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QUANTIFYING VAPOR DRIFT OF DICAMBA HERBICIDES APPLIED TO SOYBEAN

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Abstract—Recent advances in biotechnology have produced cultivars of corn, soybean, and cotton resistant to the synthetic-auxin herbicide dicamba. This technology will allow dicamba herbicides to be applied in new crops, at new periods in the growing season, and over greatly expanded areas, including postemergence applications in soybean. From past and current use in corn and small grains, dicamba vapor drift and subsequent crop injury to sensitive broadleaf crops has been a frequent problem. In the present study, the authors measured dicamba vapor drift in the field from postemergence applications to soybean using greenhouse-grown soybean as a bioassay system. They found that when the volatile dimethylamine formulation is applied, vapor drift could be detected at mean concentrations of 0.56 g acid equivalent dicamba/ha (0.1% of the applied rate) at 21 m away from a treated 18.3 × 18.3 m plot. Applying the diglycolamine formulation of dicamba reduced vapor drift by 94.0%. With the dimethylamine formulation, the extent and severity of vapor drift was significantly correlated with air temperature, indicating elevated risks if dimethylamine dicamba is applied early to midsummer in many growing regions. Additional research is needed to more fully understand the effects of vapor drift exposures to nontarget crops and wild plants. Environ. Toxicol. Chem. 2012;31:1023–1031. © 2012 SETAC

Keywords—Herbicide Dose–response modeling Plant toxicology Environmental transport Genetically modified organisms

INTRODUCTION

Recent advances in biotechnology have produced cultivars of corn, soybean, and cotton resistant to the synthetic auxin herbicide dicamba (3,6-dichloro-*o*-anisic acid) [1,2]. This technology will allow dicamba herbicides to be applied to new crops and under new conditions, including postemergence applications in soybean. Because of the increased prevalence of glyphosate-resistant weeds in glyphosate-resistant soybean and other crops, this technology package of cultivars, with stacked glyphosate- and dicamba-resistance traits, may be an attractive weed control choice for many soybean growers and may be adopted rapidly [2,3].

Dicamba is a synthetic-auxin herbicide that is active on a wide range of broadleaf plant species and has been used widely in corn, small grain, and pasture weed control for more than five decades. Dicamba is a moderately volatile compound, and vapor drift and nontarget crop and wild plant injury have been recurring problems during these 50 years of use [4–7]. These issues have previously limited use of dicamba to cereal crops and pastures, and have forced restrictions on its use in rotations with broadleaf crops. Herbicide-resistance biotechnology may expand the risks of injury to nontarget crops and vegetation by enabling dicamba to be applied to new crops, over an expanded growing season, and over significantly larger areas. For example, although current herbicide labels require as much as a 45-d delay between early season dicamba applications and the planting of a subsequent soybean crop [8], a farmer in the midwestern United States growing dicamba-resistant soybean varieties would instead have the option of applying dicamba early to midsummer after the soybean has fully emerged [9].

Although vapor drift has been a widely recognized risk when applying dicamba, there is little peer-reviewed data available to assess the extent of herbicide vapor drift and the factors that influence it in the field [4–7]. Growers typically settle disputes over drift damage to crops informally and without reporting incidents to authorities; therefore, it is very difficult to accurately estimate the frequency and severity of nontarget crop damage through vapor drift or other routes of exposure [10]. Anticipating the release of dicamba resistance biotechnology, numerous American farmers, extension scientists, and grower organizations have expressed concern over drift and crop injury [11]. Furthermore, a growing body of research has demonstrated that wild plants near farms play an important role in supporting beneficial insects such as pollinators and biocontrol agents [12–14], and herbicide drift could diminish the abundance and fitness of these plant resources [15].

Several potential management options may be available to mitigate risks of vapor drift from dicamba-resistant cropping systems. First, various formulations of the dicamba active ingredient have different volatilities and potentials for vapor drift. For example, in herbicide promotional literature, the diglycolamine salt of dicamba is purported to be eight times less volatile than the dimethylamine salt [16], although again little peer-reviewed data are available to evaluate these claims under field conditions. Second, if specific environmental conditions that promote vapor drift can be identified, herbicide applications could be avoided on the most drift-prone days. For example, because volatility is driven by temperature, postemergence applications when daytime temperatures are above a certain threshold may be especially problematic.

In light of these concerns, we thought it essential to carefully assess the potential for vapor drift under some of the new application conditions that herbicide-resistant biotechnology will enable before the resistant cultivars are commercialized. Working in the context of postemergence dicamba applications on soybean, we used a bioassay approach to measure and map dicamba vapor drift in the field. We used our data to examine three questions: (1) How far and at what concentrations does dicamba vapor drift from an area treated with dicamba? (2) What is the influence of herbicide formulation on the amount

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and extent of dicamba vapor drift? and (3) What are the environmental factors (air temperature, air pressure, humidity, and wind speed) influences on the amount and extent of vapor drift?

MATERIALS AND METHODS

Field trials

We tracked dicamba vapor drift by conducting experiments using field soybeans and greenhouse-grown bioassay soybeans. Research was conducted in 2009 and 2010 at the Russell Larson Agricultural Experiment Station in Rock Springs, Pennsylvania, USA. In each year, six (2009) or eight (2010) fields were planted with a dicamba-susceptible, glyphosate-resistant cultivar (Chemgrow #3539) on staggered dates between mid-May and early June. Soybeans were no-till drilled in 19-cm rows in fields that had been planted with corn the previous year. Weed control was provided with a preplant application of chloransulam-methyl at 18 g active ingredient/ha and an early postemergence application of glyphosate at 1,262 g acid equivalent/ha. We then applied dicamba treatments to each field in late June to mid July, while soybean were in the V3 to V5 stage [17], which is a typical timing for postemergence herbicide applications on soybean. These treatment dates covered a range of environmental conditions that may influence vapor drift, including air pressure, relative humidity, air temperature, and wind speed. Therefore, the results span the likely range of vapor drift from postemergence applications on soybean.

