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Cotton, Peanut, and Soybean Response to Sublethal Rates of Dicamba, Glufosinate, and 2,4-D

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Development and utilization of dicamba-, glufosinate-, and 2,4-D-resistant crop cultivars will potentially have a significant influence on weed management in the southern United States. However, off-site movement to adjacent nontolerant crops and other plants is a concern in many areas of eastern North Carolina and other portions of the southeastern United States, especially where sensitive crops are grown. Cotton, peanut, and soybean are not resistant to these herbicides, will most likely be grown in proximity, and applicators will need to consider potential adverse effects on nonresistant crops when these herbicides are used. Research was conducted with rates of glufosinate, dicamba, and 2,4-D designed to simulate drift on cotton, peanut, and soybean to determine effects on yield and quality and to test correlations of visual estimates of percent injury with crop yield and a range of growth and quality parameters. Experiments were conducted in North Carolina near Lewiston-Woodville and Rocky Mount during 2009 and 2010. Cotton and peanut (Lewiston-Woodville and Rocky Mount) and soybean (two separate fields [Rocky Mount] during each year were treated with dicamba and the amine formulation of 2,4-D at 1/2, 1/8, 1/32, 1/128, and 1/512 the manufacturer's suggested use rate of 280 g ai ha^{-1} and 540 g ai ha^{-1}, respectively. Glufosinate was applied at rates equivalent to 1/2, 1/4, 1/8, 1/16, and 1/32 the manufacturer's suggested use rate of 604 g ai ha^{-1}. A wide range of visible injury was noted at both 1 and 2 wk after treatment (WAT) for all crops. Crop yield was reduced for most crops when herbicides were applied at the highest rate. Although correlations of injury 1 and 2 WAT with yield were significant ($P \leq 0.05$), coefficients ranged from −0.25 to −0.50, −0.36 to −0.62, and −0.40 to −0.67 for injury 1 WAT vs. yield for cotton, peanut, and soybean, respectively. These respective crops had ranges of correlations of −0.17 to −0.43, −0.34 to −0.64, and −0.41 to −0.60 for injury 2 WAT. Results from these experiments will be used to emphasize the need for diligence in application of these herbicides in proximity to crops that are susceptible as well as the need to clean sprayers completely before spraying sensitive crops.

Nomenclature: Dicamba; glufosinate; 2,4-D; cotton, *Gossypium hirsutum* L.; peanut, *Arachis hypogaea* L.; soybean, *Glycine max* (L.) Merr.

Key words: Herbicide-resistant crops, off-target spray, spray drift.

El desarrollo y la utilización de cultivares resistentes a dicamba, glufosinate y 2,4-D, tendrá potencialmente una influencia importante en el manejo de malezas en el sur de los Estados Unidos. Sin embargo, la deriva de estos herbicidas a cultivos adyacentes no tolerantes y a otras plantas, es una preocupación en muchas áreas del este de Carolina del Norte y otras regiones del sureste de los Estados Unidos, especialmente donde se siembran cultivos sensibles. El algodón, el maní y la soyano son resistentes a estos herbicidas, y muy probablemente serán sembrados con cierta cercanía y los aplicadores necesitarán tomar en consideración los efectos adversos potenciales en cultivos no resistentes cuando éstos herbicidas sean usados. Se realizó una investigación con dosis de glufosinate, dicamba, y 2,4-D, diseñadas para simular deriva sobre algodón, maní y soya, para determinar los efectos en el rendimiento y la calidad y para probar las correlaciones de estimaciones visuales del porcentaje de daño con el rendimiento del cultivo y un rango de parámetros de crecimiento y calidad. Los experimentos se realizaron en Carolina del Norte cerca de Lewiston-Woodville y Rocky Mount durante 2009 y 2010. El algodón y el maní (Lewiston-Woodville y Rocky Mount) y la soya en dos campos separados en Rocky Mount durante cada año, se trataron con dicamba y una formulación amina de 2,4-D a 1/2, 1/8, 1/32, 1/128 y 1/512, de la dosis sugerida por los fabricantes, de 280 g ia ha^{-1} y 540 g ia ha^{-1}, respectivamente. El glufosinate se aplicó a dosis equivalentes a 1/2, 1/4, 1/8, 1/16 y 1/32 de la dosis recomendada en la etiqueta, de 604 g ia ha^{-1}. Se observó una amplia gama de daño visible a una y dos semanas después del tratamiento (WAT) para todos los cultivos. El rendimiento se redujo para la mayoría de los cultivos cuando los herbicidas se aplicaron a la mayor dosis. Aunque las correlaciones de daño a una y dos WAT con respecto al rendimiento fueron significativas ($p \leq 0.05$), los coeficientes variaron de −0.25 a −0.50, de −0.36 a −0.62 y de −0.40 a −0.67 de daño a una WAT, en comparación con el rendimiento de algodón, maní y soya, respectivamente. Estos cultivos respectivos tuvieron rangos de correlación de −0.17 a −0.43, de −0.34 a −0.64 y de −0.41 a −0.60 de daño a dos WAT. Los resultados de estos experimentos serán usados para enfatizar la necesidad de ser diligentes en la aplicación de estos herbicidas al estar cerca de cultivos susceptibles, así como la necesidad de limpiar completamente los aspersores antes de aplicar sobre los cultivos sensibles.

According to the International Survey of Herbicide-Resistant Weeds, there are currently 352 resistant biotypes, consisting of 197 species in over 420,000 fields worldwide. Also of note, the list of resistant weeds encompasses over 13 different known modes of action (Heap 2011). There are a number of agronomic practices that contribute to selection pressure on weed populations, including: crop rotation, tillage, herbicide use, soil amendments, and mechanization of harvesting. Herbicide use, however, has by far had the greatest impact on weed selection in recent years. The introduction of transgenic crops has no doubt resulted in extensive changes in weed management and cropping systems.

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Genetically modified crops have been adopted rapidly in North America (Murphy and Lemerle 2006), with over 62.5 million ha grown in the United States, including alfalfa (*Medicago sativa* L.), canola (*Brassica napus*), corn (*Zea mays* L.), cotton, papaya (*Carica papaya* L.), soybean, squash (*Cucurbita moschata*), and sugar beet (*Beta vulgaris* subsp. *vulgaris*) (James 2008).

Currently, the two transgene traits with herbicide resistance commercially available are LibertyLink® and Roundup Ready®, with tolerance to glufosinate and glyphosate, respectively. Glyphosate can be applied to crops from emergence through flowering to control emerged weeds (Anonymous 2010). Therefore, growers can apply a single herbicide at elevated rates of active ingredient and at multiple times during the growing season without concern for injury to the crop (Owen and Zelaya 2005).

Cultivars are currently being developed that tolerate topical applications of dicamba and 2,4-D (Sauer 2010). Dicamba and 2,4-D are both synthetic auxins, meaning they mimic the plant growth hormone indole-3-acetic acid, disrupting growth and development processes, and eventually causing plant death (Senseman 2007). Auxin-like herbicides control a large spectrum of broadleaf weeds, including key weeds that have evolved resistance to glyphosate (Green and Owen 2010). Development of this technology provides growers with alternatives to current weed management systems. However, it is important to use this technology correctly to provide new uses for existing herbicides as well as to help growers manage glyphosate-resistant weed problems and sustain the usability of glyphosate-resistant traits (Green and Owen 2010).

Although selection pressure and increased incidence of herbicide-resistant weeds are serious issues, there are other concerns associated with new tolerant crop cultivars. One major concern is the off-target movement or drift of those herbicides onto sensitive adjacent crops. Herbicides such as glufosinate, dicamba, and 2,4-D can cause damage to nontargeted plants due to physical drift or volatilization (Bayley et al. 1992; Behrens and Lueschen 1979; Ramsdale and Messersmith 2001; Sciumbato et al. 2004a,b, 2005) and reduce crop yield (Al-Khatib and Peterson 1999; Andersen et al. 2004; Brown et al. 2009; Burke et al. 2005; Everitt and Keeling 2009; Fagliari et al. 2005; Sciumbato et al. 2004a,b; Vangessel and Johnson 2005; Wax et al. 1969).

Lassiter et al. (2007) studied drift of glyphosate on peanut by applying sublethal rates of the manufacturer's suggested use rate over the top of peanut plants approximately 4 wk after planting. Loss of peanut yield was found to be highly correlated with visual observations of peanut injury.

