DETERMINATION OF COTTON PLANT INJURY BY AERIAL APPLICATION OF GLYPHOSATE USING REMOTE SENSING AND SPRAY DRIFT SAMPLING

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Abstract

Off-target drift of aerially applied glyphosate can cause plant injury, which is of great concern to farmers and aerial applicators. To determine the extent of crop injury due to near-field drift, an experiment was conducted from a single aerial application of glyphosate. For a larger-scoped project involving identification of the drift effect on different crops, a field was planted in alternating blocks of cotton, soybeans, and corn. Spray samplers were placed in the spray swath and in several downwind orientations to quantify relative concentration of applied chemical. An Air Tractor 402B spray airplane equipped with fifty-four CP-09 nozzles was flown down the center of the field to apply 22 oz/acre of Roundup Weathermax and Rubidium Chloride (RbCl) tracer at a 5 gal/acre spray rate. Relative concentrations of this tracer were quantified at downwind spray samplers. At one week intervals aerial Color-Infrared (CIR) imagery was obtained over the crop field using a Global Positioning System (GPS)-triggered Geospatial Systems MS-4100 camera system. This study's main focus was to assess glyphosate spray drift injury to cotton using the CIR imagery and spray drift sampling. The processed image data were compared with data from spray drift samplers placed downwind. Results will be helpful for determining the extent of near-field drift sampling, and demonstrated that multispectral imaging can be viable tools for determining the extent of damage relative to derived concentrations of glyphosate.

Introduction

Aerial application of crop production and protection materials has been employed for effective crop management. However, the possibility of off-target drift from aerial application can be a problem not only for environmental pollution but also for potential injury to crops in neighboring or nearby fields. Aerial spray drift has been studied with regard to factors such as spray droplet size, application release height, nozzle configurations, and weather (Kirk et al., 1991; Salyani and Cromwell, 1992; Smith et al., 2000; Wolf et al., 2005; Huang and Thomson, 2008; Hoffman et al., 2009; Fritz et al., 2009; Huang et al., 2009b).

Glyphosate drift injury has been reported in corn (Buehring et al. 2007; Brown et al. 2009; Ellis et al. 2003), soybean (Bellaloui et al. 2008), rice (Ellis et al. 2003; Koger et al. 2005), and peanut, *Arachis hypogaea* L. (Lassiter et al. 2007). Although drift rates are typically sub-lethal, injury can be severe in sensitive crops depending on growth stage and can reduce yield (Buehring et al. 2007; Brown et. al. 2009, Ellis et al. 2003).

Glyphosate (N-(phosphonomethyl) glycine) is a broad-spectrum systemic herbicide used to kill weeds, especially perennials. In the United States glyphosate-resistant (GR) crops have been widely adopted for weed control, and this has led to an unprecedented increase in glyphosate usage in recent years. Glyphosate is typically sprayed and absorbed through the plant leaves. Aerial application of glyphosate can rapidly cover large areas to provide effective treatments for weed problems in crop fields. However, glyphosate is a non-selective herbicide, and the off-target drift of aerially applied glyphosate is highly active on sensitive plant species even at low rates. Numerous studies have been conducted to determine the effect of glyphosate drift. Bird et al. (1996) analyzed the results of 117 aerial applications and concluded that, in general, pesticide deposits decreased from 5% of the nominal application rate at 30 m downwind to 0.5 % at 150 m downwind during low-altitude applications. In a crop field, aerial glyphosate applications resulted in downwind drift of 70% at 10 m, 29% at 20 m, 6% at 40 m, and 0.1% at 320 m, regardless of glyphosate formulation (Kirk, 2000). Similarly, in forestry aerial application, Payne (1993) indicated that downwind drift from application of glyphosate decreased from 36% at 10 m to 3.7% at 50 m to 0.2% at 200 m. Approximately one-third of the off-target loss occurred in the first 10 to 20 m downwind, with aerial drift deposits decreasing rapidly thereafter. Numerous studies have examined droplet size, drift distance, and spray deposition of herbicides from ground and aerial applications. However, few studies have specifically quantified the impact of glyphosate drift on sensitive plant species. Information is needed on how the glyphosate drift from aerial application influences sensitive plants.

Remote sensing has been widely used and developed in agriculture (Pinter et al., 2003; Lan et al., 2009; Huang et al., 2009a). For glyphosate drift, Rowland (2000) determined that low rates of glyphosate could reduce the yield of corn, and that stand height was one of the best indicators for estimating the degree of damage. If a crop is injured to the degree that height is limited and yield is decreased, perhaps a remotely sensed image could be used to detect these injury symptoms seemingly invisible to the naked eye. Henry et al. (2004) conducted research to determine whether hyperspectral remote sensing could be used to identify and quantify herbicide injury to crops. Soybean and corn plants were grown in 3.8-L pots to the five- to seven-leaf stage, at which time applications of nonselective herbicides were made. Visual injury estimates were made, and hyperspectral reflectance data were recorded 1, 4, and 7 days after application. Several analysis techniques including multiple indices, signature amplitude with spectral bands, and wavelet analysis were used to distinguish between herbicide-treated and non-treated plants. The results indicated that hyperspectral reflectance could distinguish between healthy and injured plants to which herbicides had been applied.

This study examines the effect of glyphosate drift from aerial application on non-GR cotton by remote sensing and spray drift sampling. Specific objectives of this research were:

1. To determine the in-swath deposition and downwind drift characteristic of aerially applied glyphosate in a single swath of 18.2 m at a rate of 866 g ha^{-1}
2. To determine the crop injury by the downwind drift of sprayed chemical using aerial multispectral imaging

Materials and Methods

Experimental Field and Spray Experiment

A crop field located at Stoneville, MS (33°26'N, 90°55'W), at the U.S. Department of Agriculture-Agricultural Research Service, Crop Production Systems Research Unit research farms, was used to conduct an aerial application experiment to determine injury and biological responses to glyphosate drift on non-GR cotton, corn, and soybean. Analytical results herein will deal only with those for cotton.

