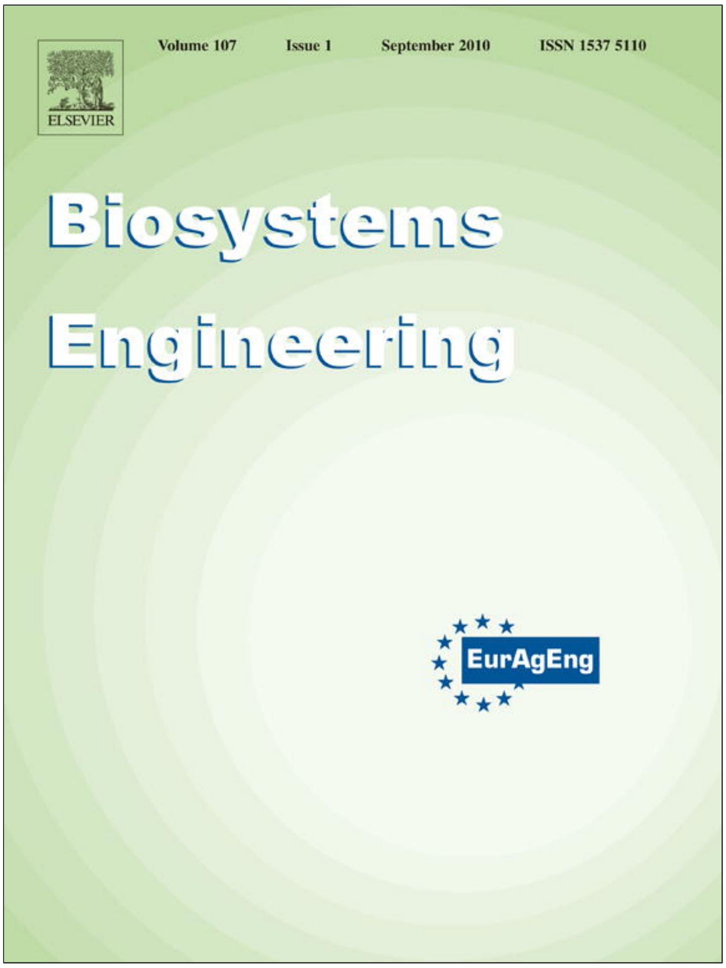
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Research Paper

Ground-based spectral reflectance measurements for evaluating the efficacy of aerially- applied glyphosate treatments

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Aerial application of herbicides is a common tool in agricultural field management. The objective of this study was to evaluate the efficacy of glyphosate herbicide applied using aircraft fitted with both conventional and emerging aerial nozzle technologies. A weedy field was set up in a randomised complete block experimental design using three replicates. Four aerial spray technology treatments, electrostatic nozzles with charging off, electrostatic nozzles with charging on, conventional flat-fan hydraulic nozzles and rotary atomisers, were tested. To evaluate the glyphosate efficacy and performance of aerial spray technologies, spectral reflectance measurements were acquired using a ground-based sensing system for all treatment plots. Three measurements were taken at 1, 8, and 17 days after treatment (DAT). The statistical analyses indicated that glyphosate applied with different methods killed the weeds effectively compared to untreated areas at 17 DAT. Conventional flat-fan nozzles and rotary atomisers performed better than the electrostatic nozzles with charging off. There was no evidence to show that the electrostatic nozzle performed better with charging on or charging off. The results could provide applicators with guidance equipment configurations that can result in herbicide savings and optimised applications in other crops.

1. Introduction[1]

Glyphosate, a non-selective contact herbicide, is used extensively for weed control in agricultural production systems. Use of glyphosate has increased dramatically due to the introduction of transgenic crop varieties that can tolerate over-the-top or directed applications during some growth phases without significant impact on yield. It has also increased because of the increase use of reduced-tillage or no-tillage farming systems. Jordan et al. (1997) evaluated the efficacy of glyphosate alone and in combination with other herbicides, but their work was limited to ground applications.

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Specialised agricultural aircraft have developed largely as a result of convenience as they allow for better timing of and greater efficiency in application treatments. Aircraft are able to apply agricultural products, such as fertilizers and pesticides, in a timely manner over large areas. Aerial applications of glyphosate have increased with the requirement for more effective weed management prior to planting spring-seeded crops. Many studies have been conducted to evaluate the performance of aerial spray technologies. For the most part these studies have indicated that optimum spray rate and droplet size combinations vary with pesticide product, pest, and specific crop (Bouse, Whisenant, & Carlton, 1992, Hoffmann, Lingren, Coppedge, & Kirk, 1998, and Kirk, Bode, Bouse, Stermer, & Carlton, 1989, Kirk, Bouse, Carlton, Frans, & Stermer, 1992, Kirk, Esquivel, Porteous, & Hendrix, 1998 and Kirk, Hoffmann, & Carlton, 2001). Latheef, Carlton, Kirk, and Hoffmann (2009) investigated the efficacy of different insecticides applied with aerial electrostatic-charged sprays and conventional sprays and found comparable deposition and insect control with both electrostatic and conventional flat-fan nozzles.