Another study involved cotton yield and physiological response to simulated drift rates of glyphosate (Thomas et al. 2005). When cotton was at the four-leaf growth stage, the researchers applied an early POST application of glyphosate ranging from 8.7 to 1,250 g ai ha^{-1}, representing 0.78 to 100% of the commercial use rate, respectively. Visual estimates of injury were based on a summation of stunting, discoloration, and stand reduction and were taken 7 d after treatment (DAT) at all locations both years and 47 DAT at all locations 1 year. As expected, visible injury 1 wk after treatment (WAT) increased at all locations with increasing glyphosate rates, with symptoms mainly consisting of discoloration and stunting. Cotton yield varied among treatments, but the overall conclusion was that nontransgenic cotton can tolerate drift rates of glyphosate at the four-leaf stage as high as 70 g ai ha^{-1}.

Marple et al. (2008) studied cotton injury and yield as affected by simulated drift of 2,4-D and dicamba. They found that 2,4-D and dicamba injury symptoms were more severe when herbicides were applied at the three- to four-leaf stage compared with applications later in the season. Dicamba caused slight stem and petiole epinasty with leaf cupping and general chlorosis of developed leaves at the time of application. Leaves that were not fully expanded at the time of dicamba treatment were stunted and distorted. In addition, cotton growth after dicamba treatment exhibited shoot and petiole epinasty, as well as leaf cupping and stunting. Plants treated with 2,4-D had similar injury to plants treated with dicamba; however, symptoms were more intense, with distinct strapping of the leaf. Symptoms caused by 2,4-D were evident at 1 WAT and intensified throughout the season; consequently, the recovery from 2,4-D injury was less than the recovery from dicamba injury. This research revealed that plants were susceptible to both 2,4-D and dicamba drift; however, yields were reduced more when plants were exposed to 2,4-D. In addition, cotton is most susceptible to dicamba and 2,4-D exposure at early growth stages (Marple et al. 2008).

Researchers looking at soybean response to simulated drift applied 1/100, 1/33, 1/10, and 1/3 of the recommended use rates of glyphosate, dicamba, glufosinate, and selected sulfonylureas at the two- to three-trifoliate growth stage. Observations for injury symptoms and recovery were taken every week during the entire growing season and injury ratings were estimated every 2 wk. All rates of dicamba injured the soybean plants, whereas only the two highest rates of glyphosate and glufosinate injured soybeans (Al-Khatib and Peterson 1999).

Miller et al. (2003) studied the response of nonglufosinate-resistant cotton to reduced rates of glufosinate. They found that injury symptoms after an application of glufosinate ranged from slight chlorosis to severe necrosis and plant death and that less response to glufosinate was observed as application timing was delayed. Cotton was able to recover and have a yield equivalent to nontreated cotton. However, rates evaluated in this study are representative of those that would be expected in sprayer contamination or drift situations, and rates greater than 105 g ha^{-1} may result in more serious effects (Miller et al. 2003).

In addition to physical drift, vapor drift, specifically that of auxin herbicides, is common (Sciumbato et al. 2004b). Volatilization and movement resulting in crop injury by 2,4-D and dicamba is well documented (Behrens and Lueschen 1979; Chang and Born 1971; Sciumbato et al. 2004b). As a result, application of synthetic auxin herbicides is restricted in some geographical areas.

Everitt and Keeling (2009) attempted to correlate simulated 2,4-D and dicamba drift on cotton but found that in most cases visual estimates of injury overestimated yield reduction. Marple et al. (2007) also found that postdrift symptomology caused by most applied treatments was not a reliable indication of effects on yield. Injury to plants treated with 2,4-D and picloram was well correlated with yield loss; however, these injury ratings were later in the season, indicating that 2,4-D and picloram injury symptoms late in the growing season are highly correlated with yield reduction. This research showed that cotton plants can sustain some plant injury without large reductions in yield (Marple et al. 2007). This is not surprising because of the indeterminate growth habit of cotton and the ability of this crop to compensate for stress. After a drift or misapplication event farmers are interested in knowing the long-term effects of herbicide injury on yield. Developing data to correlate visible injury symptoms with yield would be beneficial in making additional management decisions. Therefore, research was conducted to determine cotton, peanut, and soybean sensitivity to sublethal rates of dicamba, glufosinate, and 2,4-D and to correlate visible injury symptoms with yield and other growth parameters.

Materials and Methods

Experiments were conducted in North Carolina at the Upper Coastal Plain Research Station near Rocky Mount and the Peanut Belt Research Station near Lewiston-Woodville during 2009 and 2010. Soil at Rocky Mount was Norfolk loamy sand (fine-loamy, kaolinitic, thermic Typic Kandiudults). Soil at Lewiston-Woodville was a Goldsboro fine sandy loam (fine-loamy, siliceous, subactive, thermic Aquic Paleudults). Soil pH ranged from 5.8 to 6.3 and organic matter content ranged from 1.5 to 2.3%. Cotton (DP0912 B2RF cotton, Monsanto Company, St. Louis, MO 63167), peanut (Isleib et al. 2006), and soybean (DG36T60 RR soybean, Crop Production Services, Loveland, CO 80538)were planted in early to mid-May in the same field at Rocky Mount during both years. At Lewiston-Woodville, cotton (DP0920 B2RF cotton, Monsanto Company, 800 N. Lindbergh Blvd., St. Louis, MO 63167)and peanut were evaluated during both years in separate fields. Soybean was also evaluated in one additional field at Rocky Mount during both years. Plot size was two rows (91-cm spacing) by 9 m. Nontreated rows were included between treated rows to minimize movement of herbicide to other treatment rows. Production and pest management practices based on Cooperative Extension recommendations were followed to optimize crop yield and to maintain crops pest free. A nontreated control was included.

Treatments consisted of five sublethal rates of dicamba (Clarity® herbicide, BASF Corporation, Research Triangle Park, NC 27709), glufosinate (Ignite 280® herbicide, Bayer Cropscience, Research Triangle Park, NC 27709), and 2,4-D (Weedar 64® herbicide, Nufarm Americas Inc., Burr Ridge, IL 60527) applied when cotton and soybean were 20 to 30 cm in height and when peanut was 15 to 20 cm wide, approximately 3 wk after crop emergence. Five sequential rates were determined on the basis of the registrant's use rate for each herbicide: dicamba (280 g ha^{-1}), glufosinate (604 g ha^{-1}), and 2,4-D (540 g ha^{-1}) (Anonymous 2011a,b,c). Rates for glufosinate relative to the manufacturer's suggested use rate included 1/2, 1/4, 1/8, 1/16, and 1/32, equivalent to 302, 123, 63, 31, and 16 g ha^{-1}. Rates for dicamba and 2,4-D relative to the manufacturer's suggested use rate were 1/2, 1/8, 1/32, 1/128, and 1/512, equivalent to 140, 41, 11, 3, and 0.6 g ha^{-1} for dicamba and 269, 78, 20, 5, and 1 g ha^{-1} for 2,4-D. Herbicides were applied at 140 L ha^{-1} using 8002 nozzles (Teejet® TP8002EVS nozzles, Spraying Systems Co., Wheaten, IL 60189) at 145 kPa.

Visual estimates of percent crop injury were recorded 1 and 2 WAT using a scale of 0 (no injury) to 100 (complete plant death). Foliar chlorosis, necrosis, and plant stunting were considered when making the visual estimates. Digital images were taken 1 and 2 WAT to record injury symptomology. After cotton defoliation, six plants from each cotton plot were plant mapped to determine fruiting patterns in 2009 and