For the experiment, non-GR cotton cultivar 'FM955LL' at 100,000 seed ha^{-1}, non-GR corn hybrid 'Pioneer 31P41' at 75,000 seed ha^{-1}, and non-GR soybean cultivar 'SO80120LL' at 285,000 seed ha^{-1} were planted on July 23, 2009. Each crop was planted in eight rows spaced 102-cm apart and 80 m long with four replications (Figure 1).

Aerial application of glyphosate was made over the crops in the field on August 12, 2009. An Air Tractor 402B airplane equipped with fifty-four CP-09 spray nozzles (CP Products, Tempe, AZ) set at 5 degree deflection angle was used for the application. The aircraft was configured to deliver the liquid at the rate of 46.8 L ha^{-1} with a release height of 3.7 m and an operating speed of 225 km h^{-1} over an 18.3 m wide spray swath. The sprayed liquid was a glyphosate solution of Roundup Weathermax® (Monsanto Co., St. Louis, MO) applied at a rate of 866 g ai ha^{-1}, with 2.6 g Rubidium Chloride (RbCl) tracer to allow relative indications of drift and downwind proportional concentrations of Glyphosate to be estimated. One spray run in the west to east direction at the center of the field perpendicular to the crop rows was made over a marked swath line (Figure 1). Weather conditions were recorded during the four second flight run. The average wind speed was 11.2 km h^{-1} from the northeast direction averaging 64° from true north. Average air temperature was 28.5°C and relative humidity was 72% as acquired during the spray run using a Kestrel 4500 weather tracker mounted on a tripod (Nielsen-Kellerman, Boothwyn, PA). At application, cotton was at two- to three-leaf stage, corn was at four-leaf stage, and soybean was at two- to three-trifoliolate leaf stage.

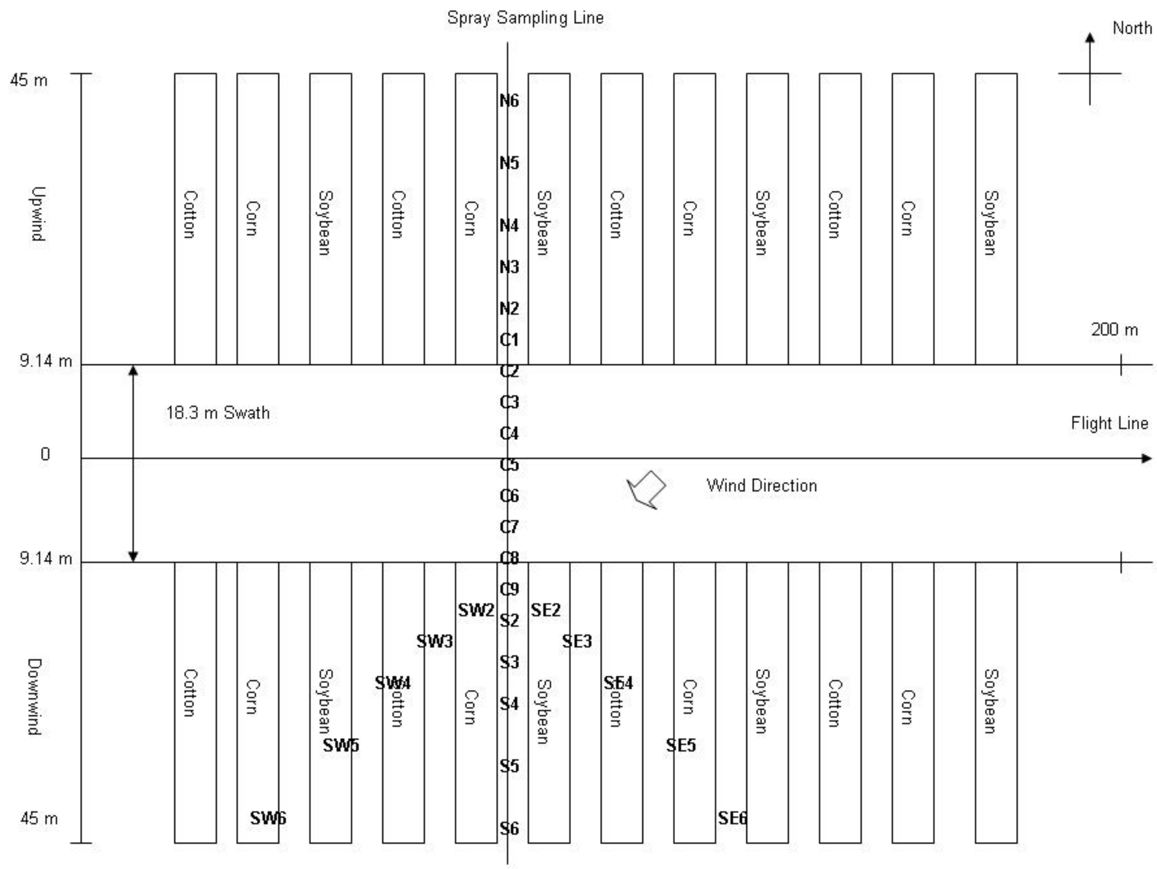


Figure 1. Field layout for the spray test (drift sampling stations are indicated by direction: N=north, S=south, SE=southeast, SW=southwest)

Spray Sampling and Data Processing

The spray downwind drift lines were established along the crop rows and perpendicular to spray swath (Figure 1). The downwind in-swath and drift sampling stations were marked in one line from north to south at 0 (C5), 3 (C6), 6 (C7), 9 (C8), 12 (C9), 15 (S2), 20 (S3), 25 (S4), 35 (S5) and 45 (S6) m measured from the flight line downwind in the 18.3 m swath. Additional downwind drift sampling stations were set up in the 45 degree southwest and 45 degree southeast to the north-south sampling line. As Figure 1 shows, the two additional drift sampling lines all started at the sampling station of C9 (12 m) with the sampling stations at 3 (SW2 and SE2), 8 (SW3 and SE3), 13 (SW4 and SE4), 23 (SW5 and SE5), and 33 (SW6 and SE6) m in the lines.