Spectral reflectance properties based on the absorption of light at a specific wavelength are associated with specific plant characteristics. The spectral reflectance in the visible wavelengths (400–700 nm) is low because of the high absorption of light energy by chlorophyll. Reflectance of the near-infrared (NIR) wavelengths (700–1300 nm) is high because of the multiple scattering of light by different leaf tissues (Taiz & Zeiger, 2006). For example, plant stress usually results in an increase in visible reflectance and a decrease in NIR reflectance. Lamb and Brown (2001) suggested that differences in spectral reflectance between weeds and their background could be used to remotely sense weeds. Detecting weeds against a soil background on fallow ground is a straightforward process as the weeds and soil have significantly different spectral reflectance characteristics in the Red and NIR wavelength bands. It is also well known that the Normalized Difference Vegetative Index (NDVI) is a good indicator of vegetation, crop biomass and health in agricultural applications (Rouse, Haas, Schell, & Deering, 1973; Sembiring et al., 1998; Tucker, 1979). NDVI is calculated by: $\text{NDVI} = (\text{NIR} - \text{Red})/(\text{NIR} + \text{Red})$, where Red and NIR are the spectral reflectance measurements acquired in the red and near-infrared regions, respectively. Healthier crop canopies will absorb more red and reflect more near-infrared light than stressed or unhealthy canopies, and consequently have a higher NDVI value.

Many on-the-go, ground-based sensors are available for collecting real time spectral reflectance data and calculating NDVI. The Greenseeker® (NTech Industries, Inc., Ukiah, CA, USA) has been widely used for mapping NDVI in a variety of different crops. Martin et al. (2005 and 2007) used this sensor to collect NDVI data at multiple growth stages during the life cycle of maize and evaluate the relationship between NDVI and maize grain yields. Jones et al. (2007) estimated chlorophyll yield and concentration in spinach by using NDVI values from a Greenseeker sensor and a multispectral imaging system. Freeman et al. (2007) collected Greenseeker sensor NDVI values and plant height measurements on individual corn plants at various growth stages and related them to individual plant biomass, forage yield and nitrogen (N) uptake. Flynn, Dougherty, and Wendroth (2008) evaluated spatial properties of grassland biomass with Greenseeker sensor NDVI data. A spectroradiometer is also a useful tool for the detection and monitoring crop growing status. Bronson et al. (2005) used Greenseeker NDVI to compare to NDVI values taken by a spectroradiometer to determine which device better estimated in-season plant N status. Darvishzadeh et al. (2008) examined the utility of hyperspectral remote sensing in predicting canopy characteristics by using a spectroradiometer. Zhang, Lan, Lacey, Hoffmann, and Westbrook (2009) characterised the spatial variation of NDVI derived from spectral reflectance measurements with a FieldSpec® (Analytical Spectral Devices, Inc., Boulder, CO, USA) spectroradiometer.

At the time this study was conducted, there were no reported studies where the aerial application of glyphosate was evaluated using remotely sensed data. The objective was to characterise the glyphosate efficacy applied with conventional and emerging aerial spray nozzles using ground-based spectral reflectance data.

2. Material and methods

2.1. Study site

The field used for this study was located in Burleson County, TX, USA (30.524588°N, 96.407181°W) and was treated with glyphosate on Mar. 2, 2009. The field had been left fallow for the previous eight months and thus, was inundated with both broadleaf and grass weeds. Fig. 1 is the photo of the study weedy field which was taken on Feb 24, 2009. The soil type of the study area, ShA, was Ships

Fig. 1 – The photo of the study site taken on Feb 24, 2009.

clay, 0 to 1% slope, and rarely flooded (http://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey).

2.2. Treatment protocol

Treatments were applied in randomised complete blocks with three replications (Fig. 1). Each replicate block was subdivided into five unique randomised treatments. This design strategy improved the accuracy of the comparisons among nozzle technologies by eliminating the variability among the replicates with a block, the order in which the five treatments were tested was randomly determined. Each treatment plot was three swaths wide (59 m) and (183 m) long and was delineated with a disked strip of soil (Figs. 1 and 2).