In the center of each field, we treated an 18.3×18.3 m plot with a dicamba herbicide at a rate of 561 g acid equivalent/ha, applied with a total carrier volume of 187 L/ha. We used 561 g acid equivalent/ha because this is currently a common application rate in corn and is also within the range of rates that will be promoted for postemergence applications in dicamba resistant soybean [8,9,18]. In 2009, we treated all six fields with a formulated product containing the dimethylamine salt of dicamba [8]. In 2010, we treated five fields with dimethylamine dicamba and three fields with a formulated product containing the diglycolamine salt of dicamba [18]. We applied herbicides using a backpack CO_2 sprayer and a 3.05 m handheld boom equipped with AIXR11002 nozzles (TeeJet), calibrated to 241 kPa, and walked on at a speed of 1.3 m/s. Herbicide was applied to each field between 7:45 and 8:30 AM.

In advance of the herbicide application, we extended eight transects from the center of the treated plot in each field. These transects stretched from 25 to 90 m, depending on field size and shape. Designating the center of the treated plot as the zero point, we marked individual field soybean plants for recording dicamba herbicide injury symptoms every 3 m up to 25 m, every 5 m up to 40 m, and then every 10 m up to 100 m. To gauge variability at a single location, we marked three plants at 6, 12, and 21 m along each transect. We quantified injury symptoms on marked plants 28 d after herbicide treatment on a 100-point scale using a scale similar to that developed by Behrens and Lueschen [4] and Anderson et al. [19] (Table 1).

Injury on field soybean plants integrates both particle drift immediately following herbicide application and vapor drift potentially occurring over a longer period. To exclude particle drift and more precisely measure vapor drift occurring in the period following application, we used potted soybeans as bioassay plants. We grew sets of bioassay plants in a greenhouse under ambient light conditions, with one set for each treated field seeded one to three weeks following the planting of the corresponding field soybean. Greenhouse bioassay plants were grown in 3.8-L pots using an artificial soil mixture (Fafard pro germination mix) supplemented with 4.0 g of Osmocote 19-6-12 fertilizer (Scotts Miracle-Gro Company). The same soybean cultivar was planted in the field and greenhouse. Depending on field size, we grew between 104 and 144 bioassay plants per set. We randomly assigned each plant a position within a grid along a greenhouse table, with plants designated for the same field grouped on the same tables. We also randomly assigned each plant a position on one of the transects in its corresponding field. Greenhouse bioassay plants were assigned to the same positions as the field plants, with three plants also assigned to the 6, 12, and 21 m positions along each transect. We scored the bioassay plants for growth stage and measured height to the apical bud on the day immediately preceding field exposure.

Table 1. Dicamba injury symptom rating scale[a]

0	No effect, plant normal.
10	Slight crinkle of leaflets of terminal leaf.
20	Cupping of terminal leaflets, slight crinkle of leaflets of second leaf, growth rate normal.
30	Leaflets of two terminal leaves cupped, expansion of terminal leaf suppressed slightly.
40	Malformation and growth suppression of two terminal leaves, terminal leaf size less than one-half that of control. New axillary leaves developing at a substantially reduced rate.
50	No expansion of terminal leaf, second leaf size one-half that of control. Axillary leaf buds unable to open and develop.
60	Slight terminal growth, necrosis of terminal leaf, and axillary bud apparent. Chlorosis and necrosis in axillary leaf clusters.
70	Terminal bud dead, substantial, strongly malformed axillary shoot growth.
80	Limited axillary shoot growth, leaves present at time of treatment chlorotic with slight necrosis.
90	Plant dying, leaves mostly necrotic.
100	Plant dead.

[a] Adapted from Behrens and Lueschen [4] and Andersen et al. [19].

On the morning of each dicamba field application, we transported the bioassay plants from the greenhouse to the designated field. We parked the vehicle more than 100 m away from the treated plot, with all doors and windows closed during application. Thirty minutes after herbicide application (allowing time for particle drift to settle), a crew of four to six research technicians positioned the bioassay plants within approximately 20 cm of the marked field plants along the eight transects. In 2009, we collected the bioassay plants after 24 h of exposure in the field and then transported them back to the greenhouse. In 2010, complications with field operations (overnight rodent and deer damage) forced us to switch from a 24-h to 8-h exposure midway through the experiment. We then scored each bioassay plant for dicamba injury symptoms 14 d after herbicide treatment using the same scale used for field soybeans. A summary of the date of treatment, formulation, and exposure duration of bioassay plants for each field is provided in Table 2.

Several environmental variables were collected from each field trial to be included as potential explanatory variables in analysis of the data. A National Oceanic and Atmospheric Administration weather station at the research farm [20] located 100 to 2,100 m from each field collected temperature, air pressure, humidity, precipitation, and wind speed data in 1-min increments.

Control plants

To account for possible stresses of moving bioassay plants into the field and for possible inadvertent dicamba contamination, we included at least four plants each of two types of controls in each set of greenhouse bioassay plants. "Moved"

Table 2. Summary of field trials by formulation, duration of exposure, treatment date, number of bioassay plants, and number of false positive recordings

Field	Formulation	Exposure (h)	Treatment date	No. Plants	False-positives
KN4W	DMA	24	June 27, 2009	104	3
H	DMA	24	July 1, 2009	132	5
KN5	DMA	24	July 6, 2009	120	2
Ento	DMA	24	July 8, 2009	120	2
FryJ1	DMA	24	July 10, 2009	120	6
KN4E	DMA	24	July 16, 2009	120	1
KN6W	DMA	24	June 17, 2010	144	2
U8	DMA	24	June 23, 2010	112	1
KNE2	DMA	8	June 26, 2010	140	4
OMN	DMA	8	July 6, 2010	144	2
HarpAE	DMA	8	July 21, 2010	128	7
KN6E	DGA	24	June 18, 2010	144	2
G24	DGA	8	June 25, 2010	136	2
HarpAW	DGA	8	July 14, 2010	125	5

