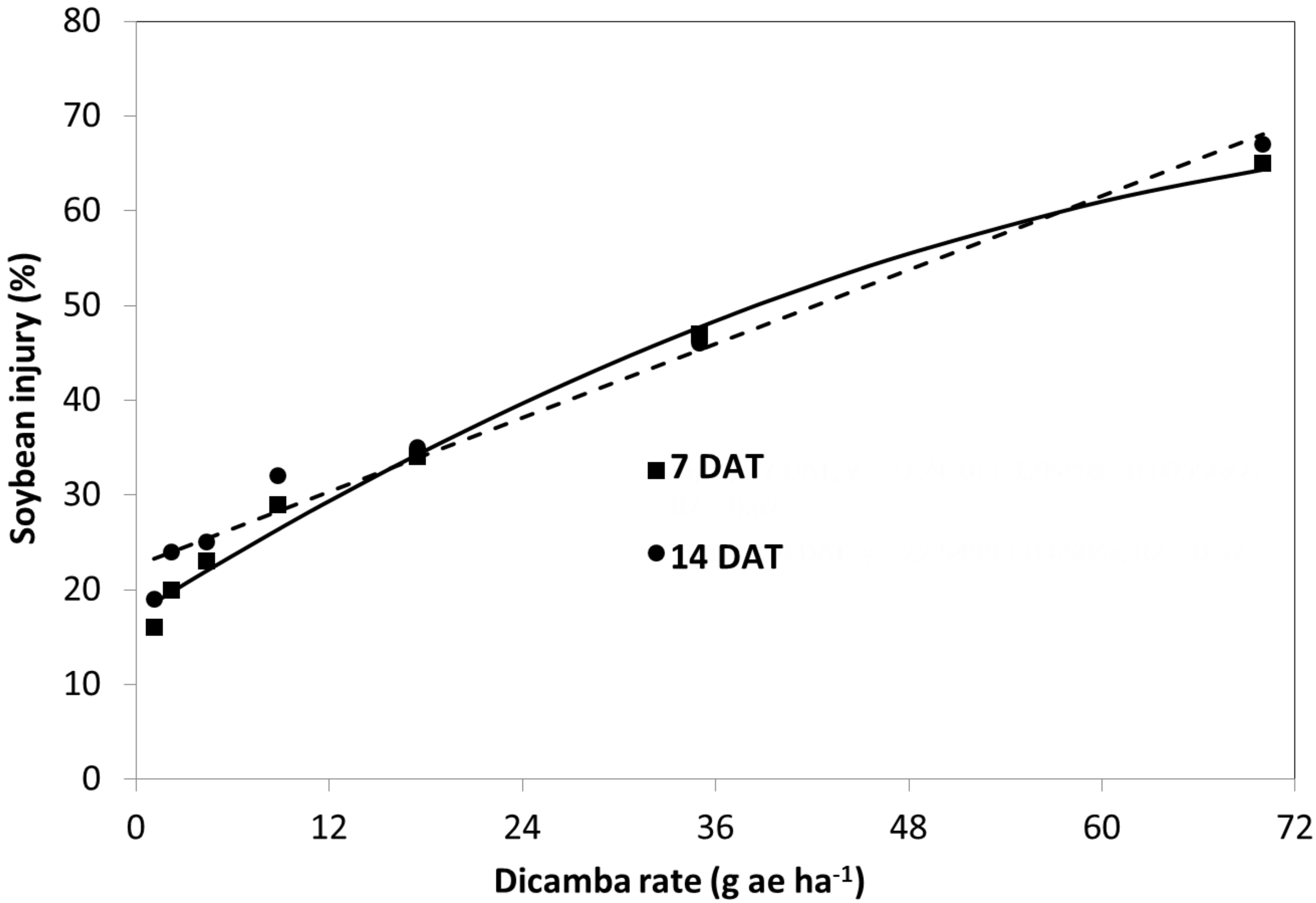

Figure 2.5. Soybean injury 7 and 14 d after treatment (DAT) at R1 with dicamba applied at 1.1, 2.2, 4.4, 8.8, 17.5, 35, and 70 g/ha. Points for 7 DAT represent observed mean values for experiments conducted in Baton Rouge in 2008, 2009, and 2010; St. Joseph in 2009 and 2010; and Alexandria, LA in 2010 and points for 14 DAT represent experiments conducted in Baton Rouge in 2009 and 2010; St. Joseph in 2009 and 2010; and Alexandria, LA in 2010. Predicted response 7 DAT (solid line) is described by $y = 17.46 + 1.059x – 0.0056x^2$, $R^2 = 0.62$. Predicted response 14 DAT (dashed line) is described by $y = 22.55 + 0.65x$, $R^2 = 0.57$.

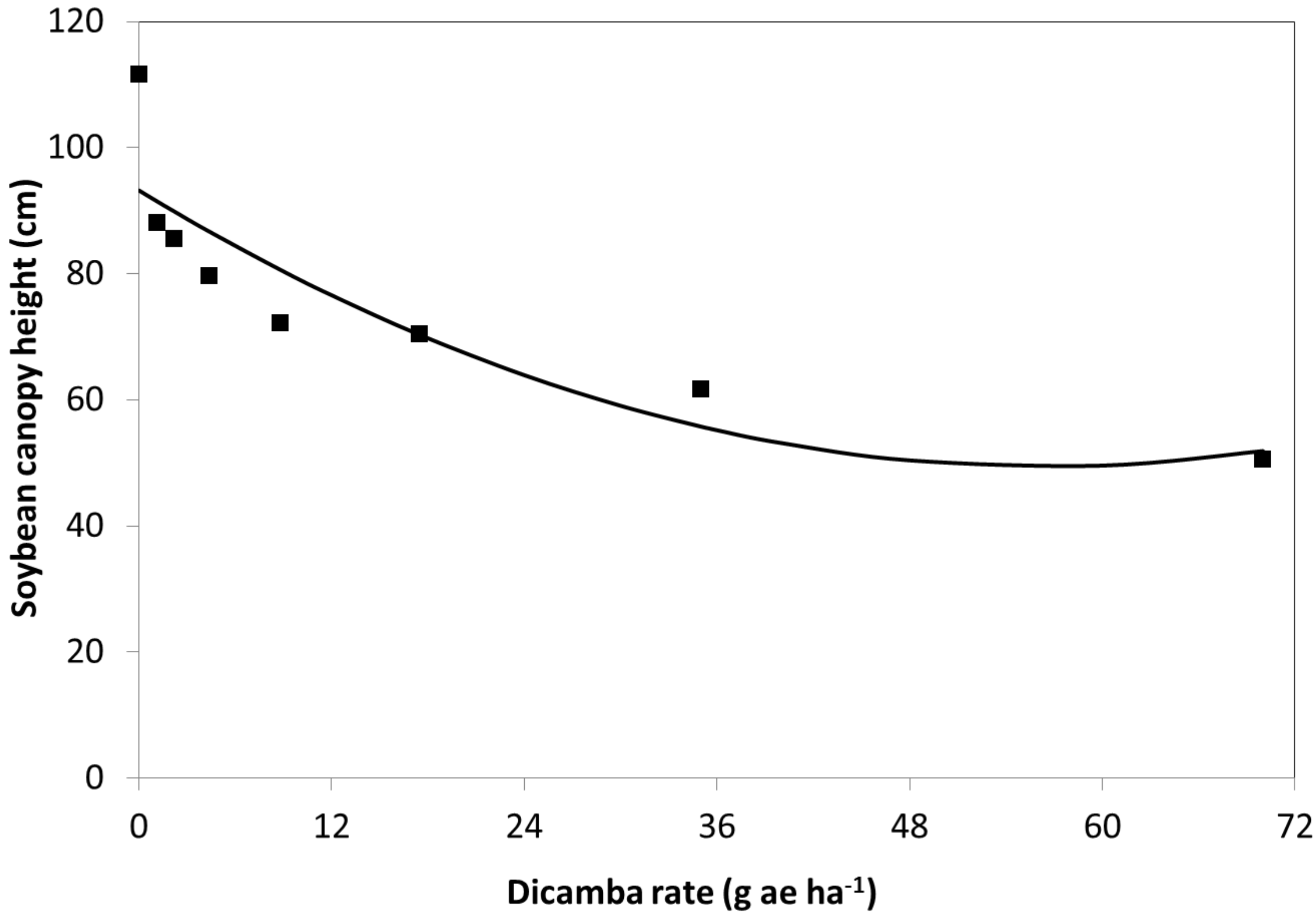

Figure 2.6. Soybean canopy height 28 d after treatment at R1with dicamba applied at 0, 1.1, 2.2, 4.4, 8.8, 17.5, 35, and 70 g/ha. Points represent observed mean values for experiments conducted in Baton Rouge in 2009 and 2010; St. Joseph in 2009 and 2010; and Alexandria, LA in 2010. Predicted response is described by $y = 93.23 – 1.55x + 0.0137x^2$, $R^2 = 0.40$.

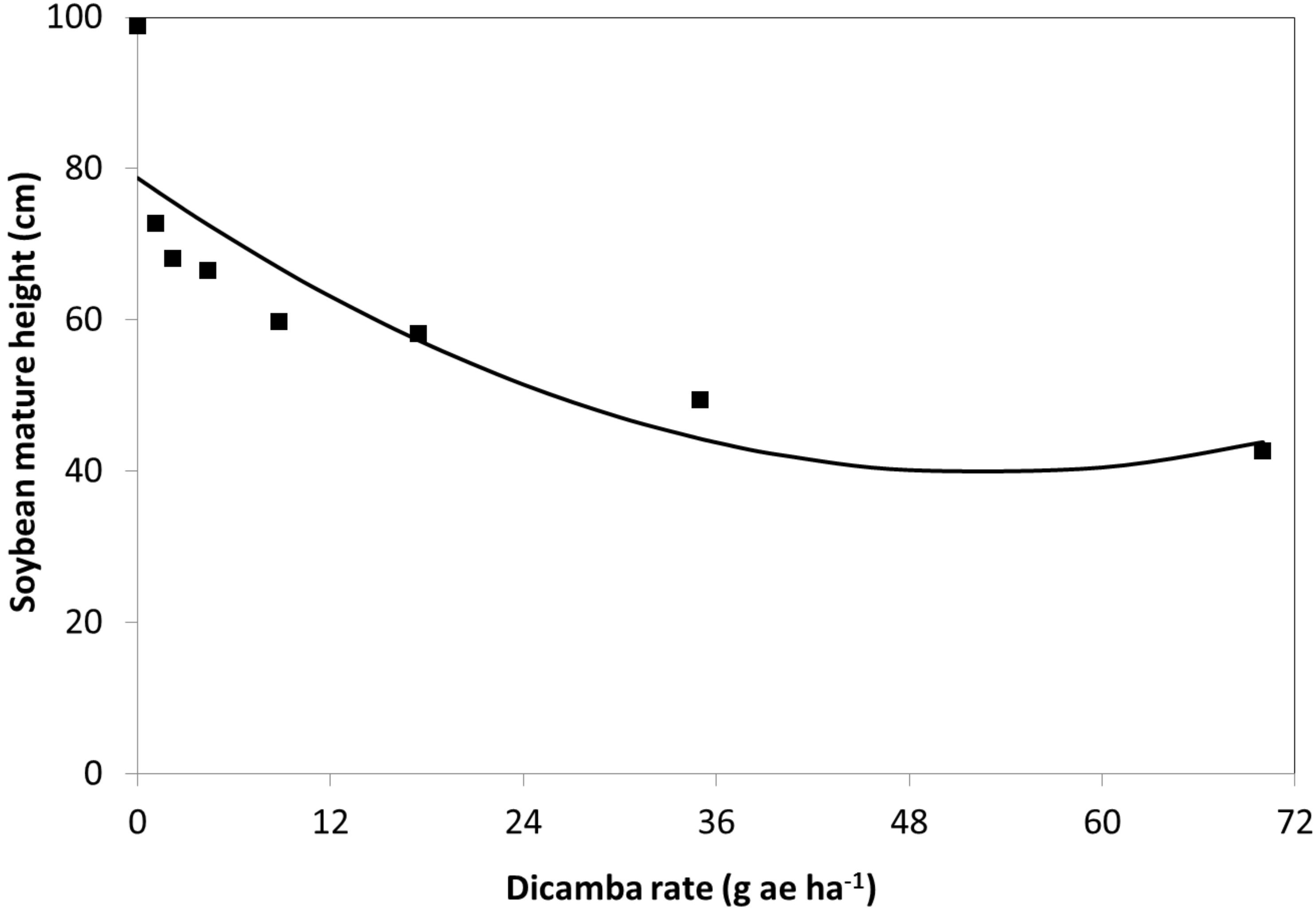

Figure 2.7. Soybean mature height after treatment at R1with dicamba applied at 0, 1.1, 2.2, 4.4, 8.8, 17.5, 35, and 70 g/ha. Points represent observed mean values for experiments conducted in Baton Rouge in 2010; St. Joseph in 2010; and Alexandria, LA in 2010. Predicted response is described by $y = 78.78 – 1.47x + 0.0139x^2$, $R^2 = 0.54$.