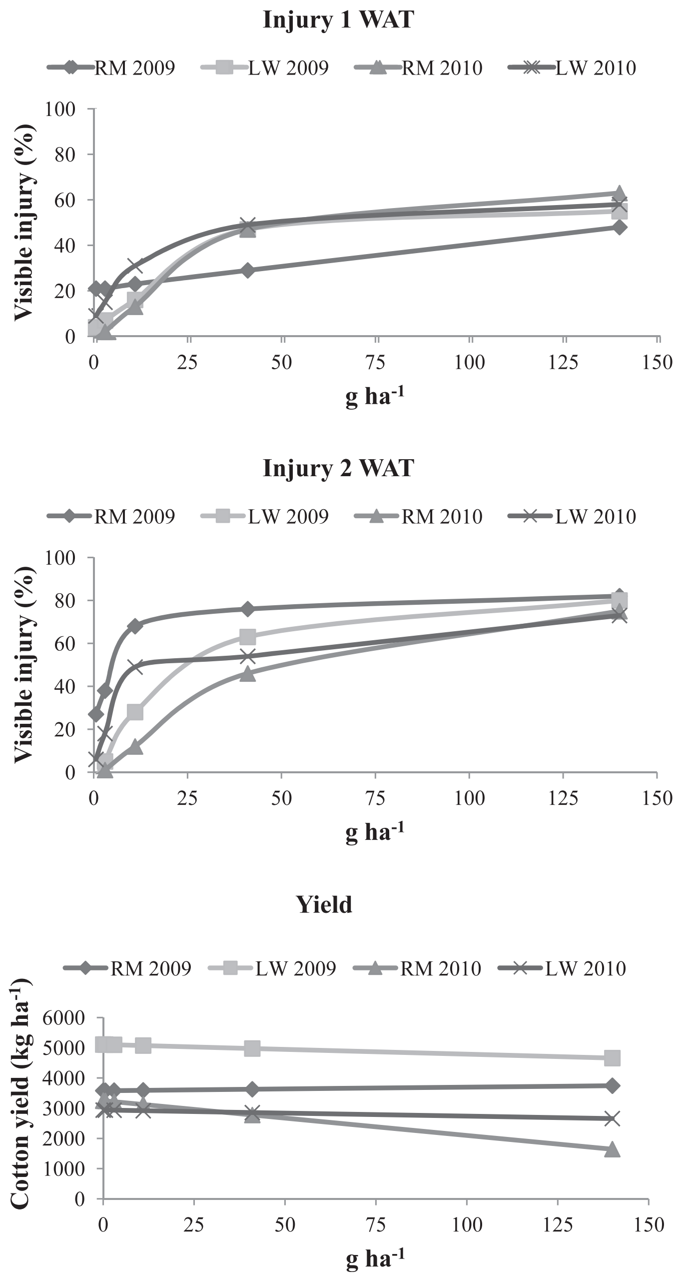

Figure 1. Cotton injury 1 and 2 wk after treatment and yield (seed cotton) after application of dicamba (RM = Rocky Mount and LW = Lewiston-Woodville).

Table 1. Regression equations for cotton, peanut, and soybean response to dicamba, glufosinate, and 2,4-D.

	Regression equation	R^2
Visual estimates of cotton injury from dicamba, 1 WAT[a]		
Rocky Mount, 2009	$y = 0.19x + 20.5$	0.32
Lewiston, 2009	$y = 1.33x - 0.069x^2 + 3.2$	0.86
Rocky Mount, 2010	$y = 1.50x - 0.0074x^2 - 2.3$	0.90
Lewiston, 2010	$y = 2.70x - 0.052x^2 + 0.00025x^3 + 7.8$	0.88
Visual estimates of cotton injury from dicamba, 2 WAT		
Rocky Mount, 2009	$y = 5.47x - 0.113x^2 + 0.00067x^3 + 24.1$	0.69
Lewiston, 2009	$y = 3.71x - 0.062x^2 + 0.00028x^3 - 4.8$	0.96
Rocky Mount, 2010	$y = 1.43x - 0.0063x^2 - 2.8$	0.98
Lewiston, 2010	$y = 5.80x - 0.14x^2 + 0.00073x^3 + 2.67$	0.91
Cotton yield response to dicamba		
Rocky Mount, 2009	$y =$ NS	
Lewiston, 2009	$y =$ NS	
Rocky Mount, 2010	$y = -11.4x + 3{,}248$	0.42
Lewiston, 2010	$y =$ NS	
Visual estimates of cotton injury from glufosinate, 1 WAT		
Rocky Mount, 2009	$y = 0.95x - 0.002x^2 - 3.3$	0.91
Lewiston, 2009	$y = 0.75x - 0.0014x^2 - 2.4$	0.95
Rocky Mount, 2010	$y = 0.96x - 0.0022x^2 + 9.3$	0.87
Lewiston, 2010	$y = 0.17x + 0.00046x^2 + 9.8$	0.96
Visual estimates of cotton injury from glufosinate, 2 WAT		
Rocky Mount, 2009	$y = 0.76x - 0.0015x^2 + 5.5$	0.76
Lewiston, 2009	$y = 0.58x - 0.00087x^2 - 2.2$	0.95
Rocky Mount, 2010	$y = 0.87x - 0.0018x^2 - 12.7$	0.87
Lewiston, 2010	$y = 0.20x + 0.0017x^2 + 9.8$	0.92
Cotton yield response to glufosinate		
Rocky Mount, 2009	$y = -6.11x + 4152.2$	0.44
Lewiston, 2009	$y = -6.4x + 5048.8$	0.71
Rocky Mount, 2010	$y = -5.23x + 3055.9$	0.37
Lewiston, 2010	$y = 2.12x - 0.033x^2 + 2871.3$	0.91
Visual estimates of cotton injury from 2,4-D, 1 WAT		
Rocky Mount, 2009	$y = 1.60x - 0.019x^2 + 0.000052x^3 + 7.3$	0.78
Lewiston, 2009	$y = 1.93x - 0.019x^2 + 0.000049x^3 + 9.9$	0.88
Rocky Mount, 2010	$y = 3.52x - 0.044x^2 + 0.0000012x^3 - 5.2$	0.94
Lewiston, 2010	$y = 2.09x - 0.026x^2 + 0.00007x^3 + 10.6$	0.80
Visual estimates of cotton injury from 2,4-D, 2 WAT		
Rocky Mount, 2009	$y = 1.89x - 0.024x^2 + 0.000065x^3 + 40.7$	0.60
Lewiston, 2009	$y = 2.9x - 0.036x^2 + 0.000097x^3 + 22.9$	0.78
Rocky Mount, 2010	$y = 2.95x - 0.036x^2 + 0.000095x^3 + 2.6$	0.97
Lewiston, 2010	$y = 1.58x - 0.019x^2 + 0.00005x^3 + 33.7$	0.75
Cotton yield response to 2,4-D		
Rocky Mount, 2009	$y =$ NS	
Lewiston, 2009	$y = -15.8x + 4{,}931$	0.93
Rocky Mount, 2010	$y = -7.3x + 2{,}870$	0.60
Lewiston, 2010	$y = -4.78x + 2{,}552.8$	0.68
Visual estimates of peanut injury from dicamba, 1 WAT		
Rocky Mount, 2009	$y = 0.11x + 30.1$	0.15
Lewiston, 2009	$y = 0.93x - 0.006x^2 + 13.2$	0.60
Rocky Mount, 2010	$y = 4.9x - 0.11x^2 + 0.0005x^3 - 5.5$	0.94
Lewiston, 2010	$y = 3.2x - 0.069x^2 + 0.00034x^3 + 11.9$	0.91
Visual estimates of peanut injury from dicamba, 2 WAT		
Rocky Mount, 2009	$y = 1.6x - 0.0087x^2 + 22$	0.86
Lewiston, 2009	$y = 2.05x - 0.044x^2 + 0.00023x^3 + 5.9$	0.89
Rocky Mount, 2010	$y = 1.4x - 0.006x^2 + 0.36$	0.99
Lewiston, 2010	$y = 5.1x - 0.11x^2 + 0.0005x^3 + 1.7$	0.96
Peanut yield response to dicamba		
Rocky Mount, 2009	$y = -15.9x + 3{,}660$	0.62
Lewiston, 2009	$y = -39.4x + 0.21x^2 + 5{,}983$	0.52
Rocky Mount, 2010	$y = -7.1x + 4{,}111$	0.07
Lewiston, 2010	$y = -18.7x + 5{,}018$	0.47

Table 1. Continued.