DMA = dimethylamine; DGA = diglycolamine.

controls were transported out to the research farm along with the other bioassay plants, but positioned in an untreated field at least 1,000 m from the dicamba application. "Moved" plants were left in the field for the same period as the corresponding bioassay plants and transported back to the greenhouse in the same van. Plants that were "not moved" were left in the greenhouse for the duration of the experiment. We scored both types of controls for injury at the same time intervals as the other bioassay plants in a set. Very slight injury symptoms were observed on one "not moved" plant in 2009 and one "not moved" plant in 2010 (ratings of 5 and 8 on our scale, respectively), and we suspected these observations as being false-positives.

Controlled dose–response experiments

We conducted dose–response experiments to relate injury symptoms observed on greenhouse bioassay plants to the amount of dicamba exposure. In 2009, a randomized complete block design experiment was conducted using six rates (56.1, 5.61, 0.561, 0.056, 0.006 g acid equivalent/ha plus a water control) of dimethylamine dicamba and 12 replications. Seeds were planted on September 29, 2009, using the same methods for the plants positioned in the field. Dicamba was applied in a closed chamber using a track sprayer on October 29, 2009, while plants were in the V3 stage. In 2010, a similar experiment was conducted using 10 rates (561, 56.1, 17.7, 5.61, 1.77, 0.561, 0.177, 0.056, 0.018, 0.006 g acid equivalent/ha plus a water control), two formulations (dimethylamine and diglycolamine), and five replications. Plants were seeded on June 9 and treated on July 2 using the track sprayer, while plants were in the V4 stage. In both years, we quantified injury symptoms on all plants 14 d after herbicide treatment.

Statistical analysis

Data preprocessing. In certain cases, we suspected a positive injury rating on a bioassay plant of being a false-positive. We judged a recording as a false-positive if it met all of the following three criteria: (1) no injury symptoms 28 d after herbicide treatment on the corresponding field soybean plant, (2) no injury on the bioassay plants located at either of the adjacent points along a transect, and (3) if more than one bioassay plant was located at the same position on the transects, these replicate plants all had zero injury ratings. For all subsequent data analysis, we took a conservative approach and removed all false positive data points to generate a reduced dataset (Table 2).

Dose–response curves. In both years, we found that a ln-linear model, where injury 14 d after herbicide treatment is described by the natural logarithm of the dicamba dose, fit the data very well. Although log-logistic models are often recommended for herbicide dose–response data, we did not find that these models were supported by the data [21]. We based this conclusion on lack-of-fit tests comparing a four-parameter log-logistic model to a one-way analysis of variance (ANOVA) model (for 2009, $F_{(2,68)} = 85.66$, $p < 0.001$; for 2010, $F_{(7,106)} = 31.91$, $p < 0.001$) [21].

For the 2010 data, we conducted a two-way ANOVA to test for the effects of dicamba dose, formulation (diglycolamine vs dimethylamine), and interactions of dose and formulation on injury 14 d after herbicide treatment. We found no evidence for any effect of formulation or interaction between formulation and dose on injury symptoms, and therefore pooled data across formulations to produce one ln-linear dose response curve for the 2010 data.

For each year, the ln-linear regression was then used to produce the inverse relationship describing ln (dose) as a function of injury value 14 d after herbicide treatment. This value was then converted to the arithmetic scale in units of g acid equivalent dicamba/ha. The 2009 curve was used strictly for 2009 plants, and the 2010 curve for 2010 plants.

Inverse distance weighted spatial interpolation surfaces. Data from our field trials includes information on both the extent (distance traveled) and severity (estimated dose of exposure) of dicamba vapor drift. We refined these aspects of the data into a concise spatial metric by building inverse distance weighted (IDW) spatial interpolation models [22] with the geostatistical analyst tools in ArcGIS [23]. For each field, we imported the data on each bioassay plant's location in the field and its estimated dose of exposure into an X/Y coordinate system in ArcGIS. We then evaluated a set of IDW models for each field that systematically varied the major and minor search radii and the minimum and maximum number of neighboring plants. We used the optimize power function in ArcGIS to set the power for the inverse distance weighting. For points where two or more replicate bioassay plants were positioned, we used the mean-estimated dose value. We selected the IDW model that minimized the root mean square of a regression model comparing the cross-validated predicted and measured estimated dose values. We then integrated across the interpolated surface to produce an estimate of the total g acid equivalent dicamba of vapor drift that resettled on plant surfaces outside of the treated plot across a given field (Fig. 1).

Mean comparisons of formulation and exposures. For the dimethylamine field trials, we conducted mean comparisons of the 2009 and 2010 data. For the 2010 data, we conducted mean comparisons of duration of exposure (8 vs 24 h) for the dimethylamine field trials and across formulations (dimethylamine vs diglycolamine). For each comparison, we conducted multiple *t* tests using the following three drift indices: (1) the total g acid equivalent dicamba of resettled vapor drift outside of the treated plot (calculated from the IDW surface); (2) the number of injured bioassay plants outside of the treated plot; and (3) the distance from the center of the treated plot of the farthest injured plant.