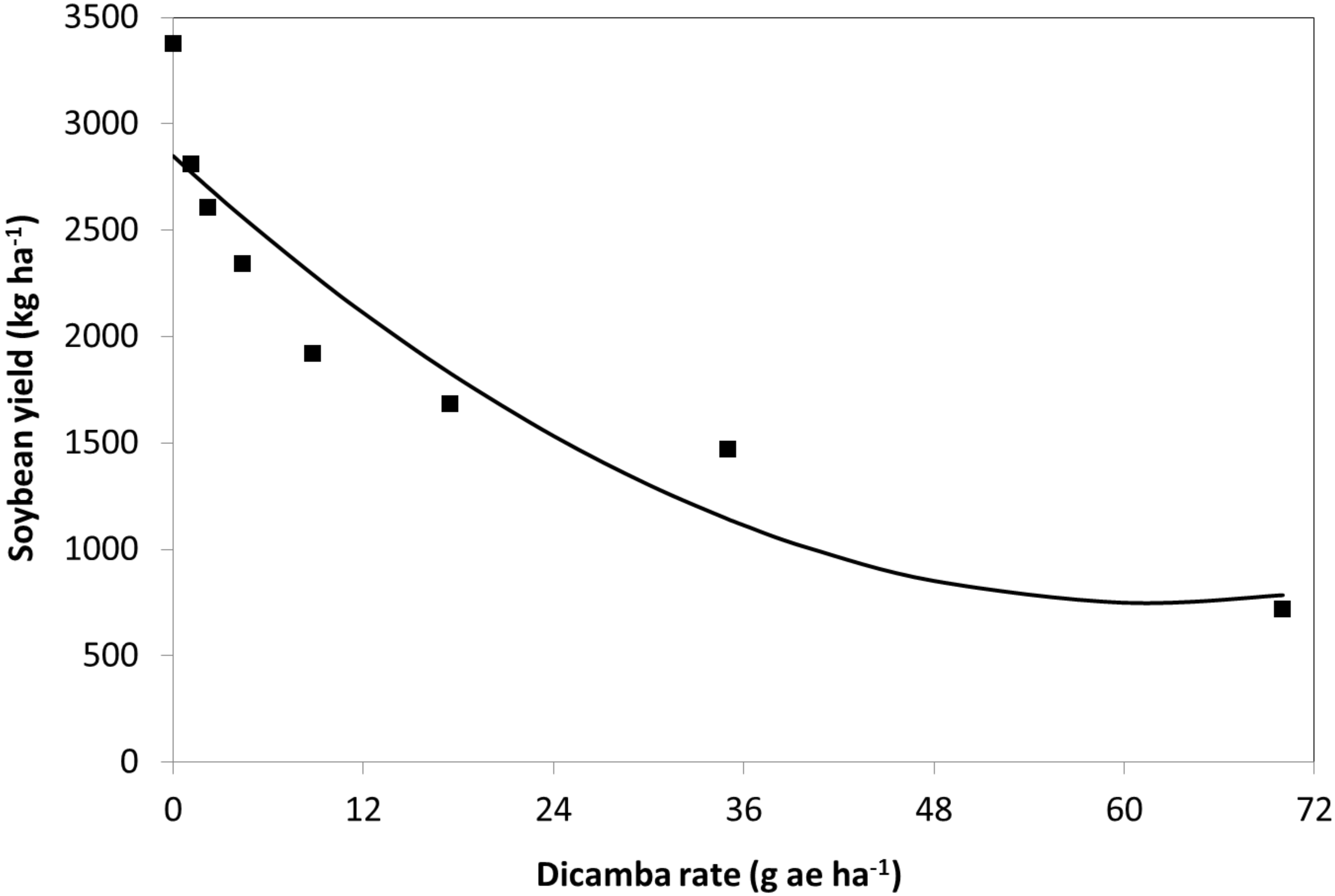

Figure 2.8. Soybean yield after treatment at R1with dicamba applied at 0, 1.1, 2.2, 4.4, 8.8, 17.5, 35, and 70 g/ha. Points represent observed mean values for experiments conducted in Baton Rouge in 2008, 2009, and 2010; St. Joseph in 2009 and 2010; and Alexandria, LA in 2010. Predicted response is described by $y = 2849.04 – 68.033x + 0.5507x^2$, $R^2 = 0.52$.

height following dicamba at 17.5 g/ha was reduced 28% (Figure 2.7) and yield was reduced 36% (Figure 2.8). Weidenhamer et al. (1989) reported mature soybean height reduction of 25% for dicamba applied at mid-bloom at16 g/ha and a reduction in soybean yield of 23%.

V3/V4 vs. R1 Application. For dicamba rates of 4.4, 8.8, 17.5, and 35 g/ha included in both the V3/V4 and R1 studies, predicted soybean injury 14 DAT was greatest (9 to 14 percentage points) for application at V3/V4 (Figures 2.1 and 2.5). In contrast, predicted mature height was reduced 9 and 32% for 17.5 and 70 g/ha, respectively, when applied at V3/V4 and 28 and 44%, respectively, when applied at R1 (Figures 2.3 and 2.7). Soybean yield reduction was greatest for dicamba applied at R1 (Figures 2.4 and 2.8).

In research comparing soybean response to dicamba applied at both vegetative and reproductive growth stages, Wax et al. (1969) and Auch and Arnold (1978) reported greater soybean yield loss with dicamba (4.4 to 56 g/ha) applied during the early/mid-bloom stage compared with the vegetative (V2 to V4) stage. Although the apical meristem was damaged or killed with pre-bloom dicamba application, plants were able to rapidly produce branches, commonly producing multiple branches from the node below the damaged apical meristem (Wax et al. 1969). With the extended growing season, additional branching helped to improve seed production per plant. Weidenhamer et al. (1989), however, reported greater yield loss for dicamba at 5 and 40 g/ha applied pre-bloom (vegetative) compared with mid-bloom. In contrast, Kelley et al. (2005) reported equivalent soybean yield for dicamba at 5.6 g/ha applied at V3 and R2. At 0.56 g/ha dicamba, soybean yield loss in their study occurred with application at V3, but not at R2.

For a field application rate of 560 g/ha dicamba, a dose rate of 0.56 g/ha (1/1000th of use rate) would correspond to vapor drift exposure (Egan and Mortensen 2012). In the present study, based on the yield response to dicamba rate, predicted soybean yield reduction for dicamba at 0.56 g/ha would be no more than 1% for application at V3/V4 or R1. Al-Khatib and Peterson (1999), Auch and Arnold (1978), Johnson et al. (2012), Kelley et al. (2005), Wax et al. (1969), and Weidenhamer et al. (1989) reported yield reductions of 0 to as high as 13% for dicamba at 0.4 to 1.1 g/ha applied to soybean at vegetative/prebloom growth stages. For dicamba application at bloom at 0.63 to 1.1 g/ha, Auch and Arnold (1978), Kelley et al. (2005), Wax et al. (1969), and Weidenhamer et al. (1989) reported yield reduction of 0 to as high as 20%. Results from the present study under high temperature and relative humidity conditions show that although significant soybean injury would be expected from dicamba vapor drift exposure during the vegetative and reproductive growth stages, soybean should recover with only minimal yield reduction.

Derksen (1989) reported that spray tank contamination rates range from 0.25 to 2% of the herbicide rate. For dicamba at 560 g/ha, a probable contamination rate range would be 1.4 to 11.2 g/ha. Predicted yield loss for 1.4 and 11.2 g/ha based on the present study would correspond to 1 and 10%, respectively, for V3/V4 application and 3 and 24%, respectively, for R1 application. Sprayer contamination with dicamba can result in significant soybean injury and yield reduction especially at the higher contamination levels and when exposure occurs at flowering.

Maybank et al. (1978) reported spray particle drift of 1 to 8% from ground sprayers. For a spray particle drift rate of 1% and an application rate of 560 g/ha dicamba, particle drift exposure would correspond to a rate 5.6 g/ha (1/100th of use rate). In the present study, predicted soybean yield reduction for dicamba applied at 5.6 g/ha was 5% at V3/V4 and 13% at R1. In previous research, dicamba applied to soybean at a rate of 3 to 11 g/ha at V2-V3 (prebloom) reduced yield none to 34% (Al-Khatib and Peterson 1999; Andersen et al. 2012; Auch and Arnold 1978; Johnson et al. 2012; Kelley et al. 2005; Wax et al. 1969; Weidenhamer et al. 1989) and when applied at bloom, yield was reduced none to as much as 42% (Auch and Arnold 1978; Johnson et al. 2012; Kelley et al. 2005; Wax et al. 1969; Weidenhamer et al. 1989).

Wolf et al. (1992) reported drift from unshielded sprayers in the range of 2 to 16% of applied liquid. For an application rate of 560 g/ha dicamba, this would correspond to a particle drift exposure rate 11.2 to 90 g/ha. In the R1 study the highest dicamba rate evaluated was 70 g/ha, which would correspond to a particle drift rate of 12.5%. In the present study, predicted soybean yield reduction for dicamba at 70 g/ha was 52% at V3/V4 and 73% at R1. In previous research, dicamba at 33 to 56 g/ha reduced soybean yield none to as high as 85% when applied at V2-V3 (prebloom) (Al-Khatib and Peterson 1999; Andersen et al. 2012; Auch and Arnold 1978; Johnson et al. 2012; Wax et al. 1969; Weidenhamer et al. 1989). Soybean yield was reduced none to as high as 75% for dicamba applied at early to mid-bloom (Auch and Arnold 1978; Wax et al. 1969; Weidenhamer et al. 1989).

The variability and inconsistency in soybean response to dicamba observed in previous research may be related to several factors. Environmental conditions before, during, and in the period immediately following herbicide exposure can affect soybean response. Al-Khatib and Peterson (1999) reported increased soybean sensitivity with high temperature at time of exposure to dicamba. Dry conditions at time of exposure to dicamba have also increased soybean sensitivity (Andersen et al. 2012; Auch and Arnold 1978; Kelley et al. 2005; Weidenhamer et al. 1989). Herbicide carrier volume has been attributed to variability in crop sensitivity to glyphosate (Ellis et al. 2002; Roider et al. 2008). Weidenhamer et al. (1989) reported a greater negative effect on yield of indeterminate soybean exposed to dicamba at flowering than for determinate soybean that cease vegetative growth at the onset of flowering.   Wax et al. (1969) stated that determinate soybean may be more sensitive to exposure to dicamba during the vegetative growth stage, but indeterminate soybean was likely more sensitive during the flowering stage.