	Regression equation	R^2
Visual estimates of peanut injury from glufosinate, 1 WAT		
Rocky Mount, 2009	$y = 0.22x + 27.9$	0.76
Lewiston, 2009	$y = 0.04x + 0.00079x^2 + 9.3$	0.99
Rocky Mount, 2010	$y = 2.34x - 0.016x^2 + 0.00003x^3 - 31.1$	0.96
Lewiston, 2010	$y = 0.31x + 2.1$	0.92
Visual estimates of peanut injury from glufosinate, 2 WAT		
Rocky Mount, 2009	$y = 0.27x + 13.2$	0.72
Lewiston, 2009	$y = -0.079x + 0.0012x^2 + 5.1$	0.99
Rocky Mount, 2010	$y = 0.36x - 6.1$	0.96
Lewiston, 2010	$y = -0.119x + 0.0014x^2 + 1.9$	0.99
Peanut yield response to glufosinate		
Rocky Mount, 2009	$y = -6.4x + 6{,}301$	0.67
Lewiston, 2009	$y = 2.6x - 0.029x^2 + 6{,}039$	0.76
Rocky Mount, 2010	$y = -10.9x+4{,}319$	0.52
Lewiston, 2010	$y = 7.3x - 0.049x^2 + 4{,}643$	0.50
Visual estimates of peanut injury from 2,4-D, 1 WAT		
Rocky Mount, 2009	$y = 0.085x + 8.7$	0.51
Lewiston, 2009	$y = 0.016x + 6.5$	0.13
Rocky Mount, 2010	$y = -0.027x + 0.0006x\mathrm{X}^2 + 0.59$	0.82
Lewiston, 2010	$y = 0.14x + 0.096$	0.87
Visual estimates of peanut injury from 2,4-D, 2 WAT		
Rocky Mount, 2009	$y = 0.11x + 12.5$	0.43
Lewiston, 2009	$y = 0.12x + 1.2$	0.87
Rocky Mount, 2010	$y = 0.011x + 0.00027x^2 - 0.11$	0.97
Lewiston, 2010	$y = 0.107x - 0.98$	0.73
Peanut yield response to 2,4-D		
Rocky Mount, 2009	$y = 8.79x - 0.044x^2 + 3{,}554$	0.47
Lewiston, 2009	$y = -1.59x\mathrm{X} + 5{,}842$	0.12
Rocky Mount, 2010	$y = -4.45x + 4{,}454$	0.13
Lewiston, 2010	$y = -3.3x + 4{,}471$	0.10
Visual estimates of soybean injury from dicamba, 1 WAT		
Rocky Mount #1, 2009	$y = 0.42x\mathrm{X} + 19.7$	0.84
Rocky Mount #2, 2009	$y = 1.7x - 0.008x^2 + 7.4$	0.95
Rocky Mount #1, 2010	$y = 2.4x - 0.01x^2 - 1.2$	0.93
Rocky Mount #2, 2010	$y = 1.6x - 0.007x^2 + 15$	0.93
Visual estimates of soybean injury from dicamba, 2 WAT		
Rocky Mount #1, 2009	$y = 3.3x - 0.08x^2 + 0.00045x^3 + 45.6$	0.86
Rocky Mount #2, 2009	$y = 2.6x - 0.06x^2 + 0.00029x^3 + 43.4$	0.82
Rocky Mount #1, 2010	$y = 3.6x - 0.0x^2 + 0.0003x^3 + 3.9$	0.96
Rocky Mount #2, 2010	$y = 3.8x - 0.06x^2 + 0.00030x^3 + 8.3$	0.96
Soybean yield response to dicamba		
Rocky Mount #1, 2009	$y = -55.4x + 0.26x^2 + 2{,}710$	0.86
Rocky Mount #2, 2009	$y = -5.2x + 1{,}655$	0.52
Rocky Mount #1, 2010	$y = -108.5x + 2.36x^2 - 0.012x^3 + 1{,}535$	0.86
Rocky Mount #2, 2010	$y = -64.5x + 0.309x\mathrm{X}^2 + 3{,}239$	0.90
Visual estimates of soybean injury from glufosinate, 1 WAT		
Rocky Mount #1, 2009	$y = 0.62x - 0.001x^2 + 9.5$	0.96
Rocky Mount #2, 2009	$y = 1.5x - 0.009x^2 + 0.000018x^3+1.7$	0.97
Rocky Mount #1, 2010	$y = 2.3x - 0.015x^2 + 0.000028x^3 - 26.2$	0.99
Rocky Mount #2, 2010	$y = 0.29x + 7.7$	0.92
Visual estimates of soybean injury from glufosinate, 2 WAT		
Rocky Mount #1, 2009	$y = 0.18x - 8.5$	0.80
Rocky Mount #2, 2009	$y = 0.54x - 0.00079x^2 - 4.6$	0.91
Rocky Mount #1, 2010	$y = 1.3x - 0.009x^2 + 0.000019x^3 - 15.2$	0.97
Rocky Mount #2, 2010	$y = 0.025x + 0.001x^2 + 1.3$	0.98
Soybean yield response to glufosinate		
Rocky Mount #1, 2009	$y = -1.56x + 2{,}772$	0.17
Rocky Mount #2, 2009	$y = -0.71x + 1{,}598$	0.06
Rocky Mount #1, 2010	$y = -2.1x + 1{,}594$	0.39
Rocky Mount #2, 2010	$y = 7.4x - 0.036x^2+2{,}784$	0.53

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Table 1. Continued.

	Regression equation	R^2
Visual estimates of soybean injury from 2,4-D, 1 WAT		
Rocky Mount #1, 2009	$y = 0.19x + 3.8$	0.83
Rocky Mount #2, 2009	$y = 0.64x - 0.0015x^2 - 0.38$	0.97
Rocky Mount #1, 2010	$y = 0.03x + 4.3$	0.85
Rocky Mount #2, 2010	$y = -0.067x + 0.001x^2 + 0.36$	0.99
Visual estimates of soybean injury from 2,4-D, 2 WAT		
Rocky Mount #1, 2009	$y = 0.54x - 0.0012x^2 - 0.87$	0.87
Rocky Mount #2, 2009	$y = -0.27x + 0.016x^2 - 0.8005x^3 + 1.1$	0.98
Rocky Mount #1, 2010	$y = -0.032x + 0.0014x^2 + 0.09$	0.98
Rocky Mount #2, 2010	$y = -0.136x + 0.0015x^2 + 1.3$	0.99
Soybean yield response to 2,4-D		
Rocky Mount #1, 2009	$y = -2.04x + 2{,}554$	0.18
Rocky Mount #2, 2009	$y = -3.5x + 0.017x^2 + 1{,}645$	0.32
Rocky Mount #1, 2010	$y = -4.17x + 1{,}547$	0.51
Rocky Mount #2, 2010	$y = -8.25x + 3{,}114$	0.79

[a] Abbreviations: WAT, weeks after treatment; NS, not significant.

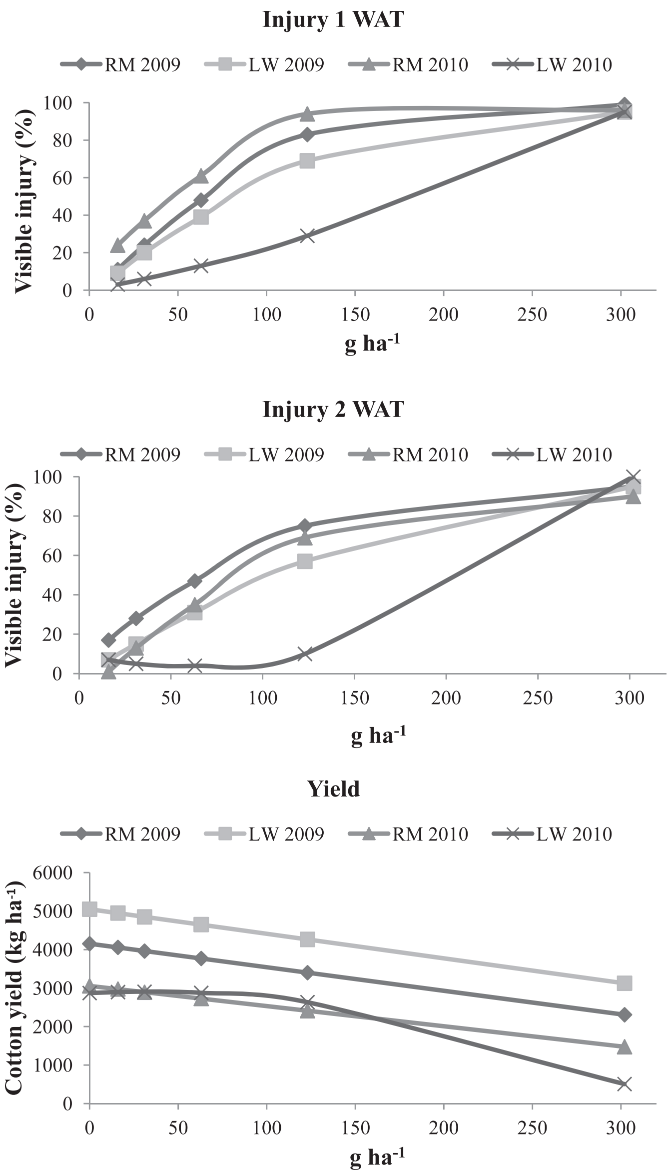

Figure 2. Cotton injury 1 and 2 wk after treatment and yield (seed cotton) after application of glufosinate (RM = Rocky Mount and LW = Lewiston-Woodville).