Dose-distance functions. We developed dose-distance functions to relate the estimated dose of exposure to the distance from the center of the treated plot. For each field, we visually

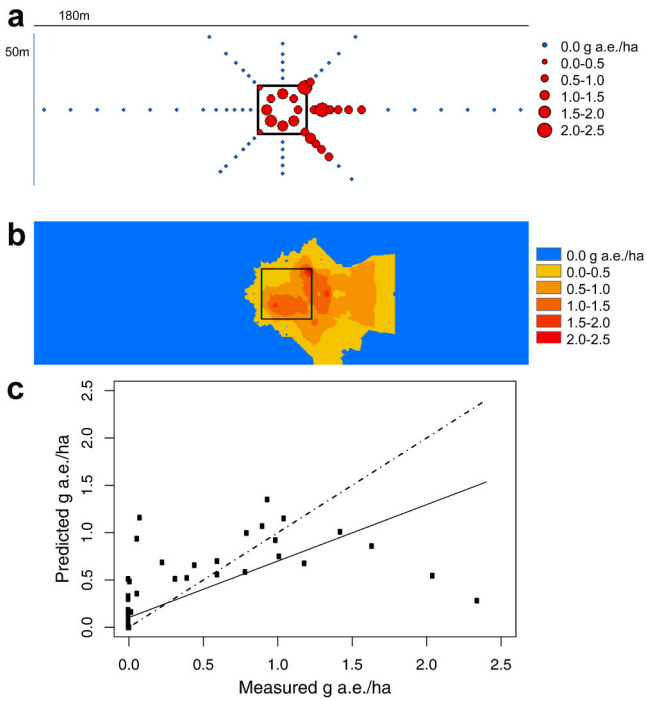

Fig. 1. Distribution of injured plants and estimated dose values (**a**), the resulting inverse distance weighted interpolated surface (**b**), and cross-validation plot of measured values and predicted values from the interpolated surface (**c**) for field KN4E (2009). In a and b, the square box in the center marks the border of the treated plot. In c, the solid line indicates the least-squares linear regression function of predicted against measured values, and the dashed line is the ideal 1:1 line. [Color figure can be seen in the online version of this article, available at wileyonlinelibrary.com].

inspected graphs of the vapor drift pattern in ArcGIS and then selected the two primary transects along which vapor drift was detected. We then pooled data from each field into one of three datasets, including dimethylamine 2009, dimethylamine 2010, and diglycolamine 2010. We then fit power functions of the form d = a*m^b [24,25], where d is the estimated dose, m is the distance from the center of the treated plot, and a and b are constants fitted using the non-linear least squares (nls) function in the statistical program R [26]. We also fit 95% upper and lower bootstrapped confidence bands for each curve using the nlsBoot function in R [26]. These confidence bands were used to calculate mean and upper and lower estimated doses of exposure at 5, 15, 25, 50, and 100 m from the center of the treated plot.

Correlations between drift indices and meteorological variables. We found that the mean value for air temperature, air pressure, relative humidity, and wind speed in the 8-h period after positioning the bioassay plants in the field adequately summarized the daily variation in these meteorological variables for each field trial. Using the data for the dimethylamine field trials, we tested for correlations between vapor drift and the meteorological variables by running separate stepwise multiple linear regression models on each of the three drift indices (total gram acid equivalent, number of points, and farthest distance). We used a p value of less than 0.10 as the criteria to retain a variable in the final model. Because the data set only includes 11 total dimethylamine field trials over two years, we were unable to include interaction terms between variables in the regression analyses. Also, because we had only three diglycolamine field trials, we were not able to explore correlations for this formulation.

RESULTS

Dose–response experiments

Log-linear models produced a very tight correlation between observed injury and treatment dose (in 2009, $r^2 = 97.3$, $p < 0.001$; in 2010, $r^2 = 96.6$, $p < 0.001$; Fig. 2). Based on a 95% confidence interval for the slope parameters of these models, the 2009 and 2010 data sets showed statistically distinct relationships between injury 14 d after herbicide treatment and ln(dose) (in 2009,95% CI of $b_1 = [0.131, 0.143]$; 2010, 95% CI of $b_1 = [0.103, 0.112]$). The 2010 model had a smaller slope, indicating that for the same scored level of injury, plants in 2010 were exposed to a smaller dose of dicamba. In 2010, bioassay plants grown in the greenhouse were significantly taller at the V3 to V4 stage immediately preceding exposure, likely due to warmer and sunnier conditions in the greenhouse in 2010.

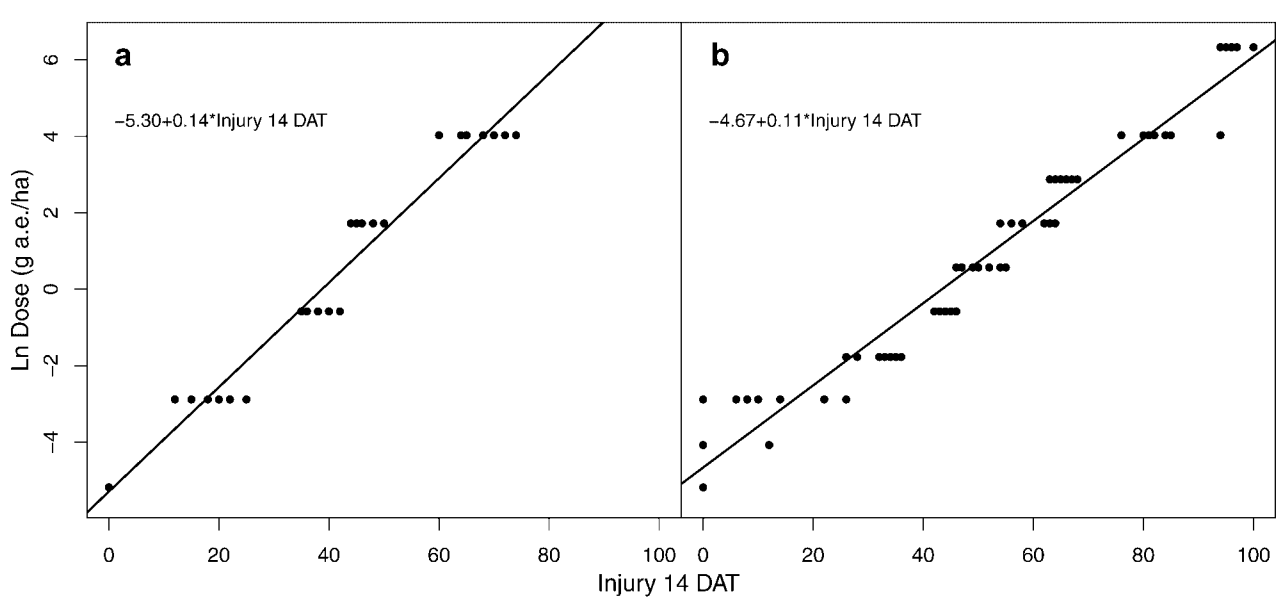

Fig. 2. Log-linear dose response curves and regression equations for 2009 (**a**) and 2010 (**b**) greenhouse bioassay dose-response experiments. DAT = days after herbicide treatment.