The variable response observed in previous research for soybean exposed to dicamba makes it difficult to draw definitive conclusions. Results from research conducted in Louisiana show the potential severity of injury associated with soybean exposure to sub-lethal rates of dicamba under high temperature and relative humidity conditions experienced in the mid-South. Although injury at 14 d to Maturity Group 4 (indeterminate) and 5 (determinate) soybean was less for application at R1 compared with V3/V4, the negative effect on mature height and yield was greatest for the R1 application. For dicamba at 4.4 and 17.5 g/ha, anticipated exposure doses due to sprayer contamination or particle drift (Derksen 1989; Maybank et al. 1978), soybean yield in the present study was reduced 4 and 15%, respectively, when applied at V3/V4 and 10 and 36%, respectively, when applied at R1. Based on yield reductions with 4.4 and 17.5 g/ha dicamba, soybean at flowering was around 2.5 times more sensitive compared with vegetative exposure. For dicamba at 70 g/ha, anticipated high end exposure due to particle drift (Wolf at al. 1992), soybean yield in the present study was reduced 52% for application at V3/V4 and 73% for R1 showing that soybean was 1.4 times more sensitive to dicamba at R1.

When dicamba-resistant soybean becomes available, significant hectares will still be planted to non-dicamba resistant cultivars. It is important that growers be aware of the sensitivity of soybean to dicamba, especially during flowering, and that appropriate steps be taken to avoid off-target movement. Proper sprayer cleanout will be critical to avoid inadvertent soybean exposure to dicamba.

Literature Cited

Al-Khatib, K. and D. Peterson. 1999. Soybean (*Glycine max*) response to simulated drift from selected sulfonylurea herbicides, dicamba, glyphosate, and glufosinate. Weed Technol. 13:264-270.

Andersen, S. M., S. A. Clay, L. J. Wrage, and D. Matthees. 2004. Soybean foliage residues of dicamba and 2,4-D and correlations to application rates and yield. Agron. J. 96:750-760.

Auch, D. E. and W. E. Arnold. 1978. Dicamba use and injury on soybeans (*Glycine max*) in South Dakota. Weed Sci. 26:471-475.

Behrens, R. and W. E. Lueschen. 1979. Dicamba volatility. Weed Sci. 27:486-493.

Carmer, S. G., W. E. Nyquist, and W. M. Walker. 1989. Least significant differences for combined analyses of experiments with two- and three- factor treatment designs. Agron. J. 81:665-672.

Derksen, D. A. 1989. Dicamba, chlorsulfuron, and clopyralid as sprayer contaminants on sunflower (*Helianthus annuus*), mustard (*Brassica juncea*), and Lentil (*Lens culinaris*), respectively. Weed Sci. 37:616-621.

Egan, J. F. and D. A. Mortensen. 2012. Quantifying vapor drift of dicamba herbicides applied to soybean. Environ. Toxicol. Chem. 31:1023-1031.

Ellis, J. M., J. L. Griffin, and C. A. Jones. 2002. Effect of carrier volume on corn (*Zea mays*) and soybean (*Glycine max*) response to simulated drift of glyphosate and glufosinate. Weed Technol. 16:587-592.

Hatterman-Valenti, H., M. D. K. Owen, and N. E. Christians. 1995. Comparison of spray drift during postemergence herbicide applications to turfgrass. Weed Technol. 9:321-325.

Heap, I. 2012. International Survey of Herbicide Resistant Weeds. Available at http://www.weedscience.org/in.asp. Accessed: January 15, 2013.

Johnson, V. A., L. R. Fisher, D. L. Jordan, K. E. Edmisten, A. M. Stewart, and A. C. York. 2012. Cotton, peanut, and soybean response to sublethal rates of dicamba, glufosinate, and 2,4-D. Weed Technol. 26:195-206.

Kelley, K. B., L. M. Wax, A. G. Hager, and D. E. Riechers. 2005. Soybean response to plant growth regulator herbicides is affected by other postemergence herbicides. Weed Sci. 53:101-112.

Maybank, J., K. Yoshida, and R. Grover. 1978. Spray drift from agricultural pesticide applications. Air Pollut. Control Assoc. J. 28:1009-1014.

Roider, C. A., J. L. Griffin, S. A. Harrison, and C. A. Jones. 2008. Carrier volume affects wheat response to simulated glyphosate drift. Weed Technol. 22:453-458.

Seifert-Higgins, S. and C. L. Arnevik. 2012. Development of weed management recommendations for dicamba tolerant soybeans. Proc. So. Weed Sci. Soc. 65:266.

Wax, L. M., L. A. Knuth, and F. W. Slife. 1969. Response of soybeans to 2,4-D, dicamba, and picloram. Weed Sci. 17:388-393.

Weidenhamer, J. D., G. B. Triplett, Jr., and F. E. Sobotka. 1989. Dicamba injury to soybean. Agron. J. 81:637-643.

Wolf, T. M., R. Grover, K. Wallace, S. R. Shewchuk, and J. Maybank. 1992. Effect of protective shields on drift and deposition characteristics of field sprayers. *In* The Role of Application Factors in the Effectiveness and Drift of Herbicides. Agric. Canada, Regina, SK. pp. 29-52.

CHAPTER 3
FIELD EVALUATION OF AUXIN HERBICIDE VOLATILITY USING TOMATO AND COTTON

Introduction

Introduction of glyphosate-resistant crops in the mid-1990's allowed growers to effectively manage problem weeds that had limited production in the past. Long-term use of glyphosate, however, has selected for glyphosate-resistant weeds (Heap 2014). Two novel weed management systems to address herbicide-resistant weed management are currently under investigation. The Roundup Ready Xtend Crop System (Monsanto Co., St. Louis, MO) will allow for use of both glyphosate and dicamba in soybean [*Glycine max* (L.) Merr.] and cotton (Sandbrink et al. 2013). A premix will be marketed containing glyphosate and the diglycolamine (DGA) salt of dicamba with a polybasic polymer added to reduce dicamba volatility. The DGA salt of dicamba will also be sold separately to allow growers flexibility in use and in selection of glyphosate formulations. Dicamba as a BAPMA (N,N-Bis-(aminopropyl)methylamine), a tridentate amine salt that provides binding of dicamba residues to suppress volatilization (Xu et al. 2012) will also be available for use in Roundup Ready Xtend Crop System. The Enlist Weed Control System with Colex-D Technology (Dow AgroSciences, Indianapolis, IN) will allow for use of 2,4-D, glyphosate, and glufosinate in cotton and soybean (Braxton et al. 2010). A premix will contain glyphosate and 2,4-D choline, a quaternary ammonium salt, with reduced volatility (Perry et al. 2013). The 2,4-D choline salt will also be marketed as a stand-alone product.

All herbicides are susceptible to off-target movement through physical drift of the liquid spray solution. Wind speed, spray pressure, and nozzle height above the intended target are primary contributors to herbicide drift (Hatterman-Valenti et al. 1995). Off-target movement of some herbicides can also occur through volatility. Que Hee and Sutherland (1974) stated that volatilization of 2,4-D contributes 2 to 3 orders of magnitude less than spray (physical) drift. They also reported that vapor drift of 2,4-D could be essentially eliminated by use of amine salts. Losses from volatilization of dicamba as an unformulated acid of 29% during 7 d at 35C (Burnside and Lavy 1966) and 58% in 4 d at 30C (Baur et al. 1973) have been reported. Behrens and Luechen (1979) reported 92% of the acid dicamba had volatilized at 12 h compared with 43% for the dimethylamine (DMA) salt. In a field study where potted soybean was placed in corn (*Zea mays* L.) treated with dicamba, significant soybean injury from volatility of the DMA salt was observed for 3 d after application to corn. Symptoms caused by dicamba vapors were observed on soybean placed up to 60 m downwind of treated corn. Use of less volatile dicamba salt formulations, diethanolamine and tallow amine, did not eliminate dicamba symptoms on soybean. The volatile component of the DMA dicamba was identified as dicamba acid. Volatility ceased when treated corn received rainfall of 1mm or more.

Egan and Mortensen (2012) in a field study detected vapor drift of dicamba DMA salt at a mean concentration of 0.56 g ae/ha (1/1,000th of the applied rate of 560 g/ha) 21 m away from the treated plot. The extent and severity of vapor drift for the DMA salt was positively correlated with air temperature and relative humidity at time of application. Vapor drift was reduced for the DGA formulation compared with the DMA, but was not eliminated. Although with auxin herbicides symptomology is easily recognized, subsequent yield loss would be dependent on the herbicide rate, specific crop and growth stage, and weather conditions prior to and following application.

In a study to evaluate cotton response to volatility of 2,4-D, potted plants left in the field for 48 h following application at 2.2 kg/ha were injured less than 2% when placed at 1.5 and 3 m from where the amine salt formulation was applied and visual injury was not detected with the choline salt at either distance (Sosnoskie et al. 2012). Cotton injury due to volatility of 2,4-D ester was 57% when placed 3 m from the treated area. In another study treated soil was placed between rows of cotton and soybean to evaluate volatility of 2,4-D and dicamba (Hayden et al. 2013). Within 0.9 m of the treated area, cotton injury was 12 to 15% for 2,4-D ester compared with no more than 3% for 2,4-D choline and DMA. Differences in soybean injury due to volatility were not observed among the 2,4-D ester, 2,4-D amine, and 2,4-D choline formulations and injury was equal to the nontreated.

In an attempt to quantify volatility and to model herbicide rate versus injury, extreme variability in plant response to 2,4-D, dicamba, and triclopyr was observed for data collected before 14 DAT and was more variable in the field than greenhouse (Sciumbato et al. 2004b). For the field study, injury to cotton from volatilization was greater for 2,4-D DMA than for dicamba DGA salts, but both herbicides were less volatile than triclopyr butoxyethy ester.

Future use of 2,4-D and dicamba in herbicide-resistant crops should offer viable weed management alternatives. Although physical drift of auxin herbicides can cause significant injury and yield losses (Griffin et al. 2013; Johnson et al. 2012), there is also concern as to potential off-target movement due to herbicide volatility. For the dicamba and 2,4-D-resistant crop technologies currently under development, it is uncertain as to whether formulations other than the dicamba DGA and tridentate salts and 2,4-D other than the choline salt will be allowed for in-crop use. The objectives of this research was to compare volatility of ester, amine salt, and acid formulations of 2,4-D, dicamba, and triclopyr under field conditions using cotton and tomato as bioassay plants and to develop and evaluate a visual rating system to quantify overall injury based on specific injury criteria associated with sub-lethal exposure rates to auxin herbicides.