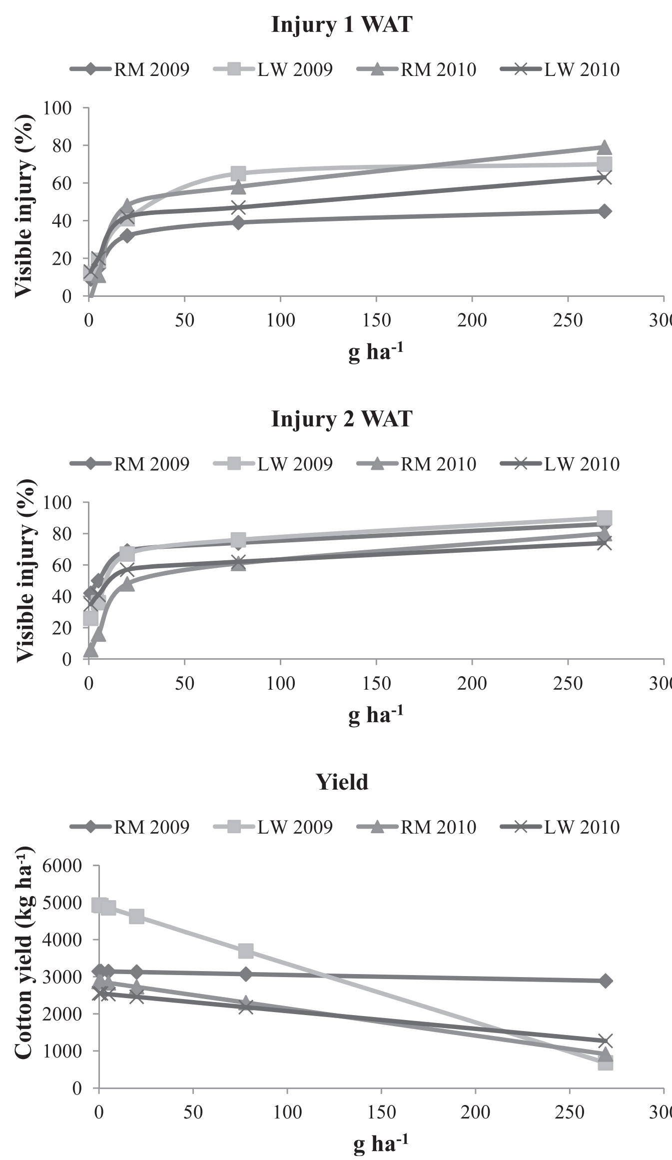

Figure 3. Cotton injury 1 and 2 wk after treatment and yield (seed cotton) after application of 2,4-D (RM = Rocky Mount and L W=Lewiston-Woodville).

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Table 2. Pearson correlations among visible injury, yield, and plant mapping characteristics of cotton. Data are pooled over years and locations.

Variable	P > *F*	Regression coefficient
Glufosinate		
Injury 1 WAT[a] vs. yield	< 0.0001	−0.45
Injury 2 WAT vs. yield	< 0.0001	−0.42
Yield vs. plant height	0.0015	0.34
Yield vs. terminals removed	0.0166	−0.37
Yield vs. monopodial bolls	0.1380	−0.16
Yield vs. sympodial bolls	0.1947	0.14
Yield vs. total bolls	0.7594	−0.03
Yield vs. total nodes	< 0.0001	0.42
Dicamba		
Injury 1 WAT vs. yield	0.0197	−0.25
Injury 2 WAT vs. yield	0.1315	−0.17
Yield vs. plant height	< 0.0001	0.54
Yield vs. terminals removed	0.0021	−0.45
Yield vs. monopodial bolls	0.1326	−0.16
Yield vs. sympodial bolls	< 0.0001	0.43
Yield vs. total bolls	0.0052	0.30
Yield vs. total nodes	< 0.0001	0.63
2,4-D		
Injury 1 WAT vs. yield	< 0.0001	−0.50
Injury 2 WAT vs. yield	< 0.0001	−0.43
Yield vs. plant height	0.0005	0.37
Yield vs. terminals removed	0.0022	−0.45
Yield vs. monopodial bolls	0.0567	−0.21
Yield vs. sympodial bolls	< 0.0001	0.43
Yield vs. total bolls	0.0215	0.25
Yield vs. total nodes	0.1506	0.15

[a] Abbreviation: WAT, weeks after treatment.

2010. Before harvesting peanut, pod mesocarp color was determined in mid- to late September to compare pod maturity among treatments (Williams and Drexler 1981). The percentage of pods in the brown and black mesocarp color categories indicates maturity and readiness for digging (Jordan et al. 2005). After digging, the peanuts were dried for 4 to 7 d in the field before harvest. A 1-kg sample of pods was removed from each plot to determine percentages of total sound mature kernels (%TSMK), extra large kernels (%ELK), and fancy pods (%FP). Final peanut and soybean yield was adjusted to 8 and 15.7% moisture, respectively.

The experimental design was a randomized complete block for each crop with treatments replicated four times. Data for visual estimates of percent crop injury 1 and 2 WAT, crop yield, percentage of mature peanut pods (%MP), %TSMK, %ELK, %FP, cotton plant height, cotton monopodial bolls, cotton sympodial bolls, cotton total bolls, and cotton total nodes were subjected to ANOVA to determine if data could be pooled over experiments (year/location combination) using the PROC GLM procedure in SAS (SAS Institute Inc., Cary, NC 27513). Data were analyzed by experiment for each herbicide and were tested for linear, quadratic, and cubic functions for injury 1 WAT or 2 WAT or crop yield vs. herbicide rate (g ha^{-1}) for all crops. Data for visual estimates of percent crop injury were transformed for the arcsine square root to normalize data. Transformation did not affect data interpretation and therefore nontransformed data are presented. Pearson correlation coefficients (Ott and Longnecker 2001) and P > *F* values were determined for injury 1 and 2 WAT vs. crop yield, yield vs. plant height (cotton), yield vs. terminals removed (cotton), yield vs. monopodial bolls (cotton), yield vs. sympodial bolls (cotton), yield vs. total bolls (cotton), yield vs. total nodes (cotton), yield vs. %MP (peanut), yield vs. %TSMK (peanut), yield vs. %ELK (peanut), and yield vs. %FP (peanut) using the PROC CORR procedure in SAS.

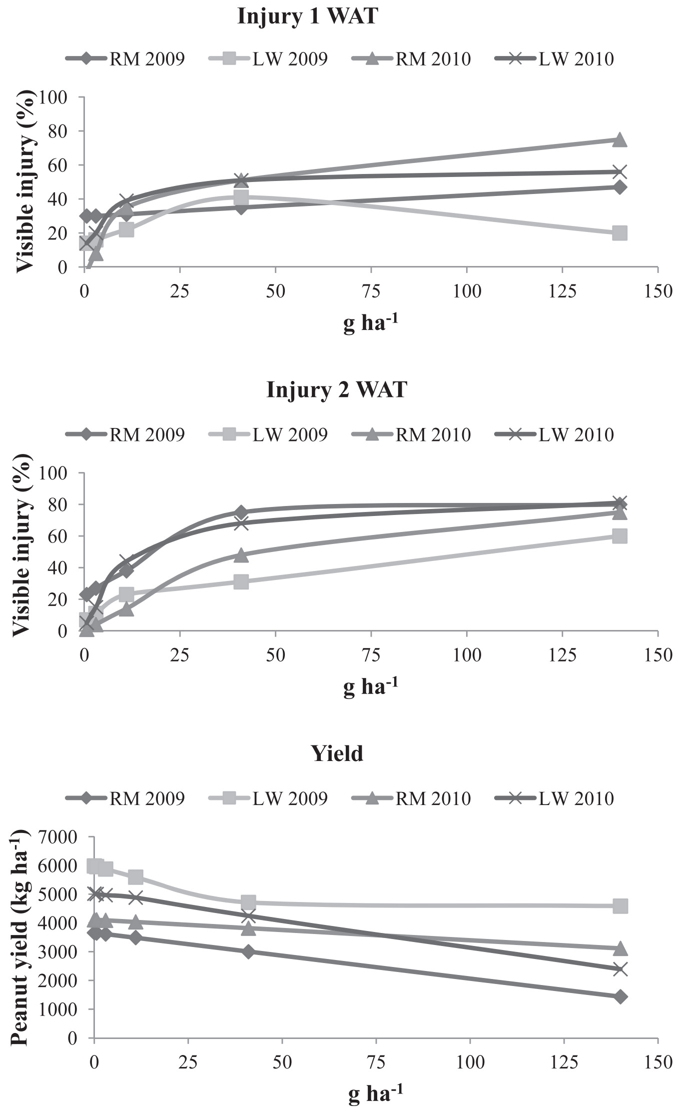

Figure 4. Peanut injury 1 and 2 wk after treatment and yield after application of dicamba (RM = Rocky Mount and LW = Lewiston-Woodville).

Results and Discussion

The interaction of experiment by herbicide rate was significant for most parameters. Therefore, data are presented by experiment (location and year).