At each of the north-south spray sampling stations, C1-C9 and S2-S6, water sensitive paper (WSP) cards (Syngenta, Basel, Switzerland) were placed. The WSP is a special slide-strip of 76 x 50 mm size, which indicates presence of droplets by a blue stain. WSPs were collected within five minutes of the spray run for subsequent analysis. In the lab, each WSP card was scanned using a camera-based imaging system and SigmaScan macros to output parameters from each of the cards, including total and percentage card area covered by spray droplets, feret diameter of each droplet, percentage of droplets showing a “compactness” less than 20, and total number of droplets on cards. Compactness is a measure of droplet “roundness” or the perimeter^2/area.

After processing by spreadsheet macros to sort the droplet data, the sorted data were fed into a Matlab (The MathWorks, Inc., Natick, MA) program developed for generating droplet spectra parameters. The program was designed to determine cumulative droplet areas and allow screening of droplets by a user-selected compactness threshold and generate parameters $D_{V0.1}$, $D_{V0.5}$, and $D_{V0.9}$ when accounting for a spread factor. Compactness in this case was set to a value of 22, with 12.57 being a perfectly round droplet. This value was chosen based on empirical observation of droplet shape distribution on cards analyzed over the past two years. The spread factor equation chosen was the USDA version as used previously by Thomson at al. (2007) and described by Hoffmann and Hewitt (2005). $D_{V0.1}$, $D_{V0.5}$, and $D_{V0.9}$ are important parameters to describe spray droplet size spectra. $D_{V0.5}$ is the droplet diameter (μm) where 50% of the spray volume or mass is contained in droplets smaller than this value. $D_{V0.5}$ is also referred as Volume Median Diameter (VMD). Sauter mean diameter $D_{V0.1}$ and $D_{V0.9}$ values describe the proportion of the spray volume (10% and 90%, respectively) contained in droplets of the specified size or less. Relative span [($D_{V0.9}$ - $D_{V0.1}$)/VMD] is a measure of the width of the droplet spectra around the $D_{V0.5.}$

Mylar sampling sheets were also placed at every sampling station. The mylar sheet was a polyester based film with a matte translucent drawing surface on one side of size 130 x 127 mm. Along with WSP, Mylar sheets were collected after the spray run. For processing in the lab, the mylar sheets were shaken on a shaker for 20 minutes (10 minutes on each side) to ensure complete washing of the sheet. The rinse solution was a 1% HNO3 (nitric acid) solution, which is also used for the calibration blank on the AAnalyst 600 Atomic Absorption Spectrometer (PerkinElmer, Waltham, MA). The AAnalyst 600 is equipped with a transversely heated THGA graphite furnace AA with longitudinal Zeeman-effect background correction. The spectrometer and furnace are controlled using WinLab 32 software. The AAnalyst 600 spectrometer was used to determine the concentration of RbCl tracer on each sheet in the unit of μg/L.

Plant Sampling

The downwind drift sample stations, C5, C6, C7, C9, S2, S4, and S5, were marked for plant sampling. One upwind sample station at 35 m (N5) measured from the flight line upwind in the 18.3 m swath was included as a control (crops not exposed to glyphosate). These stations were established in all four replications of each crop (Figure 1). Areas from the aerial multispectral images were sampled close to the sampled points.

Aerial Multispectral Imaging

The MS 4100 camera (Geospatial Systems, Inc., West Henrietta, New York) was mounted on the Air Tractor 402B airplane for acquiring color-infrared (CIR) images in red, green and near-infrared (NIR) bands. After application on August 12, 2009, the images of the experimental field were acquired on August 13, August 19, August 26 and September 2. Based on the flight records obtained from the aircraft log files, the flight altitude was 366 m above ground level. A 14 mm, f/2.8 Nikon lens with a 60 degree field of view was used on the MS4100. This configuration resulted in the ground spatial resolution of the images at 11 x 20 cm/pixel. The images were georeferenced and transformed to the NDVI (Normalized Difference Vegetation Index) and SAVI (Soil Adjusted Vegetation Index) images. NDVI is useful in visualizing crop canopy vigor and SAVI (Cyr et al., 1995) is useful in considering the impact of soil when the canopy is not developed. SAVI is calculated by the following equation:

$$\mathrm{SAVI} = \frac{\mathrm{NIR} - \mathrm{Red}}{\mathrm{NIR} + \mathrm{Red} + \mathrm{L}}(1 + \mathrm{L}) \qquad (1)$$

where L is a constant that is empirically determined to minimize the vegetation index sensitive to soil background reflectance variation. If L is zero, SAVI is as same as NDVI. For intermediate vegetation cover ranges, L is typically around 0.5 for intermediate coverage. For dense coverage, L value should be smaller such as 0.25. On the images of NDVI and SAVI, the pixel values at plant sampling points were sampled using ArcGIS (ESRI, Redlands, CA) Spatial Analyst toolbox for analysis.

Statistical Analysis

The downwind distance at discrete stations was considered as the independent variable and the drift sampling values such as droplet % area coverage on the WSPs, number of drops on the WSPs, and RbCl concentration on the mylar sheets in the spray sampling lines were considered as dependent variables. The data were fitted to a logistic model to relate the drift sampling values (*y*) to downwind drift distance (*x*):

$$y = \frac{a}{1 + b * e^{-cx}} \qquad (2)$$

Regression parameters for the equation were computed using CurveExpert 1.36 (Daniel Hyams, Starkville, MS).

Results and Discussion

Spray Sampling

Figure 2 and 3 show the spray droplet sizes and relative span on the WSP cards along the spray sampling center line, respectively. The droplet sizes were relatively large around stations C3 and C4. Then, in the downwind direction, the ranges of droplet sizes were relatively stable and decreased at the far south drift sampling stations, S2 to S6. This was a result of large droplets settling out, leaving the smaller droplets downwind. The relative span reached the peak value at C4. Because the flight center line was vertically through the spray sampling line at C5, this variability of droplet spectra could be considered as the effect of turbulence in the swath. Overall, the relative span was stable within the range of 0.4 to 0.9.