Materials and Methods

Research was conducted at the LSU AgCenter, Central Research Station, Ben Hur Research Farm in Baton Rouge, LA, to evaluate cotton and tomato response to volatility of various formulations of 2,4-D, dicamba, and triclopyr. Cotton and tomato seeds were planted in 15 cm pots in the greenhouse and after emergence were thinned to one plant per pot. Plants were fertilized weekly with 15:30:15 ($N:P_2O_5:K_2O$) (Scotts Miracle-Gro Products, Inc., Marysville, OH 43040) until cotton had 3 to 6 leaves and tomato had 3 to 10 leaves. The variability in leaf size coincided with when field conditions and weather were conducive to experiment initiation. Plants were moved from the greenhouse to the farm 5 days prior to application and were watered as needed to allow plants time to acclimate. In fields planted to corn or in non-crop fallowed fields, strips 4.6 m wide and 46 m long were mowed, disked, and smoothed. Untilled 4.6 m-wide border areas with corn or weeds present on each side of the tilled strips served as buffers. The 2,4-D formulations isooctyl ester (Weedone LV4; Nufarm Inc., Burr Ridge, IL), dimethylamine salt (Weedar 64; Nufarm Inc., Burr Ridge, IL), and acid (Unison; Helena Chemical Company, Collierville, TN) at 1,120 and 2,240 g/ha; the dicamba formulations dimethylamine salt (Banvel; Arysta LifeScience North America LLC, Cary, NC), diglycolamine salt (Clarity; BASF Corporation, Research Triangle Park, NC), and acid (Vision; Helena Chemical Company, Collierville, TN) at 560 and 1,120 g/ha; and the triclopyr formulations butoxyethyl ester (Garlon; Dow AgroSciences LLC, Indianapolis, IN) and acid (Trycera; Helena Chemical Company, Collierville, TN) at 1,680 and 3,360 g/ha were applied in the center of each tilled strip to an area 1.8 m-wide. A CO_2-pressurized backpack sprayer equipped with 11002 XR flat fan nozzles (TeeJet Technologies; Wheaton, IL) and calibrated to deliver 140 L/ha spray volume at 166 to 207 kPA was used. A nontreated tilled strip was included for comparison.

After each herbicide treatment was applied, spray hoses and spray boom were flushed with a 2% solution of ammonia and water. Knee-high rubber boots worn by the applicator were rinsed with the ammonia solution to avoid cross-contamination. Wind speed at application was no more than 3.2 km/h.

Because of the size of the experimental area needed, the 1x and 2x rates were evaluated separately and each run represented a single replication. For the 1x rate test, herbicide treatments were applied August 9, 2010, August 25, 2011, August 9, 2012, and September 20, 2012. Herbicide treatments for the 2x rate tests were applied September 13, 2010, September 27, 2011, August 9, 2012, and September 20, 2012. Applications for both the 1x and 2x tests were made between 8:00 and 9:00 A.M. Data for rainfall prior to herbicide application and average air and soil temperature and relative humidity at herbicide application are presented in Table 3.1. Total rainfall, average minimum/maximum air and soil temperature, and relative humidity for the period of 0 to 4 days after herbicide application for each of the runs are presented in Table 3.2.

One hour was allowed to pass after herbicide applications so that spray droplets would disperse and any herbicide effects on the indicator plants could be attributed to volatilization (Sciumbato et al. 2004b). As soon as the hour had elapsed an ATV equipped with a side-mounted platform traveled in the nontreated area adjacent to each treated strip and 15 x 15 cm ceramic tiles were placed on the soil surface 1.5 m apart in the center of each treated strip. During the same operation, pots containing cotton and tomato were placed alternately on top of the tile to prevent direct contact with the soil. Depending on the run, 10 to 15 pots of cotton and tomato were present in each of the treated and nontreated strips. Plants were watered by hand for the runs on September 13, 2010 and August 25, 2011 using the ATV to avoid travel in treated

Table 3.1. Rainfall prior to herbicide application and average air and soil temperature and relative humidity at herbicide application for the volatility study evaluating 1x and 2x herbicide rates.[1]

Application date/experiment	Rainfall prior to application	Average air temperature	Average soil temperature	Average relative humidity
	mm	C	C	%
August 9, 2010 (1x rate)	44 within 4 days	24	31	96
September 13, 2010 (2x rate)	13 within 7 days	22	33	83
August 25, 2011 (1x rate)	21 within 7 days	26	33	86
September 27, 2011 (2x rate)	13 within 9 days	26	29	86
August 9, 2012 (1x, 2x rates)	36 within 9 days	28	27	88
September 20, 2012 (1x, 2x rates)	34 within 4 days	21	21	87

[1]Herbicides were applied between 8:00 and 9:00 am.

areas. At 4 days after treatment (DAT) plants were removed from the field and placed under a 30% shade cloth enclosure with overhead irrigation.

For each individual pot, plants were visually rated 1 and 2 DAT in the field with care taken to avoid foot traffic in treated strips. Ratings at 7 and 14 DAT were made under the shade enclosure. Injury was quantified using the following criteria from least severe to most severe: 1) leaf cupping/crinkling/drooping; 2) leaf rolling/strapping; 3) stem epinasty; and 4) stem swelling/cracking. These criteria were selected because they encompass the range of injury symptoms that would be expected from plants exposed to phenoxy, benzoic acid, and pyridine carboxylic herbicides (Griffin et al. 2013; Johnson et al. 2012; Sciumbato et al. 2004a). Because the level of injury among the herbicides would be expected to vary based on rate and crop, severity of injury for each of the criterion was based on a 0 to 5 scale with 0= no injury; 1= slight; 2= slight to moderate; 3= moderate; 4= moderate to severe; and 5= severe. To obtain total injury for the

Table 3.2. Rainfall, average minimum and maximum air and soil temperature, and relative humidity 0 to 4 days after herbicide application (DAA) for the volatility study evaluating 1x and 2x herbicide rates.

Application date/experiment	Rainfall within 4 DAA	Average minimum/ maximum air temperature	Average minimum/ maximum soil temperature	Average minimum/ maximum relative humidity
	mm	C	C	%
August 9, 2010 (1x rate)	42	24/33	29/35	54/94
September 13, 2010 (2x rate)	0	19/33	28/36	35/94
August 25, 2011 (1x rate)	0	22/35	29/36	33/90
September 27, 2011 (2x rate)	19	17/29	24/30	41/93
August 9, 2012 (1x, 2x rates)	27	23/32	27/31	55/95
September 20, 2012 (1x, 2x rates)	0	17/31	23/31	40/95

herbicide treatments the injury criterion were weighted as follows: leaf cupping/crinkling/drooping = 2; leaf rolling/strapping = 4; stem epinasty = 6; and stem swelling/cracking = 8. The weighted values were chosen to represent the minimal effect that might occur for example from slight cupping of leaves to most detrimental injury associated with stem cracking. Assuming a maximum severity injury of 5 for all injury criteria and weighting the factors accordingly would result in total injury of 100%.

For this study the sprayed strips of each herbicide and rate served as experimental units/plots and the four runs served as replications for each experiment. Crop response data collected on the cotton and tomato plants within each plot were considered subsamples. Crop response data within each herbicide/rate experiment were subjected to ANOVA using MIXED procedure of SAS/STAT software (SAS Institute Inc., Cary NC). Four runs of each experiment were considered four replications and were treated as a random effect. Plant species and herbicides were considered fixed effects and were tested for significance at alpha = 0.05. The residuals were tested for normality using UNIVARIATE procedure of SAS/STAT software (SAS Institute Inc., Cary NC) and homogeneity of residuals was inspected graphically. Because residuals were not normally distributed, data were subjected to square root transformation to normalize the residuals. LSD (p=0.05) was used for mean separation and letter groupings were generated on non-transformed data using the PDMIX800 macro in SAS/STAT software (Saxton 1998).

Results and Discussion

For each of the runs when herbicides were applied at the 1x and 2x rates the soil surface was slightly moist due to a light to heavy dew. Rainfall of at least 13 mm had been received within 9 days preceding application (Table 3.1). For the 1x run in 2010 and for the 1x and 2x runs in September of 2012, rainfall of 44 and 34 mm, respectively, was received 4 days preceding application. Average air temperature and soil temperature at application ranged from 21 to 28C and from 21 to 33C, respectively (Table 3.1). Relative humidity at application ranged from 83 to 96% (Table 3.1).

For the 0 to 4 day period after herbicide application and prior to plants being removed from the field rainfall in the amount of 42, 19, and 27 mm was received for the 1x run in 2010, the 2x run in 2011, and the 1x and 2x runs in 2012, respectively (Table 3.2). Rainfall was not received during the 4 day period for the other runs. Maximum air temperature for the 0 to 4 day period for the runs ranged from 29 to 35C and maximum soil temperature ranged from 30 to 36C, which should promote herbicide volatility (Behrens and Lueschen 1979). Maximum relative humidity was 90 to 95% for the various runs.

Leaf cupping/crinkle/droop injury. For each of the ratings at 1, 2, 7, and 14 DAT significant plant type (cotton and tomato) and herbicide effects were observed for both 1x and 2x rates for leaf cupping/crinkling/drooping, but the plant type x herbicide interaction was not significant (Table 3.3). Averaged across herbicide treatments, the severity of injury was consistently greater for tomato than for cotton (Table 3.4). For 1x rates, average cotton injury based on a 0 to 5 scale with 0= no injury; 1= slight; 2= slight to moderate; 3= moderate; 4= moderate to severe; and 5= severe increased for cotton from 0.1 at 1 DAT to 0.3 at 2 DAT and by 14 DAT averaged 1.0. Injury to tomato at 1x rates increased from 0.7 at 1 DAT to 2.0 14 DAT. For the 2x rates, cotton and tomato injury 1 DAT averaged 0.2 and 1.7, respectively, and by 14 DAT injury for tomato averaged at least twice that of cotton (2.9 vs. 1.4, respectively).

Averaged across cotton and tomato, leaf cupping/crinkling/drooping injury 1 DAT was greatest for the 1x and 2x rates of 2,4-D ester (0.8 and 1.9, respectively) and for the triclopyr ester (1.4 and 2.4, respectively) (Table 3.4). Injury for the other herbicide treatments 1 DAT was no more than 0.3 for the 1x rates and 0.8 for the 2x rates. By 2 DAT differences among the herbicide treatments were more apparent. For the 1x rate, injury for 2,4-D ester averaged 1.4 and was equal to 2,4-D DMA (1.0) but greater than for 2,4-D acid (0.5). For the 2x rate, injury 2 DAT for 2,4-D ester averaged 2.7 and was greater than for the DMA and acid formulations; injury was less for 2,4-D acid compared with the DMA (0.6 vs. 1.4). For the 1x and 2x rates, injury 2 DAT for the dicamba formulations was equivalent and ranged from 0.8 to 1.3. Triclopyr ester injury 2 DAT averaged 1.8 for the 1x rate and 2.9 for the 2x rate, and for both rates, injury was greater than for triclopyr acid (0.7 and 1.3 for 1x and 2x rates, respectively). By 14 DAT, injury with 2,4-D ester averaged 2.1 for the 1x rate and 3.1 for the 2x (Table 3.4). Injury observed for the 2,4-D DMA and acid formulations at both rates was equivalent and less than for

Table 3.3. Results of analysis of variance for the effect of plant type, herbicide, and plant type x herbicide interaction on five injury criteria (0 to 5 scale) and total injury (0 to 100%) 1, 2, 7, and 14 days after treatment (DAT) for 1x and 2x herbicide rates.[1]

Data collection	Source of variation	Injury criteria: Leaf cupping/ crinkling/ drooping	Leaf rolling/ strapping	Stem epinasty	Stem swelling/ cracking	Total injury[2]
	1x rate	p value				
1 DAT	Plant type (cotton, tomato)	<0.0001	--[2]	--	--	<0.0001
	Herbicide (9 treatments)	<0.0001	0.0211	0.0684	--	0.0007
	Plant type x herbicide	0.3468	--[2]	--	--	0.0028
2 DAT	Plant type (cotton, tomato)	<0.0001	--	--	--	<0.0001
	Herbicide (9 treatments)	0.0014	0.0461	0.0004	--	0.0003
	Plant type x herbicide	0.4599	--	--	--	0.0003
7 DAT	Plant type (cotton, tomato)	<0.0001	--	--	--	<0.0001
	Herbicide (9 treatments)	0.0030	0.0470	0.0005	0.2128	0.0004
	Plant type x herbicide	0.1643	--	--	--	0.0144
14 DAT	Plant type (cotton, tomato)	<0.0001	--	--	--	<0.0001
	Herbicide (9 treatments)	0.0006	0.0589	0.0019	0.0210	0.0001
	Plant type x herbicide	0.0742	--	--	--	0.0475

[1]Plant type included cotton and tomato and herbicides included 2,4-D isooctyl ester, dimethylamine salt, and acid; dicamba dimethylamine salt, diglycolamine salt, and acid; and triclopyr butoxyethyl ester and acid formulations applied at 1x and 2x rates.
[2]Plant type and plant type x herbicide interactions were not included in the analysis of variance for leaf rolling/strapping, stem epinasty, and stem swelling/cracking because injury was not observed for cotton.