Cotton. Visible injury ratings associated with cotton yield loss 1 WAT and 2 WAT for dicamba ranged from 50 to 63% and 47 to 75%, respectively (Figure 1 and Table 1). At 1 and 2 WAT, significant regressions were noted for injury vs. dicamba rate at all locations (Figure 1 and Table 1). Symptomology for dicamba accompanying cotton yield loss

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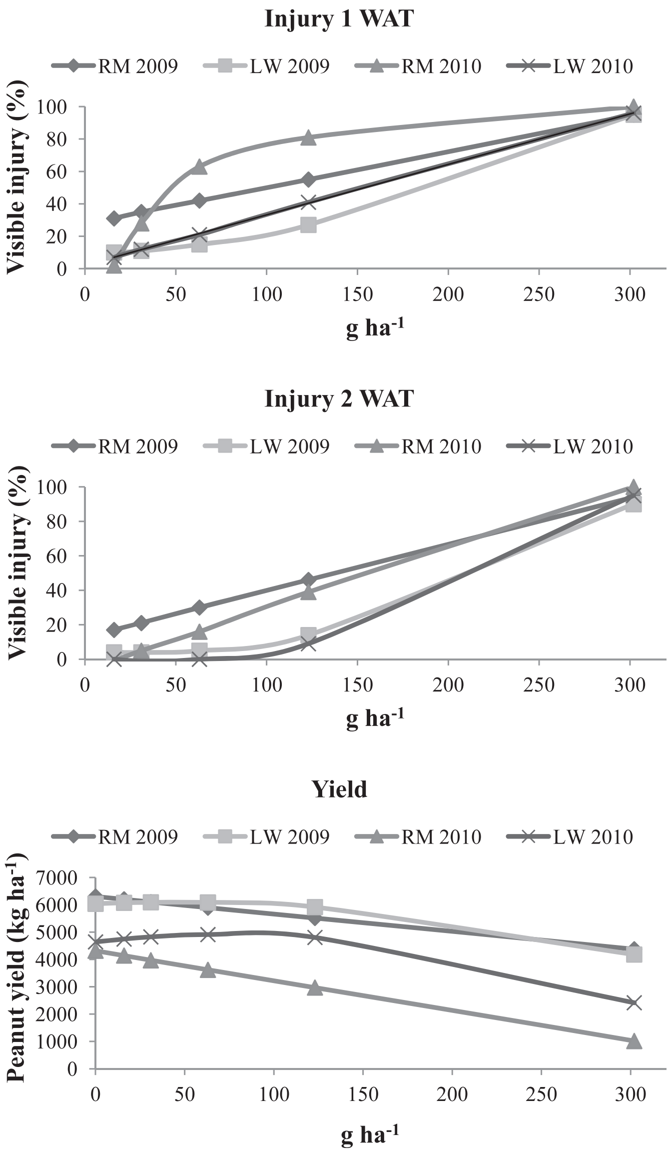

Figure 5. Peanut injury 1 and 2 wk after treatment and yield after application of glufosinate (RM = Rocky Mount and LW = Lewiston-Woodville).

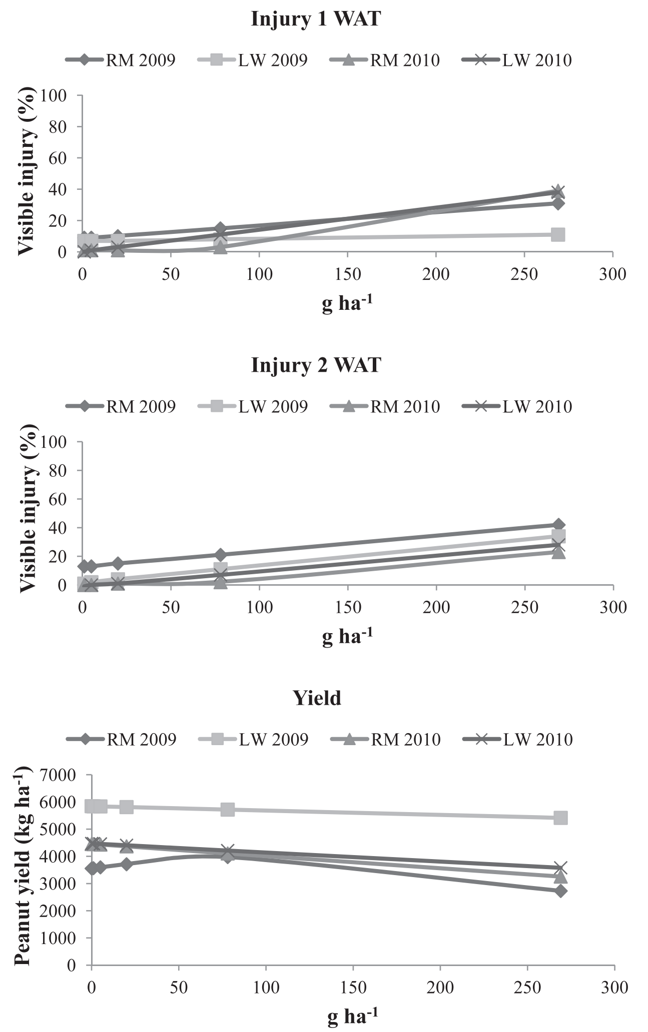

Figure 6. Peanut injury 1 and 2 wk after treatment and yield after application of 2,4-D (RM=Rocky Mount and LW=Lewiston-Woodville).

included stem epinasty, upward cupping, and curling of the top leaves as well as stunting. These were typical injury symptoms according to the literature as well as a less severe response when visually compared with 2,4-D (Everitt and Keeling 2009). Seed cotton yield was reduced at one location one year at the 1/2 (140 g ha^{-1}) and 1/8 (41 g ha^{-1}) rates of dicamba, whereas yield was not affected in 2009 at either location (Figure 1 and Table 1). Significant linear regressions were noted for yield vs. herbicide rate at only one location (Figure 1 and Table 1).

Visible injury ratings associated with yield loss 1 and 2 WAT for glufosinate ranged from 90 to 95% and 70 to 100%, respectively (Figure 2 and Table 1). At 1 and 2 WAT significant quadratic regressions were noted for injury vs. glufosinate rate at three and four locations, respectively (Figure 2 and Table 1). Symptomology of glufosinate treatments was characteristic of a contact herbicide with the older leaves burned and necrotic, whereas the new tissue formed without any injury symptoms. Sublethal rates of glufosinate applied to cotton, specifically the 1/2 (302 g ha^{-1}) rate, reduced yield at one location in 2009 and both locations in 2010 (Figure 2 and Table 1). Also the 1/4 (123 g ha^{-1}) rate of glufosinate reduced seed cotton yield at one location in 2010 (Figure 2 and Table 1). Significant regressions were noted for yield vs. herbicide rate at all locations (Figure 2 and Table 1).

Visible injury ratings associated with yield loss 1 and 2 WAT for 2,4-D ranged from 10 to 80% and 36 to 90%, respectively (Figure 3 and Table 1). At 1 and 2 WAT significant cubic regressions were noted for injury vs. 2,4-D rates at all locations (Figure 3 and Table 1). Symptomology accompanying yield loss due to 2,4-D was stunting, loss of apical dominance, strapping, and minor cupping at lower rates. Other researchers (Marple et al. 2008) have noted similar symptoms as well as a comparable but more severe response to 2,4-D than dicamba at sublethal rates. Cotton

Table 3. Pearson correlations among visible injury, yield, and grades of peanut. Data are pooled over years and locations.

Variable	P > *F*	Regression coefficient
Glufosinate		
Injury 1 WAT[a] vs. yield	0.0002	−0.62
Injury 2 WAT vs. yield	0.0006	−0.64
Yield vs. ready pods	0.0001	0.39
Yield vs. total sound mature kernels	0.0216	0.24
Yield vs. extra large kernels	0.0009	0.34
Yield vs. fancy pods	0.0049	0.29
Dicamba		
Injury 1 WAT vs. yield	0.0003	−0.36
Injury 2 WAT vs. yield	< 0.0001	−0.45
Yield vs. ready pods	0.0193	0.24
Yield vs. total sound mature kernels	0.0836	0.18
Yield vs. extra large kernels	< 0.0001	0.41
Yield vs. fancy pods	0.0002	0.37
2,4-D		
Injury 1 WAT vs. yield	< 0.0001	−0.37
Injury 2 WAT vs. yield	< 0.0001	−0.34
Yield vs. ready pods	0.0515	0.20
Yield vs. total sound mature kernels	0.0055	0.28
Yield vs. extra large kernels	0.0004	0.36
Yield vs. fancy pods	0.0010	0.33

[a] Abbreviation: WAT, weeks after treatment.

showed severe sensitivity to sublethal rates of 2,4-D, resulting in a yield loss at the 1/2 (269 g ha^{-1}), 1/8 (78 g ha^{-1}), and 1/32 (20 g ha^{-1}) rates at one location in 2009 and both locations in 2010 (Figure 3 and Table 1). In 2010, the two lowest rates of 2,4-D applied (5 and 1 g ha^{-1}) reduced seed cotton yield at one location (Figure 3 and Table 1). At three of the four locations, significant linear regressions were noted for yield vs. herbicide rate (Figure 3 and Table 1).