Figure 4 and 5 show the droplet area coverage and the number of drops on WSP cards along the spray sampling center line, respectively. Both parameters were relatively large in-swath and decreased gradually downwind. Table 1 shows Logistic modeling results of droplet area coverage and the number of drops on the WSP cards, the downwind location of 50% reduction in deposited spray, and the distances between the location of 50% deposited spray reduction and the edge of the swath. The two 50% reduction distances were calculated to be about 3.8 m.

Table 1. Logistic modeling of droplet area coverage and the number of drops on WSP cards and RbCl concentrations on mylar sheets.

Dependent Variables	Model Coefficients	Standard Error	Correlation Coefficient	Location of 50% Reduction in Deposited Spray (m)	Distance between Location of 50% Reduction in Deposited Spray and Edge of Swath (m)
Area Coverage (%)	a =0.0805 b =-2.68 c =0.0870	0.0924	0.9910	12.79	3.79
Number of Drops	a =-5.6016e+9 b =-5.8836e+6 c =-0.0881	40.43	0.9848	12.77	3.77
RbCl North to South Downwind Drift Sampling	a =0.0142 b =-0.9995 c =0.0003	0.1265	0.9997	13.31	4.31
RbCl Southwest Downwind Drift Sampling	a =-5.20 b =-0.8615 c =-0.0505	0.8922	0.9972	13.15	4.15

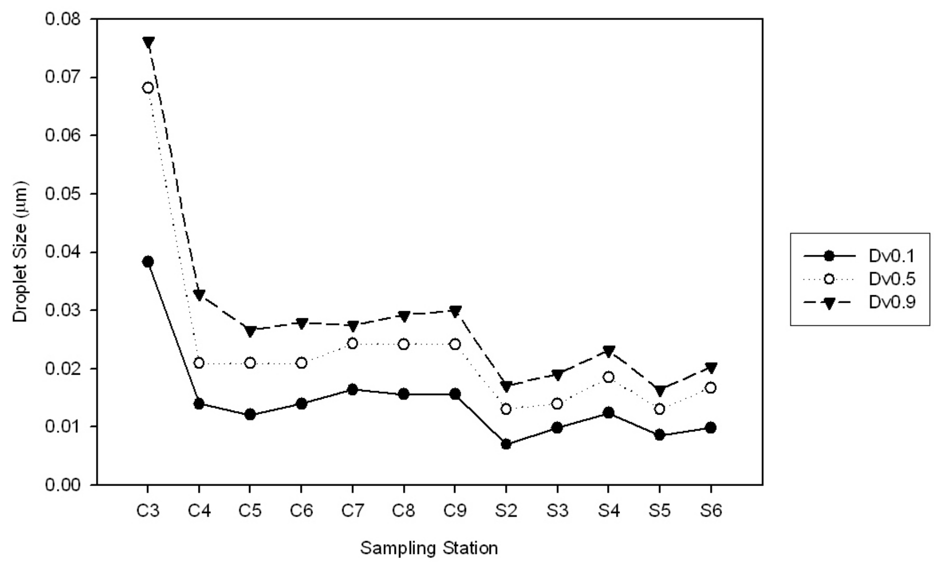


Figure 2. Droplet sizes on WSP cards along the spray sampling center line.

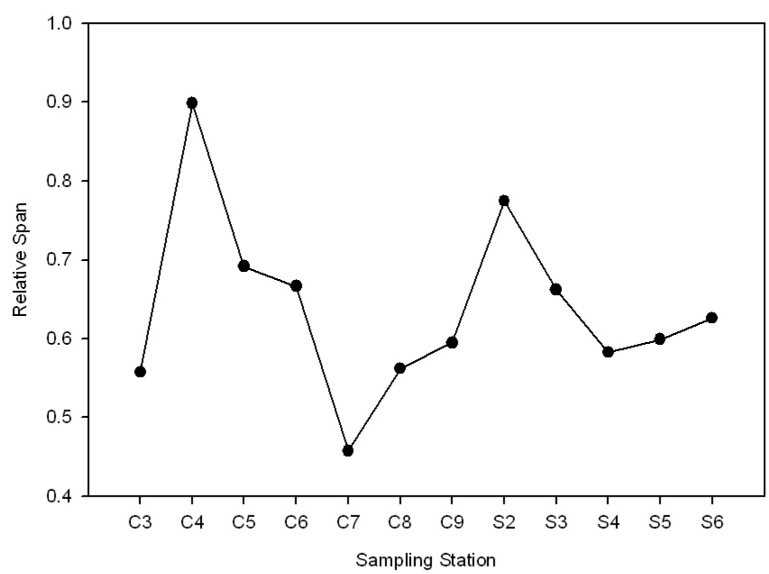


Figure 3. Droplet relative span on WSP cards along the spray sampling center line.

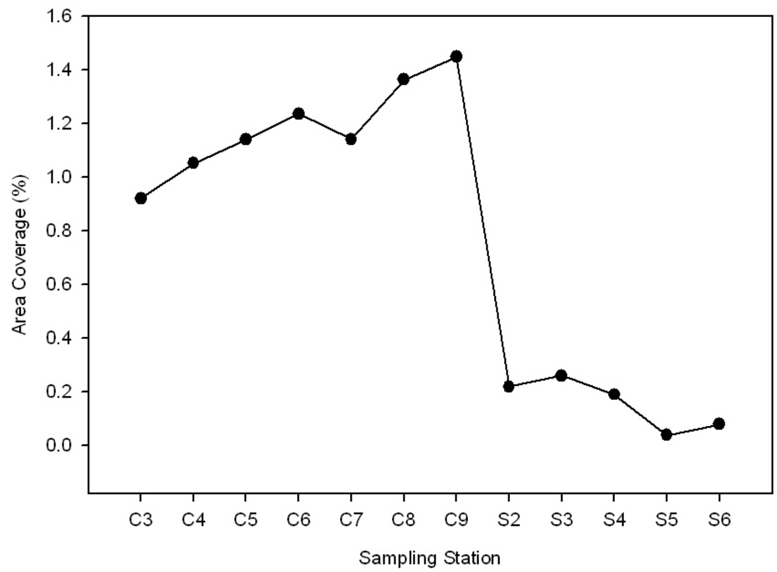


Figure 4. Droplet area coverage on WSP cards along the spray sampling center line.