Table 3.3 continued.

Data collection	Source of variation	Injury criteria: Leaf cupping/ crinkling/ drooping	Leaf rolling/ strapping	Stem epinasty	Stem swelling/ cracking	Total injury[2]
	2x rate	---------- p value ----------				
1 DAT	Plant type (cotton, tomato)	<0.0001	--	--	--	<0.0001
	Herbicide (9 treatments)	0.0003	0.0015	0.0010	--	0.0003
	Plant type x herbicide	0.3076	--	--	--	0.0002
2 DAT	Plant type (cotton, tomato)	<0.0001	--	--	--	<0.0001
	Herbicide (9 treatments)	<0.0001	0.0032	<0.0001	0.1012	<0.0001
	Plant type x herbicide	0.6854	--	--	--	0.0001
7 DAT	Plant type (cotton, tomato)	<0.0001	--	--	--	<0.0001
	Herbicide (9 treatments)	<0.0001	0.0018	<0.0001	<0.0001	<0.0001
	Plant type x herbicide	0.8200	--	--	--	0.0002
14 DAT	Plant type (cotton, tomato)	<0.0001	--	--	--	<0.0001
	Herbicide (9 treatments)	<0.0001	0.0028	0.0003	<0.0001	<0.0001
	Plant type x herbicide	0.8729	--	--	--	0.0002

[1]Plant type included cotton and tomato and herbicides included 2,4-D isooctyl ester, dimethylamine salt, and acid; dicamba dimethylamine salt, diglycolamine salt, and acid; and triclopyr butoxyethyl ester and acid formulations applied at 1x and 2x rates.
[2]Plant type and plant type x herbicide interactions were not included in the analysis of variance for leaf rolling/strapping, stem epinasty, and stem swelling/cracking because injury was not observed for cotton.

Table 3.4. Cotton and tomato leaf cupping/crinkling/drooping injury associated with volatility of 2,4-D, dicamba, and triclopyr formulations applied at 1 and 2x rates to bare soil and evaluated 1, 2, 7, and 14 days after treatment (DAT).[1]

			Leaf cupping/crinkling/drooping injury (0 to 5 scale)[2]											
			1 DAT			2 DAT			7 DAT			14 DAT		
Treatment	Form-ulation	Rate	Cotton	Tomato	Avg.	Cotton	Tomato	Avg.	Cotton	Tomato	Avg.	Cotton	Tomato	Avg.
2,4-D	ester	1x	0.6	1.1	0.8 ab[3]	1.1	1.7	1.4 ab	1.3	2.0	1.6 ab	2.2	2.0	2.1 ab
2,4-D	DMA	1x	0.0	0.3	0.1 c	0.5	1.5	1.0 bc	0.8	1.8	1.3 abc	1.7	1.8	1.7 abc
2,4-D	acid	1x	0.0	0.4	0.1 c	0.1	1.2	0.5 cd	0.2	1.7	0.8 cd	0.5	1.8	1.1 cd
dicamba	DMA	1x	0.1	0.7	0.3 bc	0.2	1.7	0.8 bc	0.4	1.9	1.0 bcd	0.8	1.9	1.3 bcd
dicamba	DGA	1x	0.0	0.6	0.2 c	0.5	1.7	1.1 abc	0.8	1.9	1.3 abc	1.6	2.1	1.8 abc
dicamba	acid	1x	0.0	0.3	0.1 c	0.3	1.5	0.8 bc	0.6	1.2	0.9 cd	1.0	1.2	1.1 cd
triclopyr	ester	1x	0.3	3.3	1.4 a	0.7	3.6	1.8 a	0.8	3.6	2.0 a	1.6	3.7	2.5 a
triclopyr	acid	1x	0.0	0.5	0.1 c	0.2	1.6	0.7 bc	0.5	2.0	1.1 abc	0.6	2.4	1.4 bcd
Nontreated	--	--	0.0	0.2	0.1 c	0.0	0.4	0.1 d	0.0	1.4	0.5 d	0.2	1.5	0.7 d
Average			0.1 b[3]	0.7 a	--	0.3 b	1.6 a	--	0.5 b	1.9 a	--	1.0 b	2.0 a	--
2,4-D	ester	2x	1.3	2.7	1.9 ab	1.9	3.7	2.7 a	2.1	3.8	2.9 a	2.5	3.8	3.1 a
2,4-D	DMA	2x	0.1	1.4	0.5 cd	0.6	2.4	1.4 b	0.8	2.8	1.7 bc	1.2	2.9	1.9 b
2,4-D	acid	2x	0.0	1.2	0.4 cd	0.1	1.7	0.6 c	0.4	2.2	1.1 cd	1.0	2.3	1.6 bc
dicamba	DMA	2x	0.0	1.8	0.6 cd	0.5	2.5	1.3 b	0.9	3.0	1.8 b	1.3	3.1	2.1 b
dicamba	DGA	2x	0.1	1.8	0.7 c	0.6	2.4	1.3 b	1.2	2.7	1.9 b	1.4	2.8	2.1 b
dicamba	acid	2x	0.0	1.6	0.5 cd	0.5	2.4	1.2 b	1.0	2.7	1.7 bc	1.5	2.7	2.0 b
triclopyr	ester	2x	1.5	3.5	2.4 a	2.0	3.9	2.9 a	2.2	3.9	3.0 a	2.3	3.9	3.1 a
triclopyr	acid	2x	0.1	2.1	0.8 bc	0.4	2.7	1.3 b	0.8	2.9	1.7 bc	1.0	3.0	1.9 b
Nontreated	--	--	0.1	0.2	0.1 d	0.1	1.2	0.5 c	0.2	1.6	0.7 d	0.5	1.7	1.0 c
Average			0.2 b	1.7 a	--	0.6 b	2.5 a	--	1.0 b	2.8 a	--	1.4 b	2.9 a	--

[1] Herbicide rates (1x and 2x) were 1,120 and 2,240 g/ha for 2,4-D isooctyl ester (ester), dimethylamine salt (DMA), and acid formulations; 560 and 1,120 g/ha for dicamba dimethylamine salt (DMA), diglycolamine salt (DGA), and acid formulations; and 1,680 and 3,360 g/ha for triclopyr butoxyethyl ester (ester) and acid formulations.
[2] Severity of injury rated on 0= no injury; 1= slight; 2= slight to moderate; 3= moderate; 4= moderate to severe; 5= severe.
[3] Herbicide means (averaged across plant types) for each rate and crop effects (averaged across herbicides) for each rate/rating date followed by the same letter are not significantly different using LSD at $p \leq 0.05$.

the ester at the 2x rate. Injury 14 DAT was equivalent for the dicamba DMA, DGA, and acid formulations and ranged from 1.1 to 1.8 for 1x rate and 2.0 to 2.1 for 2x rate. For triclopyr ester, injury 14 DAT averaged 2.5 for 1x and 3.1 for 2x and for both rates injury was greater than for the acid formulation.

Although buffer areas were present between strips and hygienic procedures were followed during application, some leaf cupping/crinkling/drooping injury was observed in both cotton and tomato in nontreated strips where 2x herbicide runs were conducted (values of 0.5 for cotton and 1.7 for tomato) (Table 3.4). This response was not unexpected since some of the herbicides were highly volatile and the buffer strips would not be expected to completely eliminate cross-contamination. Variability in evaluating volatility in field trials can also be attributed to external factors such as wind, relative humidity, and temperature can affect results (Hayden et al. 2013; Sciumbato et al. 2004b; Sosnoskie et al. 2012; Xu et al. 2012).

Leaf rolling/strapping injury. For the 1x and 2x herbicide rates, leaf rolling/strapping injury due to volatility of herbicide treatments was not observed for cotton but significant herbicide effects were observed for tomato (Table 3.3). Tomato injury 1 DAT for the 1x herbicide rates (0 to 5 scale) was greatest for triclopyr ester (1.3) but was no more than 0.3 for the other herbicides (Table 3.5). For the 2x rates, injury 1 DAT was 1.6 for 2,4-D ester, greater than for the other 2,4-D formulations but equivalent to the dicamba formulations. Tomato injury 1 DAT for triclopyr ester at the 2x rate was 2.9 and greater than for triclopyr acid (0.4). For the 1x herbicide rates, injury was equivalent for all of the 2,4-D and dicamba formulations 2 DAT (0.5 to 1.1), 7 DAT (0.9 to 1.5), and 14 DAT (1.0 to 1.5). For triclopyr ester at 1x rate, injury increased from 1.7 at 2 DAT to 2.0 14 DAT. At 2 DAT for the 1x rate of triclopyr, injury was

Table 3.5. Tomato leaf rolling/strapping injury associated with volatility of 2,4-D, dicamba, and triclopyr formulations applied at 1 and 2x rates to bare soil and evaluated 1, 2, 7, and 14 days after treatment (DAT).[1]

			Leaf rolling/strapping (0 to 5 scale)[2]			
Treatment	Formulation	Rate	1 DAT	2 DAT	7 DAT	14 DAT
2,4-D	ester	1x	0.3 b[3]	0.9 abc	1.2 ab	1.4 ab
2,4-D	DMA	1x	0.2 b	0.6 bc	0.9 bc	1.0 bc
2,4-D	acid	1x	0.2 b	0.5 bc	0.9 bc	1.0 bc
dicamba	DMA	1x	0.3 b	0.6 bc	1.4 ab	1.4 ab
dicamba	DGA	1x	0.3 b	0.9 abc	1.5 ab	1.5 ab
dicamba	acid	1x	0.2 b	1.1 ab	1.4 ab	1.5 ab
triclopyr	ester	1x	1.3 a	1.7 a	1.9 a	2.0 a
triclopyr	acid	1x	0.2 b	0.6 bc	1.2 ab	1.4 ab
Nontreated	--	--	0.1 b	0.3 c	0.6 c	0.7 c
2,4-D	ester	2x	1.6 ab	2.6 ab	3.0 ab	3.1 ab
2,4-D	DMA	2x	0.2 c	1.0 cd	2.1 bc	2.2 bc
2,4-D	acid	2x	0.2 c	0.4 d	1.6 c	1.7 cd
dicamba	DMA	2x	0.6 bc	1.1 bcd	2.4 abc	2.5 abc
dicamba	DGA	2x	0.4 bc	0.9 cd	2.3 abc	2.4 abc
dicamba	acid	2x	0.5 bc	1.8 abc	2.5 abc	2.6 abc
triclopyr	ester	2x	2.9 a	3.1 a	3.4 a	3.7 a
triclopyr	acid	2x	0.4 bc	1.2 bcd	2.2 bc	2.2 bc
Nontreated	--	--	0.0 c	0.3 d	0.7 d	0.9 d

[1] Herbicide rates (1x and 2x) were 1,120 and 2,240 g/ha for 2,4-D isooctyl ester (ester), dimethylamine salt (DMA), and acid formulations; 560 and 1,120 g/ha for dicamba dimethylamine salt (DMA), diglycolamine salt (DGA), and acid formulations; and 1,680 and 3,360 g/ha for triclopyr butoxyethyl ester (ester) and acid formulations.
[2] Severity of injury rated on 0= no injury; 1= slight; 2= slight to moderate; 3= moderate; 4= moderate to severe; 5= severe.
[3] Herbicide means for each rate/rating date followed by the same letter are not significantly different using LSD at $p \leq 0.05$.

greater for the ester compared with the acid formulation but injury was equivalent for the two formulations at 7 and 14 DAT.