Correlations between injury 1 WAT and 2 WAT and cotton yield were significant for glufosinate and 2,4-D (Table 2). For dicamba, the correlations of injury 1 WAT and cotton yield were significant; however, correlations of injury 2 WAT were not significant (Table 2). Coefficients for all three herbicides ranged from −0.25 to −0.50 and the negativity of the numbers indicates that as visible injury increases, yield decreases; however, because the absolute values of those numbers are not greater than 0.6 we observed that there was no consistent trend (Ott and Longnecker 2001). Therefore, these data suggest that use of symptomology early in the season was a poor indicator of subsequent effects on cotton yield (Table 2). Everitt and Keeling (2009) indicated that visual estimates of injury early in the season often overestimated yield reductions. The indeterminate growth habit of cotton allows for considerable compensation for stress, and this compensation depends on weather and other conditions that can vary even though early-season injury was consistent. Although other factors such as number of monopodial bolls, plant height, and total nodes had significant correlations, the coefficients associated with each were relatively poor, suggesting that these growth measurements were not good indicators of effects on yield (Table 2).

Peanut. Visible injury ratings associated with peanut yield loss for 1 and 2 WAT for dicamba treatments ranged from 40 to 55% and 30 to 80%, respectively (Figure 4 and Table 1). Both 1 and 2 WAT significant regressions were noted for injury vs. herbicide rate at three and four locations, respectively (Figure 4 and Table 1). Symptomology of dicamba treatments consisted of crinkled and cupped leaves on the newer tissue. At both locations in 2009 and one location in 2010 the 1/2 (140 g ha^{-1}) rate of dicamba reduced peanut yield (Figure 4 and Table 1). Also in 2009 at one location the 1/8 (41 g ha^{-1}) rate resulted in a yield reduction (Figure 4 and Table 1). At three of the four locations significant regressions were noted for yield vs. herbicide rate (Figure 4 and Table 1).

Visible injury ratings 1 and 2 WAT associated with peanut yield loss for glufosinate ranged from 80 to 100% and 40 to 100%, respectively (Figure 5 and Table 1). Significant

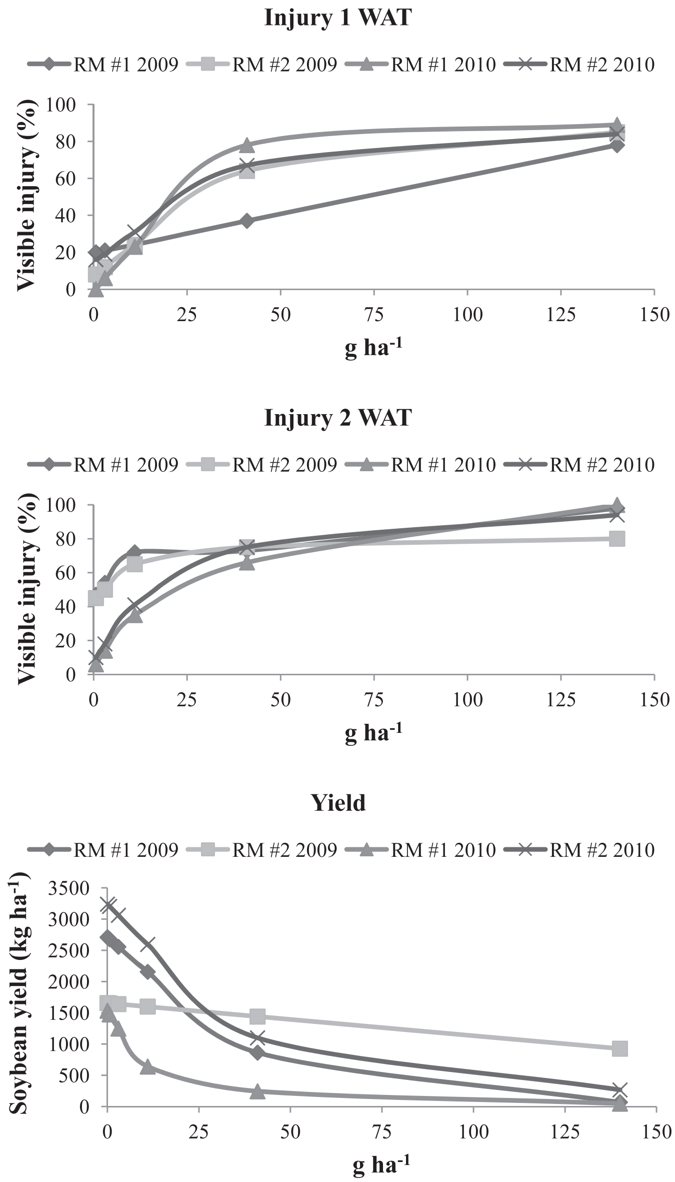

Figure 7. Soybean injury 1 and 2 wk after treatment and yield after application of dicamba (RM = Rocky Mount).

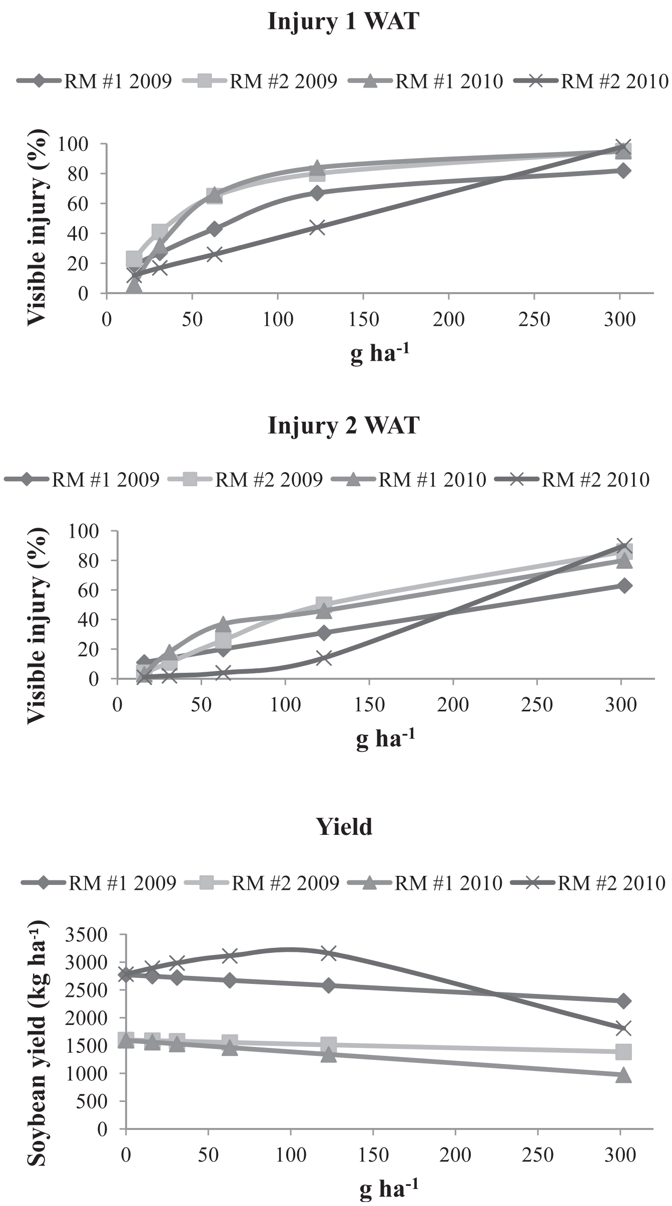

Figure 8. Soybean injury 1 and 2 wk after treatment and yield after application of glufosinate (RM = Rocky Mount).