Differences in plant morphology may have led to differences in appearance of injury symptoms such that on average, plants were scored with higher levels of injury, both in the dose response experiment, and for bioassay plants exposed to vapors in the field. However, in both years, a single investigator scored every plant so there should be little variation due to interpretation of the injury scale, and injury ratings should be consistently related to dose within a year. Therefore, we applied the 2009 curve only to 2009 bioassay plants and the 2010 curve only to 2010 bioassay plants.

Inverse distance weighted surfaces

As estimated from the IDW models, the total g acid equivalent of dicamba vapor drift resettled outside of the treated plot for the different years, exposure times, and formulations are summarized in Figure 3a. A total of 18.8 g acid equivalent dicamba was applied to each treated plot, indicating that 0.07 to 0.32% (dimethylamine 2009), 0.38 to 1.4% (dimethylamine 2010), and 0.02 to 0.04% (diglycolamine 2010) of applied dicamba resettled on nontarget plant surfaces as vapor drift. These values for dimethylamine dicamba are somewhat higher than measured volatility rates from laboratory data provided by the U. S. Environmental Protection Agency (U.S. EPA) [27]. Similar data was not available for diglycolamine herbicides. Inspection of the cross-validation regression plot for each IDW surface showed reasonable correspondence between dose values estimated from the dose–response curve and dose values predicted by the IDW surface model for low-dose estimates (i.e., bioassay plants with zero or relatively low injury 14 d after herbicide treatment). However, for higher estimated dose values, the IDW surface models tended to substantially underestimate the measured dose (Fig. 1c). This pattern suggests that our estimates for total g acid equivalent of dicamba resettled as vapor drift derived by integrating across the IDW surface are conservative estimates.

Mean comparisons

All three drift indices revealed similar patterns of vapor drift in the field trials (Fig. 3). Observed injury was more frequent and occurred at higher estimated doses over farther distances in 2010 than in 2009. There were no significant differences for any of the indices comparing 8- and 24-h exposures in 2010, indicating that the majority of vapor drift detectable by our method occurs during the first 8 h following herbicide application. In 2010, pronounced differences occurred between dimethylamine and diglycolamine exposures with diglycolamine achieving a 94.0% reduction in total dicamba vapor drift resettled outside of the treated area (0.16 vs 0.01 g acid equivalent), a 75.8% reduction in number of injured bioassay plants outside of the treated plot (40.0 vs 9.7 plants) and a 55.1% reduction in farthest distance of injury (52.0 vs 23.3 m from center). Consequently, for the dose-distance analysis, we separated the 2009 dimethylamine, 2010 dimethylamine, and 2010 diglycolamine data, but pooled data from 8-h and 24-h exposures.

Dose-distance functions

For the dimethylamine 2010 dataset, mean-estimated exposures were above 0.1% of the application rate (0.56 g acid equivalent/ha) as far as 21 m outside of the treated area (Fig. 4, Table 3). Mean predicted doses were near zero for the diglycolamine applications within 10 m from the edge of the treated plot.