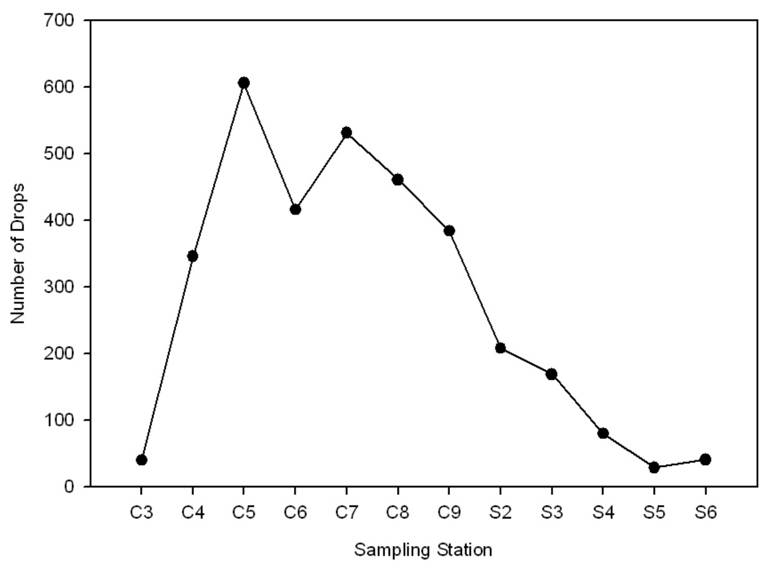


Figure 5. Number of drops on WSP cards along the spray sampling center line.

Figure 6 illustrates the distribution of RbCl concentration obtained from mylar sheets over the spray sampling center line. In the upwind part (N2-N6 and C1), concentrations were close to zero. In-swath (C2-C8) concentrations were distributed with higher values, as would be expected. In downwind part (C9 and S2-S6), the concentration decreased gradually, starting from station C7. Results of logistic modeling for RbCl concentration on mylar sheets over the sampling center line (Table 1) showed that the distance between 50% reduction in deposited spray and the edge of the swath was about 4.3 m, which is close to the result obtained from modeling WSP (3.8 m).

Figure 7 illustrates the distribution of RbCl concentration of mylar sheets over the spray sampling line in southwest direction, which was directly downwind. The RbCl concentration was also modeled, and the distance between 50% of deposited spray and the edge of the swath was determined to be 4.2 m (Table 1). Figure 8 illustrates the distribution of RbCl concentration of mylar sheets over the spray sampling line in southeast direction. It is natural for the pattern to be more random in nature, although in general it showed a decreasing trend. The pattern was skewed by the wind coming from the northeast direction.

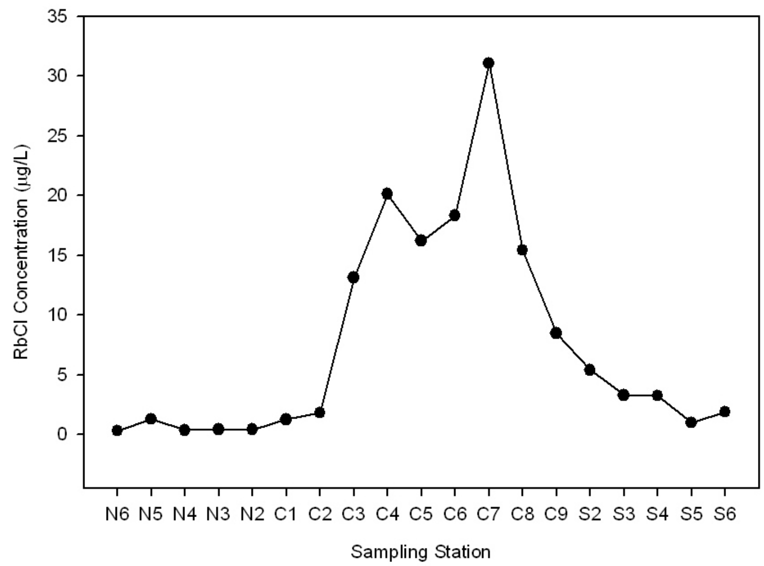


Figure 6. RbCl concentration of mylar sheets over the spray sampling center line.

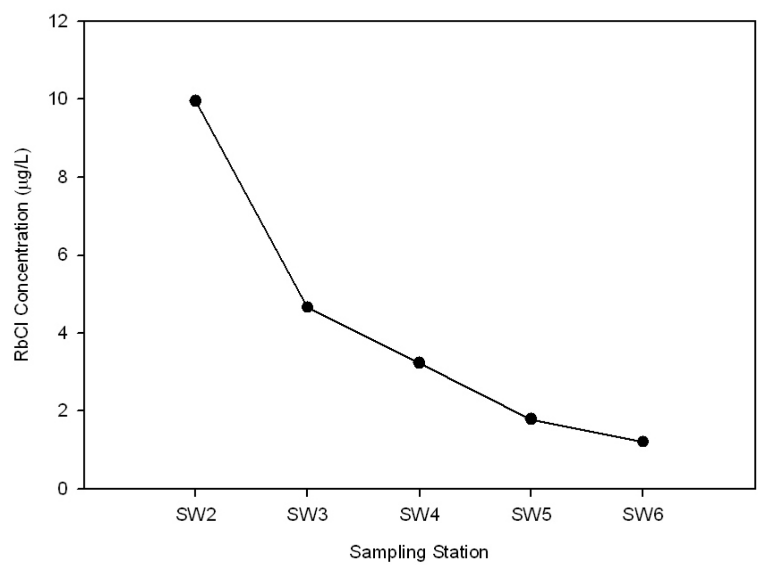


Figure 7. RbCl concentration of mylar sheets over the southwest spray sampling line.