For 2x rates of 2,4-D ester leaf rolling/strapping injury was 2.6 at 2 DAT, 3.0 at 7 DAT, and 3.1 at 14 DAT (Table 3.5). Although injury was equivalent for the 2,4-D DMA and acid formulations at each of the rating dates, injury for 2,4-D acid was less than for the ester whereas the DMA was equivalent to the ester. Injury was equivalent for the 2x rate of the dicamba formulations at 2 DAT (0.9 to 1.8), 7 DAT (2.3 to 2.5), and 14 DAT (2.4 to 2.6). For triclopyr ester at the 2x rate, injury was 3.1 2 DAT and 3.7 14 DAT. Injury with triclopyr acid was less than for the ester 2 DAT but was equivalent to the ester at 7 and 14 DAT. Injury due to volatility was observed for the nontreated in the 2x test (0.9) and the only herbicide equivalent to the nontreated was 2,4-D acid formulation.

Stem epinasty injury. For the 1x and 2x herbicide rates, stem epinasty injury to cotton due to herbicide treatments was not observed (Table 3.3). For tomato, stem epinasty (0 to 5 scale) 1 DAT was equivalent for all herbicides and formulations applied at 1x; injury for 2x rates was equivalent for 2,4-D ester (1.1) and triclopyr ester (1.7) and greater than for the other herbicides and formulations (Table 3.6). For 2,4-D ester at 1x, stem epinasty increased from 1.2 at 2 DAT to 2.5 at 14 DAT. At 7 and 14 DAT injury was equivalent for 1x rates of 2,4-D DMA and acid. At 14 DAT, however, injury for 1x rates for 2,4-D DMA and ester formulations was equivalent, but injury for the acid formulation was less than for the ester. For the 2x rates of the 2,4-D formulations injury for the ester was 3.0 at 2 DAT compared with 0.1 for the DMA and acid and was 3.5 at 14 DAT compared with 1.0 for the DMA and 0.8 for the acid. At both rating dates injury was equivalent for the DMA and acid formulations. For the dicamba DMA, DGA, and acid formulations, injury was equivalent for both the 1x and 2x rates and was as high as 2.0 14 DAT (Table 3.6). Stem epinasty injury associated with triclopyr ester at 1x and 2x rates 14 DAT (2.9 and 3.4, respectively) was equivalent to 2,4-D ester. Injury 14 DAT with triclopyr acid was 0.6, less than for triclopyr ester but equivalent to that for 2,4-D and dicamba acid formulations.

Stem swelling/cracking injury. Stem swelling and cracking injury was not observed for cotton (Table 3.3). Injury to tomato (0 to 5 scale) was not observed for any of the herbicide

Table 3.6. Tomato stem epinasty and stem swelling/cracking injury associated with volatility of 2,4-D, dicamba, and triclopyr applied at 1 and 2x rates to bare soil and evaluated 1, 2, 7, and 14 days after treatment (DAT).[1]

			Stem epinasty (0 to 5 scale)[2]				Stem swelling, cracking (0 to 5 scale)[2]			
Treatment	Formulation	Rate	1 DAT	2 DAT	7 DAT	14 DAT	1 DAT	2 DAT	7 DAT	14 DAT
2,4-D	ester	1x	0.4 a	1.2 ab[3]	2.1 ab	2.5 ab	--[4]	--	0.3 a	0.5 ab
2,4-D	DMA	1x	0.0 a	0.5 bc	0.7 c	1.2 bc	--	--	0.0 a	0.1 bc
2,4-D	acid	1x	0.0 a	0.0 d	0.1 c	0.3 cd	--	--	0.1 a	0.2 bc
dicamba	DMA	1x	0.1 a	0.3 cd	0.4 c	0.7 cd	--	--	0.0 a	0.1 bc
dicamba	DGA	1x	0.1 a	0.4 bcd	0.8 bc	1.3 abc	--	--	0.1 a	0.2 bc
dicamba	acid	1x	0.0 a	0.2 cd	0.3 c	0.7 cd	--	--	0.0 a	0.1 bc
triclopyr	ester	1x	0.7 a	2.3 a	2.7 a	2.9 a	--	--	0.4 a	1.1 a
triclopyr	acid	1x	0.0 a	0.1 cd	0.3 c	0.5 cd	--	--	0.0 a	0.2 bc
Nontreated	--	--	0.0 a	0.1 cd	0.1 c	0.2 d	--	--	0.0 a	0.0 c
2,4-D	ester	2x	1.1 a	3.0 a	3.4 a	3.5 a	--	0.2 a	1.9 a	2.3 a
2,4-D	DMA	2x	0.0 b	0.1 bc	0.7 cd	1.0 b	--	0.0 a	0.0 b	0.2 bc
2,4-D	acid	2x	0.0 b	0.1 bc	0.6 cde	0.8 bc	--	0.0 a	0.1 b	0.1 c
dicamba	DMA	2x	0.1 b	0.6 b	1.4 c	1.8 ab	--	0.1 a	0.3 b	0.7 b
dicamba	DGA	2x	0.0 b	0.6 bc	1.2 cd	1.5 b	--	0.1 a	0.4 b	0.8 b
dicamba	acid	2x	0.0 b	0.4 bc	1.6 bc	2.0 ab	--	0.0 a	0.2 b	0.7 b
triclopyr	ester	2x	1.7 a	3.0 a	3.2 ab	3.4 a	--	0.4 a	2.3 a	3.1 a
triclopyr	acid	2x	0.0 b	0.1 bc	0.3 de	0.6 bc	--	0.0 a	0.2 b	0.3 bc
Nontreated	--	--	0.0 b	0.1 bc	0.1 e	0.1 c	--	0.0 a	0.0 b	0.1 c

[1]Herbicide rates (1x and 2x) were 1,120 and 2,240 g/ha for 2,4-D isooctyl ester (ester), dimethylamine salt (DMA), and acid formulations; 560 and 1,120 g/ha for dicamba dimethylamine salt (DMA), diglycolamine salt (DGA), and acid formulations; and 1,680 and 3,360 g/ha for triclopyr butoxyethyl ester (ester) and acid formulations.

[2] Severity of injury rated on 0= no injury; 1= slight; 2= slight to moderate; 3= moderate; 4= moderate to severe; 5= severe.

[3] Herbicide means for each rate/rating date followed by the same letter are not significantly different using LSD at $p \leq 0.05$.

[4]Injury not observed.

formulations 1 DAT for 1x and 2x rates and 2 DAT for 1x rates (Table 3.6). For the 2x rates 2 DAT and for the 1x rates 7 DAT stem swelling/cracking injury was no more than 0.4 and differences among the herbicide formulations were not observed. At 7 DAT for 2x rates, injury was equivalent and greatest for 2,4-D ester (1.9) and triclopyr ester (2.3). For 2,4-D, injury 7 DAT was less for the 2x rates of DMA and acid formulations compared with the ester and injury was less for triclopyr acid compared with the ester. For dicamba, stem swelling/cracking injury 7 DAT for the 2x rate was no more than 0.4 for the DMA, DGA, and acid formulations. At 14 DAT injury for 1x rate of 2,4-D ester was 0.5 and equivalent to the DMA and acid (injury no more than 0.2). Triclopyr injury 14 DAT at 1x was 1.1 for the ester and greater than for the acid (0.2). Injury 14 DAT with the dicamba formulations at 1x was equivalent and no more than 0.2. For 2x rates 14 DAT stem swelling/cracking injury with 2,4-D ester was 2.3 compared with no more than 0.2 for the DMA and acid. For triclopyr ester at the 2x rate, injury 14 DAT was 3.1 compared with 0.3 for triclopyr acid. For the dicamba formulations at the 2x rate injury 14 DAT ranged from 0.7 to 0.8 and differences among the formulations were not observed. For the nontreated, stem swelling/cracking injury for the 2x experiment 14 DAT was 0.1. Injury observed for 2,4-D DMA and acid formlation and for triclopyr acid was equivalent to the nontreated.

Total injury. Total injury due to volatility of auxin herbicides (0 to 100%) was calculated based on severity of injury for each of the four criteria with leaf cupping/crinkling/drooping contributing less to total injury compared with stem swelling/cracking. Significant plant type by herbicide interactions were observed for total injury at each of the ratings for both the 1x and 2x herbicide rates (Table 3.3). For cotton, total injury for the herbicide formulations at both rates was equivalent to the nontreated at each of the ratings and ranged from 0 to 4% 1 DAT, 0 to 8% 2 DAT, 1 to 13% 7 DAT, and 4 to 17% 14 DAT (Table 3.7).

For tomato, total injury 1 DAT was greater compared with cotton for 2,4-D ester, dicamba DGA, and triclopyr ester at 1x rates and for 2,4-D ester, DMA and DGA dicamba, and triclopyr ester at 2x rates. Total injury 1 DAT for tomato was 11% for 2,4-D ester at the 1x rate and 24% at the 2x rate, and for both rates, injury was greater than for the 2,4-D DMA and acid formulations (4% for 1x and 5 and 6%, respectively, for 2x) (Table 3.7). Tomato injury 1 DAT was equivalent for the dicamba DMA, DGA, and acid formulations, 5 to 7% for 1x rate and 8 to 12% for the 2x rate. For triclopyr ester, tomato was injured 23% at 1x and 33% at 2x and injury was greater than for the acid formulation (5 and 7%, respectively). For the nontreated, injury was 3% for both the 1x and 2x experiments. In general injury associated with herbicide formulations, with the exception of ester formulations, was no greater than for the nontreated.