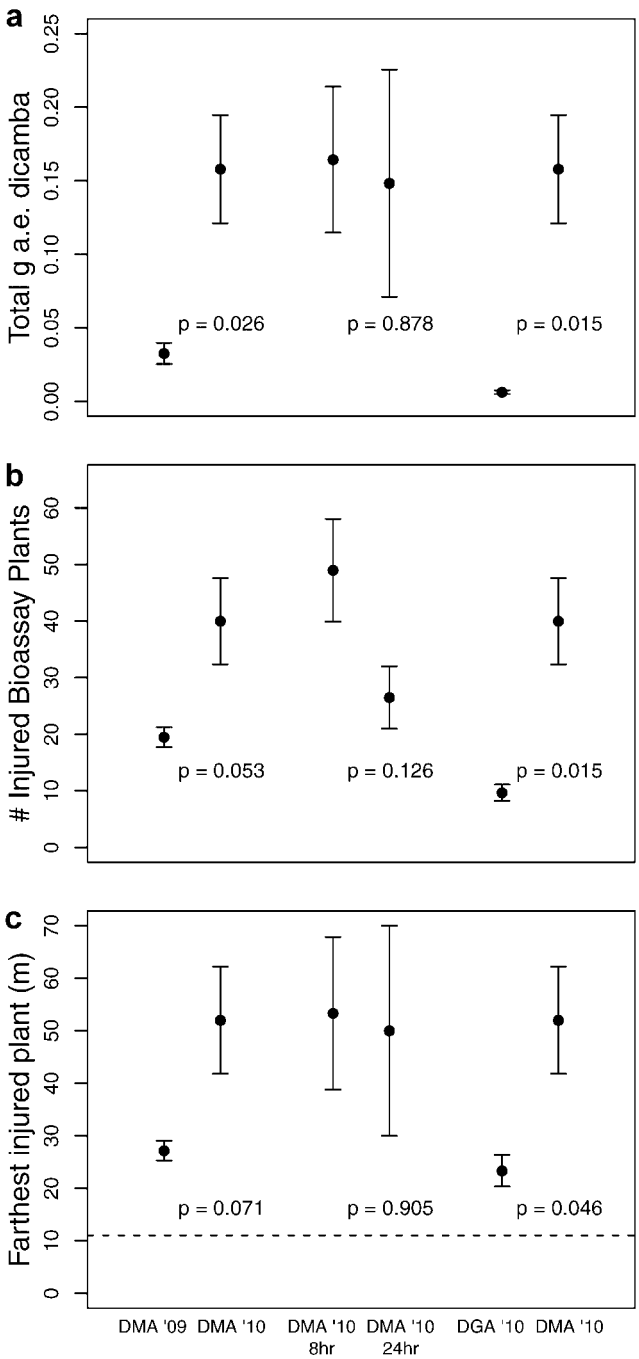

Fig. 3. Mean comparisons by year, exposure time, and formulation type for three drift indices: total g acid equivalent dicamba resettled as vapor drift outside of the treated plot (**a**), number of injured bioassay plants outside of the treated plot (**b**), and the distance from the center of the treated plot of the farthest injured bioassay plant (**c**). The dashed line in c shows the boundary of the treated plot. Displayed p values are for two-sample t tests. DMA = dimethylamine; DGA = diglycolamine.

Correlations with meteorological variables

For the dimethylamine exposures, temperature was a significant predictor in total g acid equivalent dicamba resettled as vapor drift and the distance of farthest injury, with warmer days showing more vapor drift (Fig. 5, Table 4). Relative humidity was also significantly and positively correlated with the total g acid equivalent dicamba vapor drift and the distance of farthest observed injury. Air pressure and wind speed were not significant predictors of any of the three drift indices, and none of the

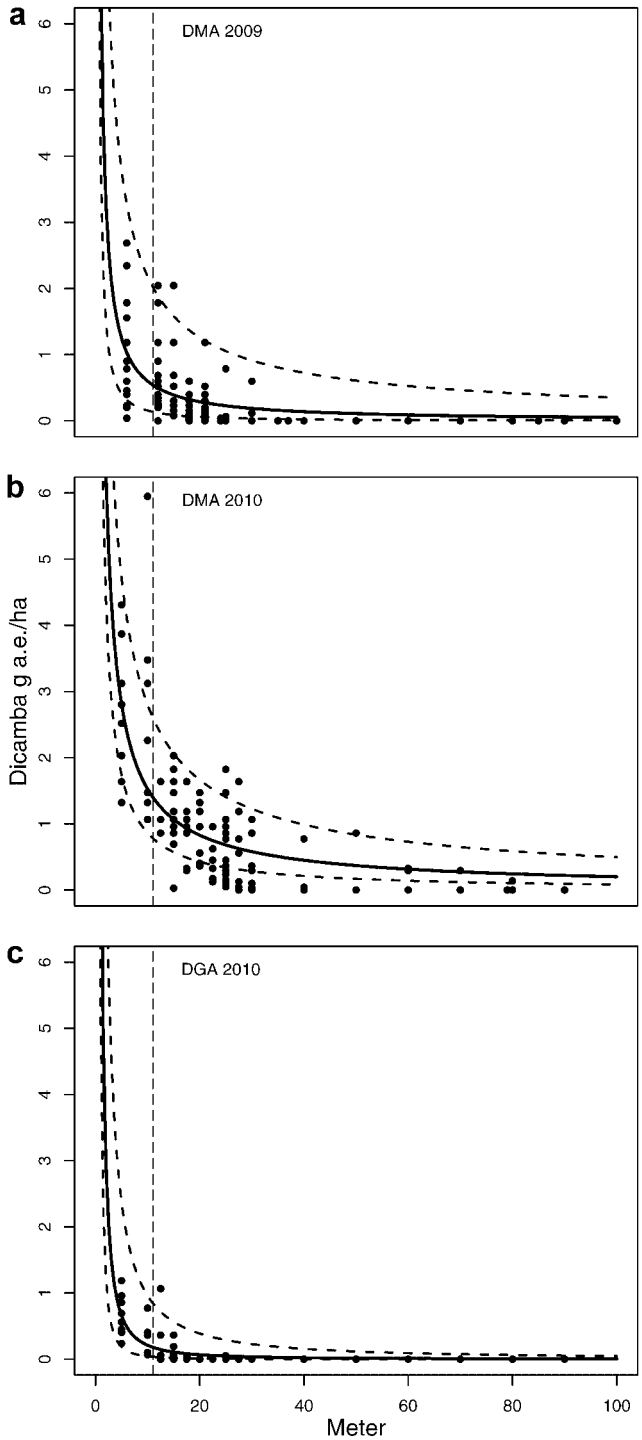

Fig. 4. Dose-distance functions along the main two transects of observed drift for dimethylamine (DMA) 2009 exposures (**a**), DMA 2010 exposures (**b**), and diglycolamine (DGA) 2010 exposures (**c**). Dashed curves reflect bootstrapped upper and lower 95% CI curves for the mean response function. The zero meter point indicates the center of the treated plot and the dashed vertical line shows the location of the plot boundary.

variables were significantly correlated with the total number of injured bioassay plants.

DISCUSSION

Advantages and limitations of the bioassay approach

Direct air sampling followed by gas chromatography/mass spectrometry has previously been used to measure the vapor drift of pesticides, particularly highly volatile soil fumigants [28–30]. Although these methods have high analytical precision, they require expensive and sensitive instrumentation, and therefore generally preclude measuring vapor drift over multiple days or with much spatial detail. Moreover, because air sampling will yield measurements in units of g/m^3 [28], it is not straightforward to translate these data into units of g/ha that are meaningful to weed scientists, agronomists, ecotoxicologists, or other researchers interested in understanding the effects of low herbicide doses on plants.