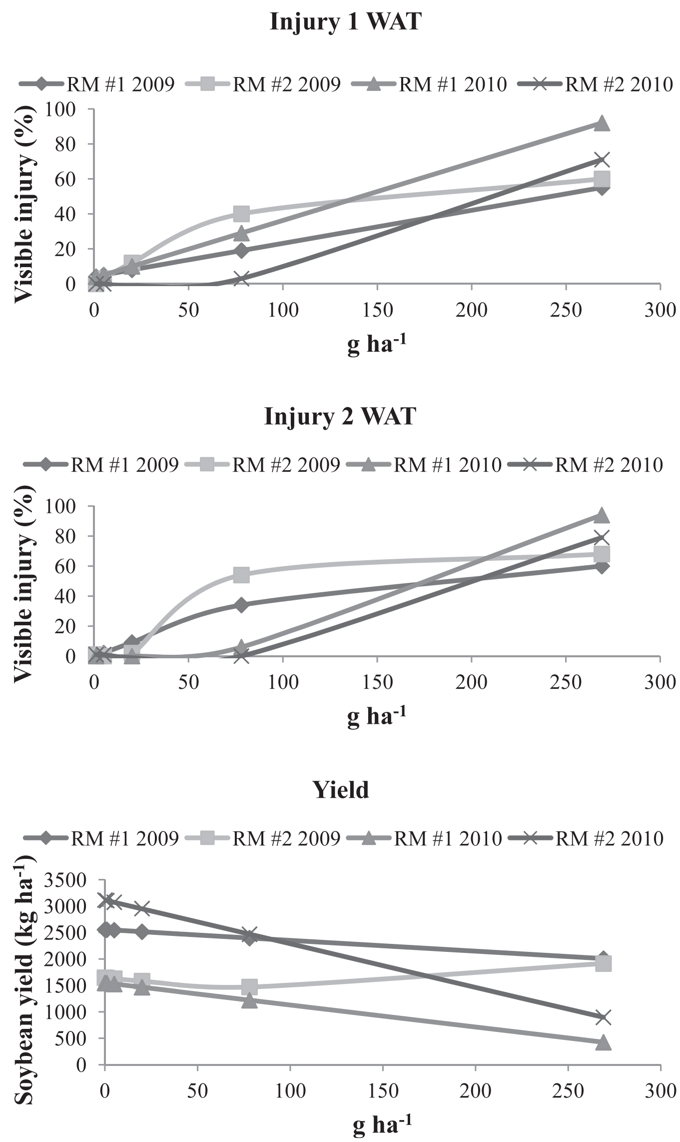

Figure 9. Soybean injury 1 and 2 wk after treatment and yield after application of 2,4-D (RM = Rocky Mount).

regressions were noted for injury vs. herbicide rate at all locations (Figure 5 and Table 1). Symptomology from glufosinate treatments was characteristic of contact herbicides, resulting in burned and necrotic leaves, whereas the new tissue formed without injury symptoms. Peanut yield was reduced by the 1/2 (302 g ha^{-1}) rate of glufosinate at both locations both years (Figure 5 and Table 1). In 2010 the 1/4 (123 g ha^{-1}) rate reduced yield at one location (Figure 5 and Table 1). At three of the four locations significant regressions were noted for yield vs. herbicide rate (Figure 5 and Table 1).

Visible injury ratings for 2,4-D treatments 1 and 2 WAT ranged from 30 to 40%, respectively (Figure 6 and Table 1). Both 1 and 2 WAT significant regressions were noted for injury vs. herbicide rate at two and four locations, respectively (Figure 6 and Table 1). Symptomology for 2,4-D treatments were minor and consisted of leaf cupping and curling at the higher rates applied. Peanut showed considerable tolerance to sublethal rates of 2,4-D only, resulting in a yield loss from the 1/2 (269 g ha^{-1}) rate at one location in 2009 (Figure 6 and Table 1). A significant quadratic regression was noted for yield vs. herbicide rate at only one location (Figure 6 and Table 1).

Correlations between visible injury 1 and 2 WAT and yield were significant for all herbicides; the strongest coefficient was that of glufosinate, −0.62 and −0.64, 1 and 2 WAT, respectively (Table 3). The negativity of these data imply that as glufosinate injury increases, peanut yield decreases and the absolute value of these coefficients being slightly greater than 0.6 suggests that glufosinate injury early in the season was a moderate indicator of peanut yield (Ott and Longnecker 2001). Other researchers (Lassiter et al. 2007) indicate that

Table 4. Pearson correlations among visible injury and yield of soybean. Data are pooled over years and locations.

Variable	P > *F*	Regression coefficient
Glufosinate		
Injury 1 WAT[a] vs. yield	< 0.0001	−0.40
Injury 2 WAT vs. yield	< 0.0001	−0.41
Dicamba		
Injury 1 WAT vs. yield	< 0.0001	−0.67
Injury 2 WAT vs. yield	< 0.0001	−0.60
2,4-D		
Injury 1 WAT vs. yield	< 0.0001	−0.55
Injury 2 WAT vs. yield	< 0.0001	−0.47

[a] Abbreviation: WAT, wk after treatment.

peanut injury and yield were highly correlated, with coefficients ranging from −0.59 to −0.92; however, they were considering glyphosate drift rates and took two additional injury ratings at 21 and 35 DAT, which may account partially for the differences compared with our own results. Correlations of peanut market grade characteristics were significant, although the correlation coefficients were relatively poor, indicating the lack of a trend (Table 3).

Soybean. Visible injury ratings for dicamba 1 and 2 WAT associated with soybean yield loss ranged from 20 to 90% and 30 to 100%, respectively (Figure 7 and Table 1). Significant regressions were noted at all locations for injury vs. herbicide both 1 and 2 WAT (Figure 7 and Table 1). Symptomology associated with yield loss from dicamba treatments included severe epinasty, leaf cupping and curling, as well as leaf burn at some of the higher rates. Other research showed similar results, indicating that soybean was more sensitive to dicamba than 2,4-D at sublethal rates (Al-Khatib and Peterson 1999; Sciumbato et al. 2004a). Soybean showed severe sensitivity to dicamba, resulting in a yield loss from the 1/2 (140 g ha^{-1}) rate at both locations, both years (Figure 7 and Table 1). At one location in 2009 and both locations in 2010, the 1/8 (41 g ha^{-1}) rate reduced soybean yield (Figure 7 and Table 1). Also in 2010 at both locations the 1/32 (11 g ha^{-1}) rate of dicamba resulted in a soybean yield reduction (Figure 7 and Table 1). Significant regressions were noted for yield vs. herbicide rate at all locations (Figure 7 and Table 1).

Visible injury ratings associated with yield loss 1 and 2 WAT for glufosinate ranged from 80 to 95% and 62 to 88%, respectively (Figure 8 and Table 1). Significant regressions were noted at all locations for injury vs. herbicide rate both 1 and 2 WAT (Figure 8 and Table 1). Symptomology from glufosinate treatments was characteristic of a contact herbicide with burned and necrotic older leaves and the new tissue formed normally. Other research (Al-Khatib and Peterson 1999) evaluating soybean response to simulated drift rates of glufosinate showed that at lower rates soybean leaves were chlorotic and the higher rates resulted in necrosis and newly emerged tissue was not injured 20 DAT. Soybean yield was reduced by the highest rate of glufosinate applied (302 g ha^{-1}) at one location in 2009 and both locations in 2010 (Figure 8 and Table 1). At three of the four locations significant regressions were noted for yield vs. herbicide rate (Figure 8 and Table 1).

Visible injury ratings 1 and 2 WAT for 2,4-D that resulted in a soybean yield loss ranged from 5 to 90% and 1 to 93%, respectively (Figure 9 and Table 1). Significant regressions were noted for injury vs. herbicide rate at all locations both 1 and 2 WAT (Figure 9 and Table 1). Symptomology of 2,4-D treatments accompanying yield loss was similar to dicamba, but was less severe and consisted of some stem epinasty, cupping, and necrotic leaves. Symptoms were not extensive in plots other than in those with the highest (269 g ha^{-1}) rate of 2,4-D used. In 2010 sublethal rates of 2,4-D reduced soybean yield at the 1/2 (269 g ha^{-1}) rate at both locations (Figure 9 and Table 1). Also in 2010 at one location the 1/8 (78 g ha^{-1}) rate reduced yield, whereas soybean yields were not affected by 2,4-D in 2009 at either location (Figure 9 and Table 1). Significant regressions were noted for yield vs. herbicide rate at all locations (Figure 9 and Table 1). Correlations among visible injury and soybean yield showed that although all were significant, only the absolute value of the coefficients for dicamba was greater or equal to 0.6, indicating that dicamba injury symptomology was a moderate predictor of yield, whereas glufosinate and 2,4-D were poor (Ott and Longnecker 2001) (Table 4).

In summary, these data provide information on relative crop sensitivity to dicamba, glufosinate, and 2,4-D. Cotton was most susceptible to injury from 2,4-D and was most tolerant to injury from dicamba on a relative basis. Peanut was the most susceptible to injury from dicamba and glufosinate while expressing an extraordinary tolerance to 2,4-D on a relative basis. Soybean was most susceptible to injury from dicamba and expressed the greatest tolerance to glufosinate on a relative basis. Visual estimates of percent injury of peanut and soybean are a moderate indicator of yield response; however, correlations of injury and yield of cotton were relatively poor. The indeterminate growth habit of cotton and ability of this crop to compensate for stress most likely contributed to the variation in response and revealed limitations in using early-season measurements of injury to predict yield.

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