For the 2, 7, and 14 DAT ratings total injury for the various herbicide formulations was greater for tomato than for cotton with the exception of 2,4-D acid at 2x at 2 DAT where injury to cotton and tomato was equivalent (Table 3.7). At 2 DAT total injury to tomato with 2,4-D ester at 1x was 19%, equal to that for the DMA (13%) but greater than for the acid (8%) (Table 3.7). At the 2x rate 2,4-D ester injured tomato 41% 2 DAT and injury was greater than for DMA and acid formulations (14 and 8%, respectively). At both 1x and 2x rates total injury to tomato 2 DAT was equivalent for 2,4-D DMA and acid formulations. Dicamba injury 2 DAT for tomato was equivalent for the DMA, DGA, and acid formulations (13 to 14% for the 1x rate and 17 to 20% for the 2x rate). The ester formulation of triclopyr injured tomato 2 DAT 34% at 1x and 48% at 2x and injury was greater than for the acid formulation (10 and 15%, respectively). For

Table 3.7. Cotton and tomato total injury associated with volatility of 2,4-D, dicamba, and triclopyr applied at 1 and 2x rates to bare soil and evaluated 1, 2, 7, and 14 days after treatment (DAT).[1]

			Total injury (0 to 100%)[2]							
			1 DAT		2 DAT		7 DAT		14 DAT	
Treatment	Formulation	Rate	Cotton	Tomato	Cotton	Tomato	Cotton	Tomato	Cotton	Tomato
2,4-D	ester	1x	2 cde[3]	11 b	3 efg	19 b	4 e	30 b	10 efg	36 b
2,4-D	DMA	1x	0 e	4 cde	2 fg	13 bcd	2 e	18 cd	7 g	24 cd
2,4-D	acid	1x	0 e	4 cde	1 g	8 cdef	1 e	16 cd	4 g	20 cde
dicamba	DMA	1x	2 cde	7 bc	4 efg	13 bcd	4 e	17 cd	7 g	20 cde
dicamba	DGA	1x	1 de	7 bc	4 efg	14 bc	4 e	21 bc	8 fg	22 cde
dicamba	acid	1x	1 de	5 cde	2 fg	13 bcd	3 e	17 cd	6 g	21 cde
triclopyr	ester	1x	3 cde	23 a	5 efg	34 a	5 e	41 a	11 efg	50 a
triclopyr	acid	1x	1 de	5 bcde	2 fg	10 cde	2 e	18 cd	4 g	24 cd
Nontreated	--	--	0 e	3 cde	0 g	6 defg	0 e	9 de	3 g	12 defg
2,4-D	ester	2x	4 cde	24 b	8 cde	41 a	13 cde	59 a	17 cde	64 a
2,4-D	DMA	2x	1 e	6 cde	3 e	14 bcd	3 e	23 bc	7 de	27 bc
2,4-D	acid	2x	0 e	5 cde	0 e	8 cde	2 e	18 cd	6 e	21 cd
dicamba	DMA	2x	0 e	12 c	1 e	20 b	3 e	32 b	5 e	40 b
dicamba	DGA	2x	1 e	9 cd	3 e	19 b	4 e	33 b	7 de	39 b
dicamba	acid	2x	1 e	8 cde	2 e	17 bc	3 e	32 b	7 de	40 b
triclopyr	ester	2x	4 cde	33 a	6 de	48 a	7 de	64 a	8 de	71 a
triclopyr	acid	2x	1 e	7 cde	3 e	15 bcd	2 e	23 bc	4 e	28 bc
Nontreated	--	--	0 e	3 de	1 e	7 cde	1 e	10 cde	4 e	14 cde

[1] Herbicide rates (1x and 2x) were 1,120 and 2,240 g/ha for 2,4-D isooctyl ester (ester), dimethylamine salt (DMA), and acid formulations; 560 and 1,120 g/ha for dicamba dimethylamine salt (DMA), diglycolamine salt (DGA), and acid formulations; and 1,680 and 3,360 g/ha for triclopyr butoxyethyl ester (ester) and acid formulations.

[2] Total injury based on 0 to 100%. To obtain total injury, injury criteria data were weighted as follows: leaf cupping/crinkling/drooping = 2; leaf rolling/strapping = 4; stem epinasty = 6; and stem swelling/cracking = 8. Assuming a maximum severity of 5 for all injury criteria and weighting each criterion accordingly would result in total injury of 100%.

[3] Herbicide x plant type means for each rate/rating date followed by the same letter are not significantly different using LSD at $p \leq 0.05$.

both 1x and 2x rates, tomato injury for 2,4-D DMA and acid, dicamba acid, and triclopyr acid 2 DAT was no greater than the nontreated.

At 7 DAT tomato was injured 30% with 2,4-D ester at 1x and 59% at 2x (Table 3.7). Injury with the DMA and acid formulations of 2, 4-D was equivalent and less than for the ester formulations. Tomato injury was equivalent for the dicamba formulations at both application rates (17 to 21% for 1x) and (32 to 33% for 2x). Triclopyr ester injured tomato 41% 7 DAT at 1x and 64% at 2x and injury was less for the acid formulation at both rates.

At 14 DAT, tomato injury for 2,4-D ester was 36% for 1x and 64% for 2x rates (Table 3.7). Injury for DMA and acid formulations of 2,4-D was equivalent (24 and 20%, respectively, for 1x rate) and (27 and 21%, respectively, for 2x rate) and for both rates, injury was less compared with 2,4-D ester. The greater injury observed for 2,4-D ester formulation is attributed to the severity of stem epinasty observed at both rates and to the stem swelling/cracking observed at the 2x rate (Table 3.6). For dicamba 14 DAT, total injury due to volatility was equivalent for the DMA, DGA, and acid formulations at 1x (20 to 22%) and 2x (39 to 40%) rates. Tomato was injured 50% with triclopyr ester at 1x and 71% at 2x. Injury from triclopyr at both rates was attributed to the severity of stem epinasty and stem swelling/cracking (Table 3.6). Compared with triclopyr ester, injury was reduced 26 percentage points for triclopyr acid at 1x and 43 percentage points at 2x.

As discussed earlier, the slight leaf cupping/crinkling/drooping injury observed on nontreated tomato was not unexpected in a large field study where highly volatile ester-formulated herbicides were applied under high temperature and high humidity conditions. When experiments were terminated at 14 DAT, injury to cotton associated with volatility for all of the herbicide formulations at both rates was no greater than for the nontreated. This suggests that regardless of 2,4-D, dicamba, or triclopyr formulation or rate applied, injury to cotton due to volatility should not be a major concern. For tomato, however, injury due to volatility was significant and the level of volatility was dependent on herbicide, herbicide formulation, and rate. Compared with the nontreated, injury due to volatility for 1x rates was no more than the nontreated for 2,4-D DMA and acid formulations, dicamba DMA, DGA, and acid formulations, and the triclopyr acid formulation. At the 2x rates, tomato injury 14 DAT was equivalent to the nontreated for only the 2,4-D DMA and acid formulations and the triclopyr acid formulation. Cotton was less sensitive to volatility than tomato for all herbicides and formulations. At 14 DAT for the 1x rate based on total injury, cotton was 3.6 times less sensitive to 2,4-D ester compared with tomato.

Previous research has shown substantial losses of unformulated 2,4-D acid due to volatility (Baur et al. 1973; Burnside and Lavy 1966; Behrens and Lueschen 1979). The 2,4-D acid formulation evaluated in this study contains proprietary surfactants that solubilize 2,4-D acid to form a water miscible liquid formulation that has very low volatility and is odorless (Helena Chemical Company Collierville, TN). The manufacturer has also been successful in developing acid formulations of dicamba and triclopyr. In this study, injury to both cotton and tomato associated with volatility was no greater for the 2,4-D acid formulation compared with DMA and for the dicamba acid formulation compared with DMA and DGA formulations. Additionally, injury due to volatility of triclopyr acid for both the 1x and 2x experiments was no greater than for the 2,4-D acid and DMA formulations and for the dicamba acid, DMA, and DGA formulations. Other field research to evaluate volatility has shown extensive cotton injury due to 2,4-D ester, but has not shown differences in crop injury between 2,4-D DMA and choline salt formulations (Hayden et al. 2013; Sosnoskie et al. 2012). In soybean, differences in injury due to volatility were not observed among the 2,4-D ester, DMA, and choline formulations and injury was equal to the nontreated (Hayden et al. 2013). These findings along with those from the present study suggest that under field conditions, differences in volatility among herbicide formulations may be of minimal importance in respect to off-target movement to sensitive crops.

Egan and Mortensen (2012) detected vapor drift of dicamba DMA salt at a mean concentration of 0.56 g/ha (1/1000th of the applied rate of 560 g/ha) 21 m away from the treated plot. In research to determine soybean yield response to dicamba, Griffin et al. (2013) reported yield reduction for dicamba at 0.56 g/ha of no more than 1% for application at V3/V4 or R1. In subsequent research, application of dicamba at 0.56 g/ha injured soybean 25% 7 d after application at V3/V4 and 19% for application at R1, but yield was reduced no more than 1% (J. Griffin, personal communication). These findings suggest that injury potential of dicamba at very low rates representative of volatility rates would not have a major effect on soybean yield. Primary concern for off-target movement of herbicides to sensitive crops would be from spray tank contamination and spray particle drift. Derksen (1998) reported that spray tank contamination rates range from 0.25 to 2% of the herbicide rate. For dicamba at 560 g/ha a probable contamination rate of 1% would correspond to a predicted soybean yield loss of 10% for application at V3/V4 and 24% at R1 (Griffin et al. 2013). Wolf et al. (1992) reported drift from unshielded sprayers in the range of 2 to 16%. For dicamba at 560 g/ha a probable drift rate of 10% would correspond to a predicted soybean yield loss of 44% for application at V3/V4 and 73% at R1 (Griffin et al. 2013).

This research was also successful in establishing injury criteria and severity ratings useful in comparing plant response to auxin herbicides. In most weed science research, an overall visual control/injury rating is made using a scale of 0 to 100% with a statement indicating that 0=

no control or crop injury and 100= all plants dead. Often this statement is accompanied by a listing of injury criteria included such as leaf cupping, leaf crinkling, leaf drooping, leaf rolling and strapping, stem and leaf petiole epinasty, terminal chlorosis/death, stem swelling, and stem cracking. Assigning an overall injury rating that encompasses all of these criteria would be subjective and expected to vary among individuals.

The present research attempted to evaluate injury symptoms based on four criteria: 1) leaf cupping/crinkling/drooping; 2) leaf rolling/strapping; 3) stem epinasty; and 4) stem swelling/cracking. These criteria encompass the primary injury symptoms that would be expected from plants exposed to auxin herbicides. With the degree of plant injury expected to vary among the herbicides and rates, each of the criterion were assigned a severity level based on a 0 to 5 scale with 0= no injury; 1= slight; 2= slight to moderate; 3= moderate; 4= moderate to severe; and 5= severe. Because injury due to leaf cupping/rolling/strapping would be considered less detrimental compared with stem epinasty and stem swelling/cracking, the injury criteria were weighted as follows: leaf cupping/crinkling/drooping = 2; leaf rolling/strapping = 4; stem epinasty = 6; and stem swelling/cracking = 8. This weighted system assumes that injury due to stem swelling/cracking is 4 times more important in estimating total crop injury when compared with leaf cupping/crinkling/drooping. Assigning a severity level of 5 for each of the criterion and weighting accordingly would result in a total injury value of 100%. This rating system proved effective in delineating specific injury criteria as to severity and in estimating total injury for both cotton and tomato when exposed to very low herbicide rates associated with volatility.

Sciumbato et al. (2004a) developed a method of quantifying injury from auxin herbicides that evaluated leaf and stem injury separately based on symptomology using a 0 to 100 scale with 100 representing plant death. The values were then averaged to provide a single estimate of crop injury. This method was used to quantify cotton and soybean response to volatility of 2,4-D and dicamba salts and triclopyr ester (Sciumbato et al. 2004b). In the field portion of the study, exposure rates (estimation of volatility) of the DGA salt of dicamba and the DMA salt of 2,4-D for cotton were equivalent and less than for triclopyr ester. However for soybean, the DMA salt of 2,4-D appeared to be most volatile. The contrast in plant response to volatility of the auxin herbicides was explained by the relative difficulty in evaluating soybean injury compared with cotton when using the injury method developed by Sciumbato et al. (2004a).

As the 2,4-D- and dicamba-resistant technologies become available it will be important that growers are aware of non-resistant crop sensitivity to 2,4-D and dicamba regardless of the formulation. In this research cotton was only minimally sensitive to volatilty of 2,4-D formulated as a DMA or acid and to dicamba formulated as a DMA, DGA, or acid. Although tomatoes were highly sensitive to both 2,4-D and dicamba volatility, differences in response between/among the various formulations for each of the herbicides were not observed. Off-target movement of 2,4-D and dicamba can occur through volatility but this method of exposure appears to be much less important when compared with spray tank contamination and physical drift. Extreme caution should be followed when tomatoes are grown near fields treated with 2,4-D and dicamba.

Literature Cited

Baur, J. R., R. W. Bovey, and H. G. McCall. 1973. Thermal and ultraviolet loss of herbicides. Arch. Environ. Contam. Toxicol. 1:289-302.

Behrens, R. and W. E. Lueschen. 1979. Dicamba volatility. Weed Sci. 27:486-493.