In contrast, our bioassay approach is simple and straightforward and therefore permits spatially explicit measurement of vapor drift over multiple exposure events (in the present study, 14 field trials). Previous research has indicated that bioassay methods can be an effective and accurate method for detecting airborne pesticides [6,31–33]. Because herbicide vapor drift may be influenced by a range of agronomic and environmental conditions, our bioassay data measuring dicamba vapor drift over multiple trial runs with a high degree of spatial resolution constitutes a valuable contribution of novel data. Moreover, our bioassay data is readily related to units of g acid equivalent/ha, which is more easily applied to agronomic and ecotoxicological problems.

Table 3. Summary of predicted values from dose-distance functions along primary drift axes for the DMA 2009, DMA 2010, and DGA 2010 data sets[a]

Curve	Distance (m)	Predicted dose (g acid equivalent/ha)
DMA 2009	5	1.25 (0.42, 3.70)
DMA 2009	15	0.39 (0.09, 1.54)
DMA 2009	25	0.23 (0.05, 1.03)
DMA 2009	50	0.11 (0.02, 0.60)
DMA 2009	100	0.05 (0.01, 0.34)
DMA 2010	5	2.81 (1.72, 4.74)
DMA 2010	15	1.07 (0.56, 2.06)
DMA 2010	25	0.68 (0.33, 1.40)
DMA 2010	50	0.37 (0.16, 0.83)
DMA 2010	100	0.20 (0.08, 0.49)
DGA 2010	5	0.66 (0.17, 2.57)
DGA 2010	15	0.11 (0.02, 0.61)
DGA 2010	25	0.05 (0.01, 0.32)
DGA 2010	50	0.02 (0.00, 0.13)
DGA 2010	100	0.01 (0.00, 0.05)

[a] Distance is from the center of the treated plot, and distance > 12 m are located outside of the treated plot. Bootstrapped 95% confidence intervals for predicted values are shown in parenthesis.
DMA = dimethylamine; DGA = diglycolamine.

Dose-distance relationships

When dimethylamine dicamba is applied, substantial vapor drift occurs (Figs. 1, 3, and 4; Table 3). For the 2010 dimethylamine data, a mean response of 0.56 g acid equivalent/ha is predicted 21 m from the edge of the treated area, with a 95% CI of 0.26 to 1.19 g acid equivalent/ha. Because our experimental design does not include assessment of particle drift or additional routes of exposure including residual herbicide in spray equipment [5] or atmospheric deposition [34], total nontarget exposures to crops and wild plants could be substantially greater than our predictions for vapor drift. Furthermore, an important related problem involves how vapor drift exposure scales up from plot, to field, to landscape scales. If approximately 0.56 g acid equivalent/ha of dimethylamine dicamba can be detected 21 m beyond a 335 m^2 experimental treated area, what will the dose-distance relationships be when a 33.5 ha field is treated (a 1,000-fold area increase)? What will the expected exposures

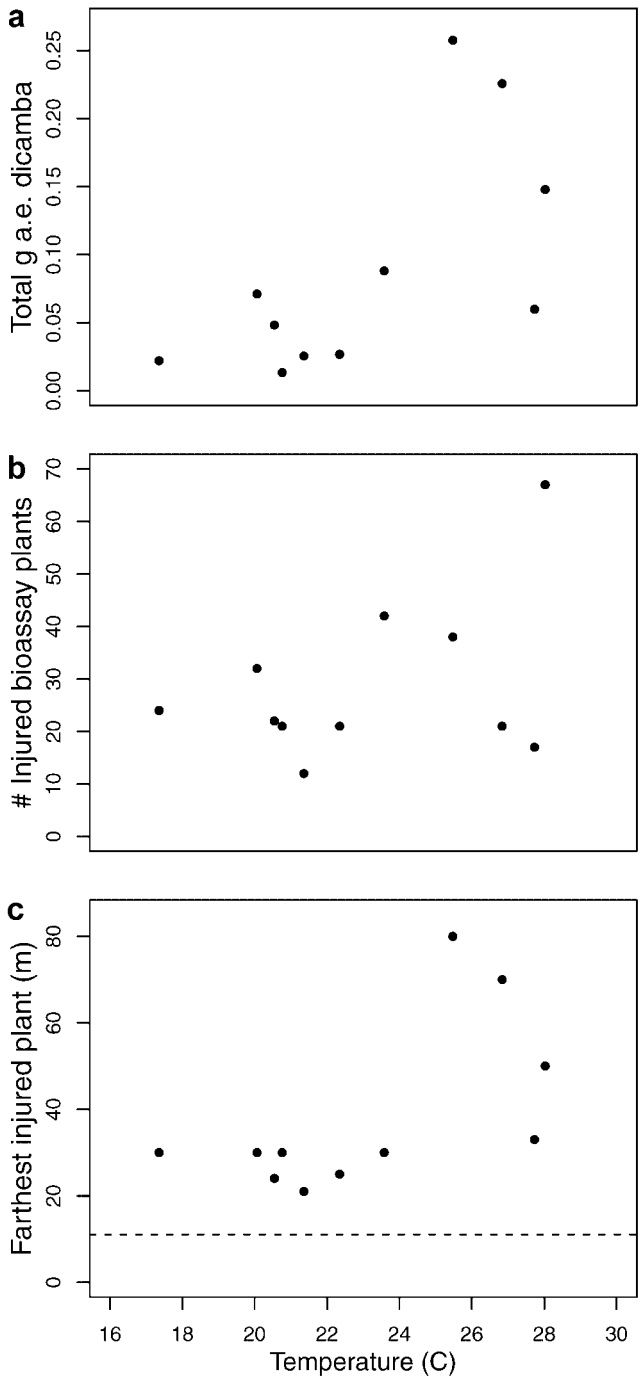

Fig. 5. Scatter plots for dimethylamine dicamba field trials of the correlation between temperature and three drift indices: total g acid equivalent dicamba resettled as vapor drift outside of the treated plot (**a**), number of injured bioassay plants outside of the treated plot (**b**), and the distance from the center of the treated plot of the farthest injured bioassay plant (**c**). The dashed line in c shows the boundary of the treated plot.

be when many fields across a landscape are treated? More research is needed to understand the scaling relationships associated with vapor drift.