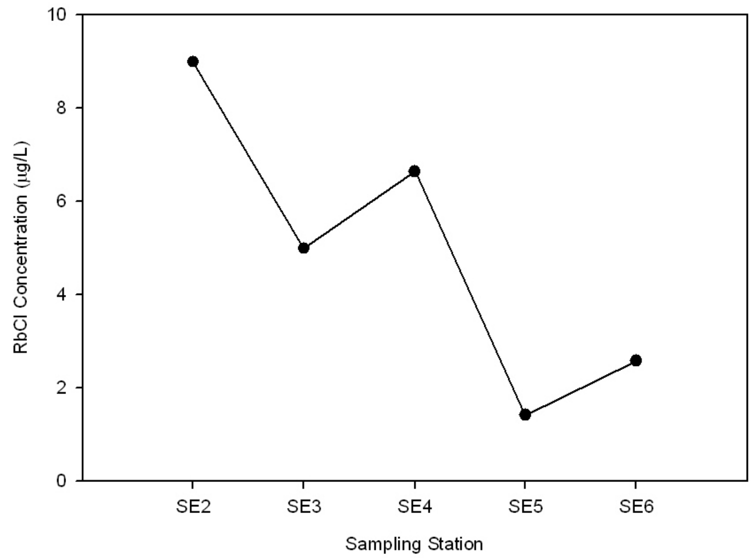


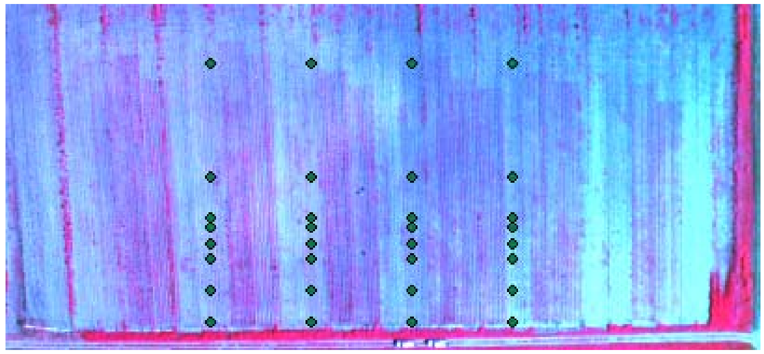
Figure 8. RbCl concentration of mylar sheets over the southeast spray sampling line.

Aerial Multispectral Image Analysis

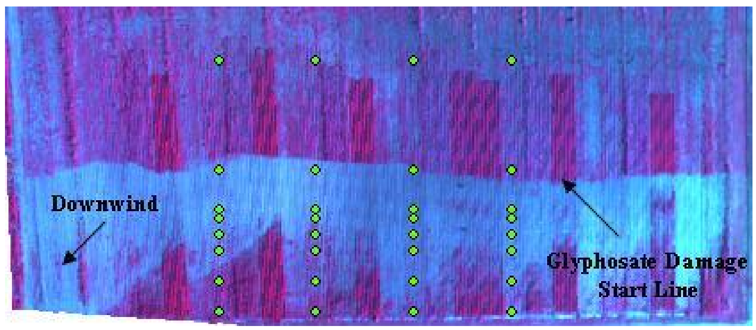
Figure 9 illustrates the CIR images on August 13 and September 2, 2009 over the field area. Figure 10 illustrates images of NDVI and SAVI on August 13, 19, 26 and September 2, 2009 over the crop sampling areas. The images on August 13 did not show visible crop damage so soon after spraying. The images on August 19 indicate clear crop damage, which was more pronounced in images of August 26 and September 2. Damage as indicated by imagery appeared to be less further downwind (reddish colors on the CIR image illustrate the vigor of the crop canopy).

Figure 11 plots average NDVI and SAVI on crop sampling points in the direction of spray drift downwind on August 19, 26 and September 2, 2009. On August 19, downwind NDVI trends were different than the SAVI trends although both increased with an increase in downwind distance from the flight line. On August 26, SAVI had a similar profile as NDVI over the sample line, except at two ends on the crop sampling line where SAVI was much larger than NDVI. On September 2, the crop canopy was well developed and SAVI had a similar profile as NDVI over the sample line downwind. However, at the upwind reference point (undamaged), SAVI was much larger than NDVI, possibly due to soil background interference at that sampling location.

Figure 12 shows a temporal comparison of NDVI and SAVI over the sampling days. On August 19 and August 26, NDVI was comparable, although the result on August 26 appeared to be more stable. The NDVI on September 2 provided a smoothly increasing trend with downwind distance. In the downwind direction from 12 to 45 m, NDVI showed significant higher values than the previous two days although values were still less than 0.3. It can be anticipated that within the period of cotton growth (a few months) NDVI would be significantly higher, and that the NDVI could be a good tool to monitor the growth gradient downwind from application. Compared to the SAVI trends indicated for August 19, the SAVI using an L= 0.5 seems to have better represented the influence of soil background for August 26. On September 2, the canopy was much better developed and the SAVI was closer to NDVI when using a smaller L=0.25. Even so, soil background interference was revealed at the upwind reference point as indicated in Figure 11 (c).



(a) CIR image on August 13, 2009.



(b) CIR image on September 2, 2009.

Figure 9. CIR image on August 13, 2009 (dots on the images are cotton crop sampling points).