Braxton L. B., C. Cui, M. A. Peterson, J. S. Richburg, D. M. Simpson, and T. M. Wright. 2010. Dow Agrosciences herbicide tolerance traits (DHT) in cotton. Page 35 in Proceedings of the Beltwide Cotton Conference, New Orleans, LA, January 4–7, 2010. Memphis, TN: National Cotton Council of America.

Burnside, O. C. and T. L. Lavy. 1966. Dissipation of dicamba. Weeds 14:211-214.

Derksen, D. A. 1989. Dicamba, chlorsulfuron, and clopyralid as sprayer contaminants on sunflower (*Helianthus annuus*), mustard (*Brassica juncea*), and Lentil (*Lens culinaris*), respectively. Weed Sci. 37:616-621.

Egan, J. F. and D. A. Mortensen. 2012. Quantifying vapor drift of dicamba herbicides applied to soybean. Environ. Toxicol. Chem. 31:1023-1031.

Griffin, J. L., M. J. Bauerle, D. O. Stephenson, IV, D. K. Miller, and J. M. Boudreaux. 2013. Soybean response to dicamba applied at vegetative and reproductive growth stages. Weed Technol. 27:696–703.

Hatterman-Valenti, H., M. D. K. Owen, and N. E. Christians. 1995. Comparison of spray drift during postemergence herbicide applications to turfgrass. Weed Technol. 9:321-325.

Hayden, C. A., D. B. Reynolds, A. N. Eytcheson, L. C. Walton, and D. H. Perry. 2013. A comparison of auxin herbicide volatility when applied under field condition. Proc. So. Weed Sci. Soc. 66:118.

Heap, I. 2014. International Survey of Herbicide Resistant Weeds. Available at http://www.weedscience.org/in.asp. Accessed: June 24, 2014.

Johnson, V. A., L. R. Fisher, D. L. Jordan, K. E. Edmisten, A. M. Stewart, and A. C. York. 2012. Cotton, peanut, and soybean response to sublethal rates of dicamba, glufosinate, and 2,4-D. Weed Technol. 26:195-206.

Perry, D. H., B. Braxton, A. T. Ellis, R. A. Haygood, R. B. Lassiter, J. S. Richburg, and L. C. Walton. 2013. Evaluating differential volatility of auxin-type herbicides utilizing novel field methodology. Proc. So. Weed Sci. Soc. 66:79.

Que Hee, S. S. and R. G Sutherland. 1974. Volatilization of various esters and salts of 2,4-D. Weed Sci. 22:313-318.

Sandbrink, J., J. N. Travers, C. Kamienski, and J. Willis. 2013. Proposed dicamba application requirements for Roundup Ready® Xtend crop systems. Proc. So. Weed Sci. Soc. 66:28.

Saxton, A. M. 1998. A macro for converting mean separation output to letter groupings in Proc.Mixed. In Proc. 23rd SAS Users Group Intl., SAS Institute, Cary, NC, pp.1243-1246.Nashville, TN, March 22-25.

Sciumbato, A. S., J. M. Chandler. S. A. Senseman, R. W. Bovey, and K. L. Smith. 2004a. Determining exposure to auxin-like herbicides. I. Quantifying injury to cotton and soybean. Weed Technol. 18:1125-1134.

Sciumbato, A. S., J. M. Chandler. S. A. Senseman, R. W. Bovey, and K. L. Smith. 2004b. Determining exposure to auxin-like herbicides. II. Practical application to quantify volatility. Weed Technol. 18:1135-1142.

Sosnoskie, L. M., A. S. Culpepper, B. Braxton, and J. S. Richburg. 2012. Comparing volatility of three forms of 2,4-D when applied in the field. Weed Sci. Soc. Am. abstr. 333.

Wolf, T. M., R. Grover, K. Wallace, S. R. Shewchuk, and J. Maybank. 1992. Effect of protective shields on drift and deposition characteristics of field sprayers. *In* The Role of Application Factors in the Effectiveness and Drift of Herbicides. Agric. Canada, Regina, SK. pp. 29-52.

Xu, W., T. M. Cannan, C. W. Finch, G. Schnabel, M. Bratz, S. J. Bowe, and C. L. Brommer. 2012. Advancements in dicamba formulations. Weed Sci. Soc. Am. abstr. 329.

CHAPTER 4
SUMMARY

With the future availability of dicamba and 2,4-D herbicide-resistant crop technologies, issues concerning off-target herbicide movement to sensitive crops are expected. Research was conducted in Louisiana with two objectives 1) to evaluate soybean response to dicamba rates representative of exposure from physical/spray particle drift, spray tank contamination, and volatility and 2) to evaluate various formulations of 2,4-D, dicamba, and triclopyr in respect to volatility using cotton and tomato as indicator plants.

For the first objective, the diglycolamine (DGA) salt of dicamba was applied at V3/V4 (two to three trifoliate) at 4.4, 8.8, 17.5, 35, 70, 140, and 280 g ae/ha (1/128 to ½ of the recommended use rate of 560 g/ha). Soybean injury 7 days after treatment (DAT) was 20% following dicamba at 4.4 g/ha and injury increased to 89% at 280 g/ha. At 14 DAT, injury for the same rates increased from 39% to 97%. In a separate study, dicamba was applied at R1 (first flower) at 1.1, 2.2, 4.4, 8.8, 17.5, 35, and 70 g/ha (1/512 to 1/8 of use rate). Soybean injury 7 DAT was 19% at 1.1 g/ha and injury increased to 64% at 70 g/ha. For the same rates of dicamba, injury at 14 DAT increased no more than 4 percentage points. For application at both growth stages, visual symptoms included cupping of soybean leaflets, crinkling of the upper leaf surface, leaf petiole drooping, swollen petiole bases, terminal chlorosis, necrosis, and epinasty, and stem epinasty. At the higher rates, plant terminals were turned down contacting the soil surface and stem swelling and cracking were observed. In some cases plants were dead by 14 DAT.

For dicamba rates in common for the V3/V4 and R1 applications, soybean injury 14 DAT was greatest for the V3/V4 timing. For dicamba at 4.4 g/ha (1/128th of use rate), soybean yield was reduced 4% when applied at V3/V4 and 10% when applied at R1. For 17.5 g/ha dicamba

(1/32 of use rate), yield was reduced 16% at V3/V4 and 36% at R1. Based on yield reductions for 4.4 and 17.5 g/ha dicamba, soybean at flowering was around 2.5 times more sensitive compared with vegetative exposure.

Because of the range in rates evaluated in the study, inferences can be made as to soybean response due to dicamba spray particle drift, sprayer contamination, and volatility. Spray particle drift from ground sprayers can range from 1 to 16%. For a spray particle drift rate of 1% and an application rate of 560 g/ha dicamba, drift exposure would correspond to 5.6 g/ha (1/100th of use rate). In the present study, predicted soybean yield reduction for dicamba applied at 5.6 g/ha was 5% at V3/V4 and 13% at R1. A drift rate of 16% would correspond to 90 g/ha dicamba and a predicted yield loss of 64% for application at V3/V4. In the R1 study the highest dicamba rate evaluated of 70 g/ha (13% drift rate) resulted in a 72% yield loss. Spray tank contamination rates can range from 0.25 to 2% of the herbicide rate, which would correspond to 1.4 to 11.2 g/ha based on 560 g/ha dicamba. Predicted yield loss for 1.4 g/ha dicamba would correspond to 1 and 3% for V3/V4 and R1 applications, respectively. For 11.2 g/ha yield loss of 10% for V3/V4 and 24% for R1 applications would be expected.

For a field application rate of 560 g/ha dicamba, a dose rate of 0.56 g/ha (1/1000th of use rate) would correspond to vapor drift exposure. Predicted soybean yield reduction for dicamba at 0.56 g/ha of 0.5% for application at V3/V4 and 1.3% for R1 would be expected. These findings suggest that soybean injury due to volatility of dicamba would be only minimally important when compared with injury and yield reduction associated with spray particle drift and spray tank contamination. When dicamba-resistant soybean becomes available, significant hectares will still be planted to non-dicamba resistant cultivars. It is important that growers be aware of the sensitivity of soybean to dicamba, especially during flowering, and that appropriate steps be taken to avoid miss-application due to spray particle drift and improper sprayer cleanout.

For the second objective, 2,4-D isooctyl ester, dimethylamine (DMA) salt, and acid formulations applied at 1,120 and 2,240 g ae/ha; dicamba DMA salt, DGA salt, and acid formulations applied at 560 and 1,120 g/ha; and triclopyr butoxyethyl ester and acid formulations applied at 1,680 and 3,360 g ae/ha were applied during August and September to tilled soil. One hour after application tomato and cotton plants in pots were placed in the center of treated strips. Injury using four criteria (leaf cupping/crinkling/drooping; leaf rolling/strapping; stem epinasty; and stem swelling/cracking) was visually rated using a severity scale of 0 to 5 (0= no injury; 1= slight; 2= slight to moderate; 3= moderate; 4= moderate to severe; and 5= severe). A weighted factor was assigned to each injury criterion to provide an estimate of total injury on a 0 to 100% scale.

When experiments were terminated 14 DAT, total injury to cotton associated with volatility of all herbicide and herbicide formulations at the 1x rates was no more than 11% and was no greater than for the nontreated. These findings are in agreement with those of the dicamba rate/timing study in regard to the contribution of volatility to off-target exposure of soybean and cotton to dicamba and 2,4-D. For tomato, injury due to volatility was significant and the level of volatility was dependent on herbicide, herbicide formulation, and rate. Based on response to 2,4-D ester for total injury 14 DAT, tomato was 3.6 times more sensitive than cotton (36 vs. 10% injury, respectively). For the 1x rates, injury due to volatility for 2,4-D ester 14 DAT was greater than for 2,4-D DMA and acid formulations, dicamba DMA, DGA, and acid formulations and the triclopyr acid formulation (20 to 24%). For the 2x rates, tomato injury 14

DAT was 64% for 2,4-D ester, 21 to 28% for the 2,4-D DMA and acid formulations and the triclopyr acid formulation, and 39 to 40% for the dicamba formulations.

The acid formulations of 2,4-D, dicamba, and triclopyr evaluated in this study contain proprietary surfactants that solubilize the active ingredient to form a water miscible liquid formulation with very low volatility (Helena Chemical Company Collierville, TN). Injury to both cotton and tomato associated with volatility was no greater for the 2,4-D acid formulation compared with DMA and for the dicamba acid formulation compared with DMA and DGA formulations. Additionally, injury due to volatility of triclopyr acid for both the 1x and 2x experiments was no greater than for the 2,4-D and dicamba formulations. Although tomato was more sensitive to auxin herbicides when compared with cotton, differences in volatility among herbicide formulations, excluding the ester formulation, were of minimal importance in respect to off-target movement.

This research was also successful in establishing injury criteria and severity ratings that are less subjective and that can help to decrease variability in ratings among individuals. Injury symptoms were separated based on four criteria: leaf cupping/crinkling/drooping; leaf rolling/strapping; stem epinasty; and stem swelling/cracking. These criteria encompass the primary injury symptoms expected for plants exposed to auxin herbicides. Assigning a severity level based on a 0 to 5 scale and weighting each injury criterion accordingly proved effective in estimating total injury for both cotton and tomato when exposed to very low herbicide rates associated with volatility.

When dicamba- and 2,4-D-resistant technologies become available it will be important that growers are aware of non-target crop sensitivity to dicamba and 2,4-D. Off-target movement of 2,4-D and dicamba can occur through volatility but this method of exposure appears to be much less important when compared with physical drift and spray tank contamination. Extreme caution should be followed especially when tomatoes are grown near fields treated with dicamba and 2,4-D.

VITA

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