More research is also needed to fully understand the response of nontarget plants to these low-dose exposures. The available literature suggests that small yield losses could be expected from a 0.56 g acid equivalent/ha exposure to susceptible soybean varieties [7,19,35–38]. However, data from the U.S. EPA vegetative vigor tests associated with the registration of dicamba products also indicate that 0.56 g acid equivalent/ha is well below the 25% effective concentration for biomass (or the dicamba dose affecting a 25% reduction in biomass) for several crops in the seedling stage, including soybean, tomato, canola, and cucumber, indicating little risk [39,40].

Table 4. Summary of results from DMA dicamba field trials from multiple linear regression models for three drift indices[a] as predicted by air temperature and relative humidity[b]

Response	Model	p	adjusted r^2
Grams of acid equivalent dicamba	$Y = -0.71 + 0.019^*(T) + 0.006^*(RH)$	0.018	0.5441
Number of injured plants	NS	NS	NS
Farthest injury	$Y = -145.01 + 4.053^*(T) + 1.402^*(RH)$	0.029	0.485

[a] Total grams of acid equivalent dicamba vapor drift resettled outside of the treated plot, number of injured bioassay plants outside of treated plot, and distance from center of the treated plot of farthest observed injury.
[b] Meteorological data was summarized as the mean of each variable for the 8-h interval following positioning of bioassay plants in the field.
DMA = dimethylamine; T = total air; RH = relative humidity; NS = No significant correlations.

Dicamba drift could also impact wild and sensitive vegetation growing in nearby crop fields. Data from Boutin et al. [39] showed that 0.56 g acid equivalent/ha is also well below the 25% effective concentration for biomass for 15 wild plant species grown in greenhouse conditions. However, to our knowledge, no other studies have examined the effects of low dicamba doses to wild plants, and more data are needed to understand the impacts of low dicamba exposures on wild plant fitness and ecosystem service provisioning under field conditions.

Effect of formulation

Our data demonstrate that the diglycolamine formulation has a dramatic effect on reducing dicamba vapor drift. Estimates of total g acid equivalent vapor drift outside of the treated area were reduced 94% relative to the dimethylamine formulation, and the dose-distance curves indicate that predicted mean exposures drop close to zero only short distances away from the treated area. However, because the diglycolamine salt is a newer chemistry packaged in name-brand products, several generic dimethylamine products are available at a significant cost savings. Perhaps largely because of these cost differences, dimethylamine is still applied on a large percentage of corn and small grain acreage. To prevent vapor drift and nontarget injury to susceptible crops and wild vegetation, it will therefore be imperative to encourage growers and applicators working with dicamba resistance biotechnology to choose diglycolamine over dimethylamine products. Wider adoption of diglycolamine products could be achieved through university extension and industry education programs, restrictions on herbicide labels (i.e., diglycolamine approved for postemergence soybean applications, but not dimethylamine), or through restrictions in the biotechnology licensing agreements that are shared between growers and seed companies. Alternatively, the U.S. EPA could enact a ban or moratorium on manufacturing and selling dimethylamine dicamba products. Although the diglycolamine formulation provided a substantial reduction in vapor drift, the mean distance of farthest injury was still 23.3 m from the center of the treated area for diglycolamine trials. This suggests that though the diglycolamine formulation will be an important tool

in mitigating vapor drift, nontarget dicamba injury to susceptible crops and wild plants may still occur.

Correlation with meteorological variables

Temperature was significantly correlated with two of the three drift summary indices (total g acid equivalent resettled and farthest injury). Air temperatures were also generally lower during the 2009 versus 2010 trials (21.7 vs 24.8°C average mean temperature over 8 h), partly explaining the higher drift indices observed in 2010. Because volatilization is driven by temperature, it is not surprising that this correlation was detected. However, temperature may have also influenced the susceptibility of the bioassay plants and their expression of injury symptoms, potentially confounding this result. Herbicide resistance biotechnology will allow dicamba to be applied later in a growing season (including postemergence applications on soybean), when air temperatures are warmer, which may increase the risk of nontarget crop injury if dimethylamine products are applied. Although current labels prohibit applying dimethylamine dicamba when temperatures exceed 29.4°C [8], our data suggests that relatively extensive vapor drift can occur on days when the mean daytime temperature is only above 25°C (Fig. 5).

The correlation between relative humidity and farthest injury may indicate that higher humidity increases the residence time of dicamba near plant surfaces or facilitates the uptake of dicamba by bioassay plants. Wind speed was not significantly correlated with any of the drift indices, indicating that unlike particle drift, vapor drift is not driven by wind transport. Due to the limited size of our dataset, these correlations should be interpreted as suggestive and warrant further investigation.

CONCLUSIONS

New herbicide resistance biotechnology will allow dicamba herbicides to be used over greatly expanded areas, and proactive research is needed to anticipate potential environmental risks, including vapor drift of dicamba herbicides. In the present study, we used a bioassay approach to track vapor drift of dicamba applied postemergence to soybean over multiple trial runs with a high degree of spatial detail. Vapor drift of the dimethylamine formulation of dicamba can be substantial (0.1% of applied concentration 20 m away from a treated plot) and was significantly correlated with air temperatures at the time of herbicide application. Relative to the dimethylamine formulation, diglycolamine dicamba greatly reduced (but did not eliminate) vapor drift. As registration and commercialization of dicamba-resistant biotechnology proceeds, additional research is needed to understand the impacts of low dicamba doses from vapor drift and other routes of exposure on nontarget crops and vegetation.

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