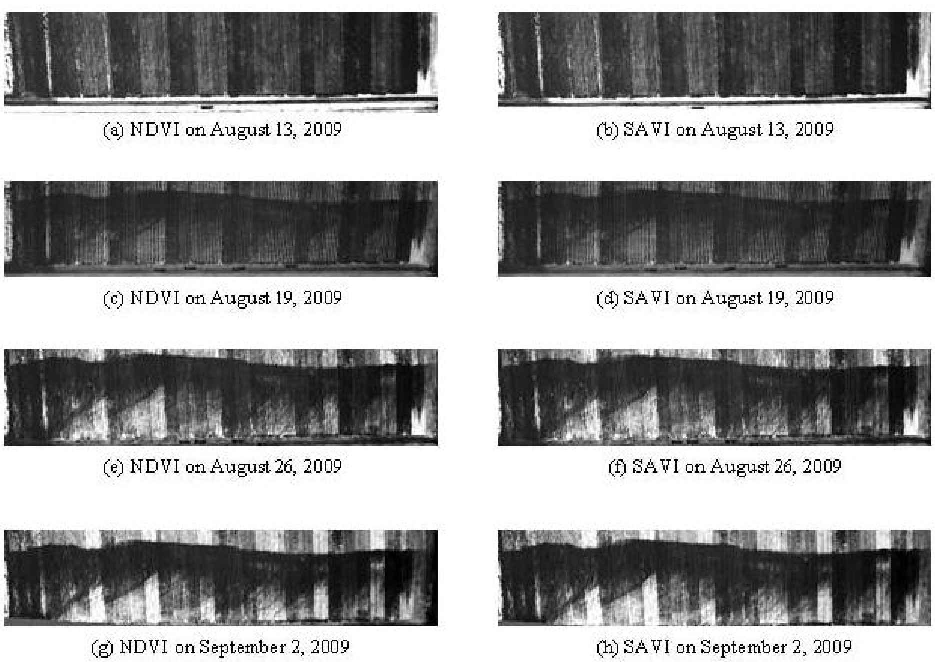
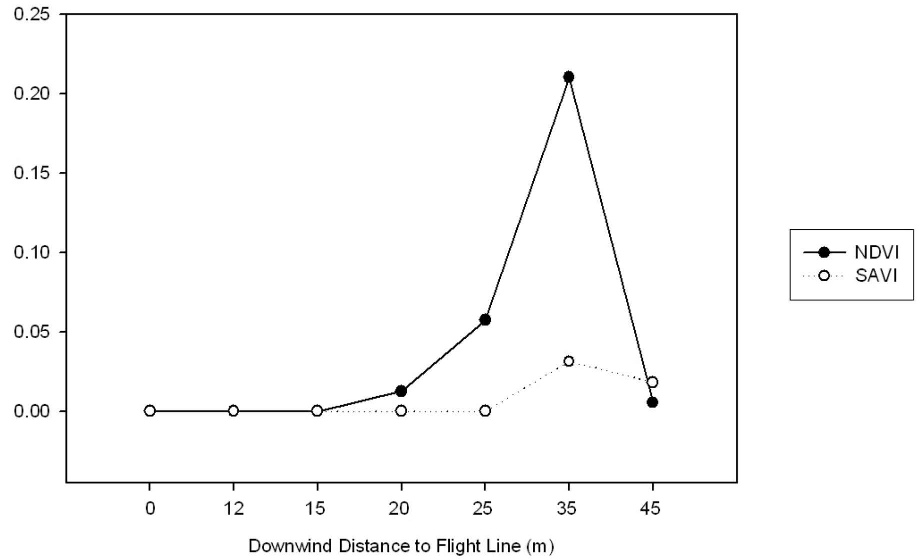
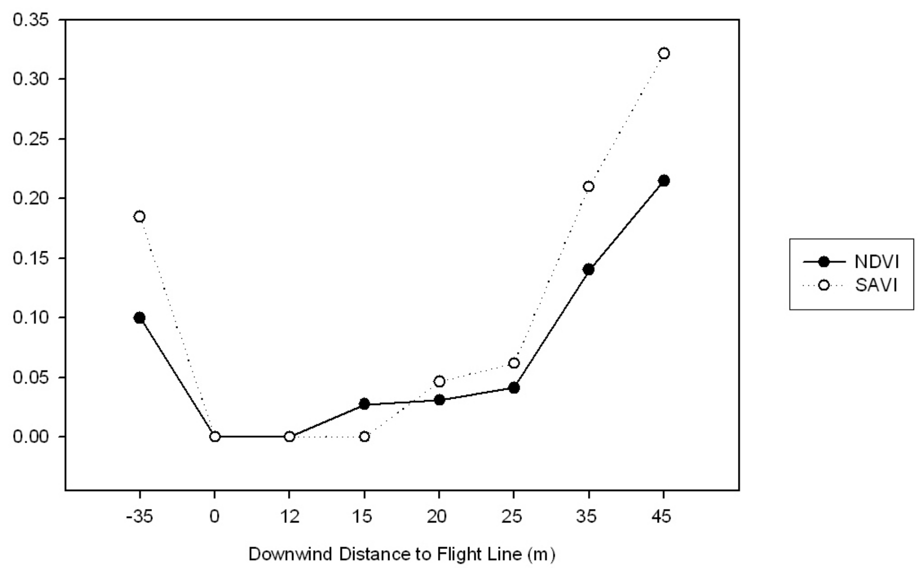


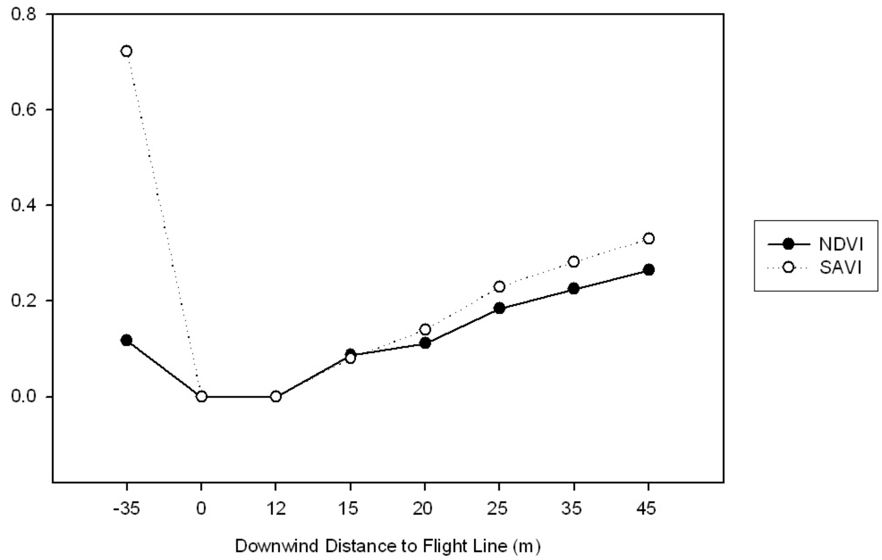
Figure 10. NDVI and SAVI images on August 13, 19, 26 and September 2, 2009 (L=0.5 for SAVIs on August 13, 19, and 26 and L=0.25 on September 2, 2009).



(a) August 19, 2009

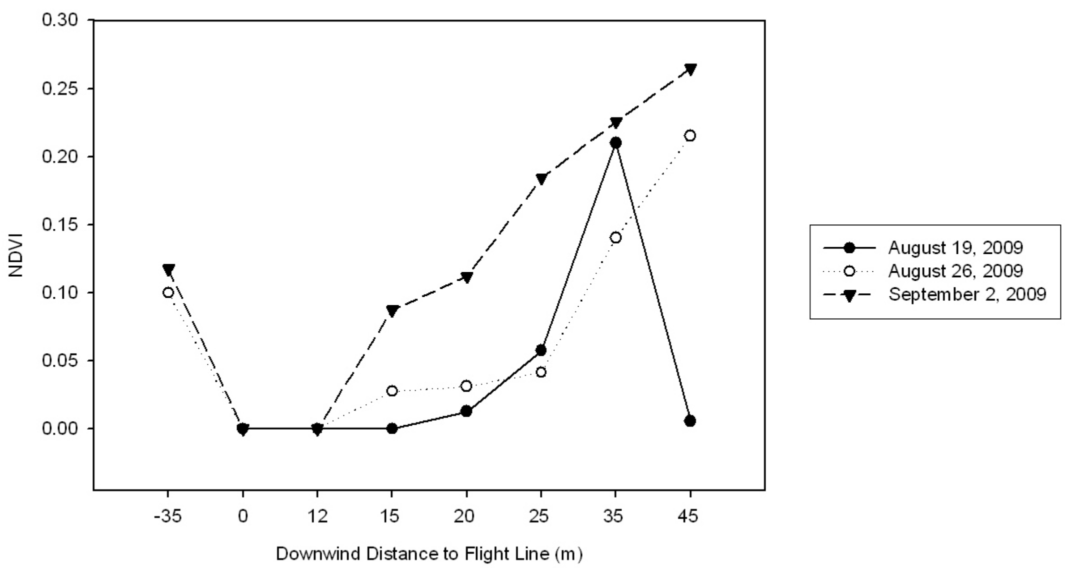


(b) August 26, 2009

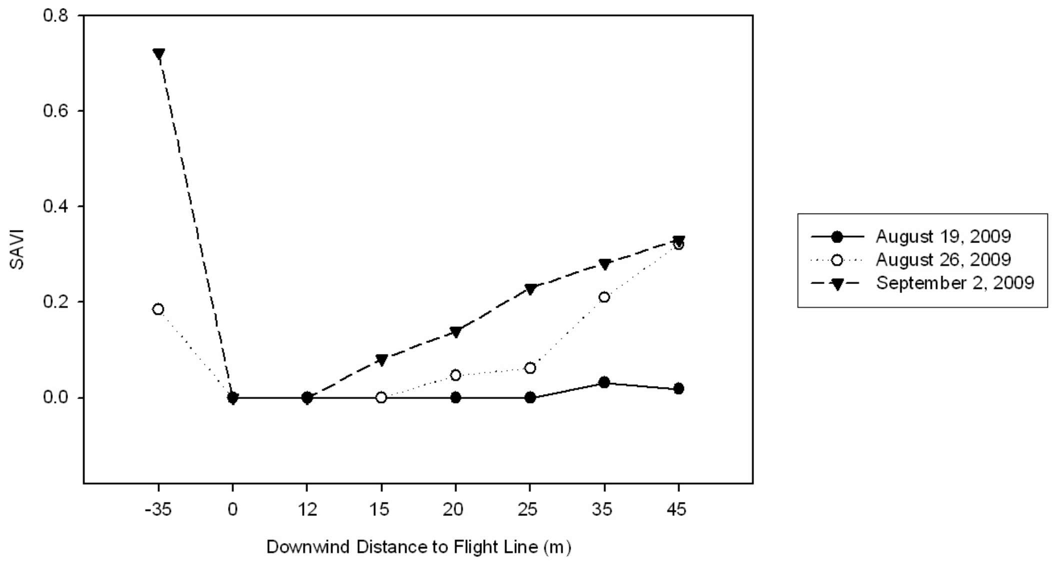


(c) September 2, 2009

Figure 11. Average NDVI and SAVI change profiles over crop sampling lines.



(a) NDVI comparison



(b) SAVI comparison.

Figure 12. Comparison of average NDVI and SAVI change profiles over crop sampling lines.

Summary and Conclusions

Droplet analysis of WSP and relative concentration of RbCl obtained from mylar samplers were used successfully to determine both the in-swath deposition and downwind drift characteristics of an aerially applied glyphosate mixture. Logistic models were fit to data from the two different spray sampling methods. Results provided distances between the location of 50% reduction in deposited spray and the edge of the swath, with values of 3.8 m and 4.3 m for droplet density (WSP) and RbCl concentration, respectively. Similarity between these values indicates that either method could be suitable for quantifying the relative concentration of RbCl tracer that could, in turn, be used to infer the concentration of active ingredient (A.I.). NDVI and SAVI from the aerial CIR images illustrated relative crop injury downwind from spray by their increasing values with distance. Remote sensing from a low-altitude aerial platform and spray drift sampling using either WSP or RbCl tracer can be used to examine the effects of glyphosate drift from aerial application on non-GR cotton.

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Disclaimer

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