A turbine-powered Air Tractor AT-402B agricultural aircraft (Air Tractor, Inc., Olney, TX, USA) was used to make all applications. Treatments were made using aerial electrostatic nozzles (Spectrum Electrostatic Sprayers Inc, Houston, TX, USA), CP-11TT 4015 hydraulic flat-fan nozzles (CP Products, Tempe, AZ, USA) and AU-5000 windmill-driven rotary atomisers (Micron Sprayers Ltd., Bromyard, Herefordshire, UK). Table 1 shows aircraft and nozzle settings for each treatment. The droplet $D_{V0.5}$ (or Volume Median Diameter (VMD)) is the diameter of droplet such that 50% of the total volume of droplets is in droplets of smaller diameter. The VMD values were determined using the USDA-ARS Spray Quality models (Kirk, 2007) using the nozzle and aircraft operating parameters, including spray pressure, nozzle type and deflection, and airspeed. The aircraft approached the field from the northwest and made three passes (swaths) to apply the chemical over one experimental plot. The spray height was 3 m.

All treatments were made using Helosate Plus™ (Helm Agro US, Inc., Memphis, TN, USA) at 1168 ml ha^{-1} and 0.5% v/v R-11 non-ionic surfactant (Wilbur–Ellis Co., Fresno, CA, USA). Helosate Plus contains 41% glyphosate (n-(phosphonomethyl) glycine), in the form of its isopropyl amine salt. The spray mixture also contained Caracid Brilliant Flavine fluorescent dye at a rate of 37 g ha^{-1}.

2.3. Sensing system

A sensing system (Lan, Zhang, Lacey, Hoffmann, & Wu, 2009) was assembled using a Greenseeker® handheld data collecting and mapping unit (NTech Industries, Inc., Ukiah, CA, USA) and

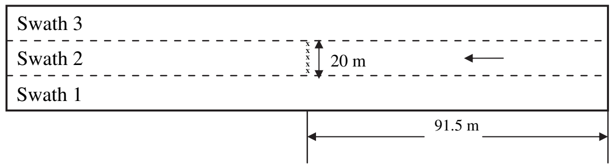

Fig. 2 – Sampling locations layout within each treatment plot.

a FieldSpec® (Analytical Spectral Devices, Inc., Boulder, CO, USA) handheld portable spectroradiometer. The Greenseeker® and FieldSpec® sensors were mounted on a tractor at the height of 1 m above the ground. Sampling was carried out as the tractor was driven along the strips which were marked in the centre of each treatment plot (Figs. 1 and 2). The spectral data collection in the centre swath was used for statistical analyses to avoid the effects of cross contamination between treatments.

As the Greenseeker® sensor moved over the field, it measured incident and reflectance light from the target and outputted NDVI readings. Weeds within each plot responded in a similar manner to treatments, so the NDVI data of the centre swath of each treatment plot were averaged to give a single value for each treatment. The analysis of variance (ANOVA) was carried out based on the experimental data using *R* statistics software (http://cran.r-project.org). Treatment variables were considered fixed and variations in experimental treatments were considered random.

The FieldSpec®, with an angular field-of-view of 25°, scanned approximately 0.23 m^2 of weedy field. The spectroradiometer collected spectral data from the ground ranging from a wavelength of 325 nm–1075 nm with a sampling interval of 1.4 nm. The spectroradiometer produced 512 continuous data points with each reading. Ten spectral measurements were taken from each treatment plot. By averaging these ten measurements, a single reflectance measurement was obtained for each treatment plot, thereby, minimising measurement noise. Instrument optimisation and white reference measurements were performed prior to each treatment plot measurements according to the method reported by Castro-Esau, Sanchez-Azofeifa, and Rivard (2006). The spectroradiometer was adjusted to 10 scans per dark current and the integration time was set at 217 ms. The

Table 1 – Spray treatment setups and droplet size information.

Treatment	Nozzle	Number of Nozzles	Rate (l ha^{-1})	Orifice	Deflection (degrees)	Pressure (kPa)	Airspeed (km h^{-1})	Target VMD[a] (μm)
1	Electrostatic off	100	9.4	TXVK-8	0	483	209	200
2	Electrostatic on	100	9.4	TXVK-8	0	483	209	200
3	CP-11TT	39	28.1	15	0	241	210	350
4	AU-5000	8	28.1	VRU = Max[b]	Blade-65	241	177	350
5	Untreated check	N/A	N/A	N/A	N/A	N/A	N/A	N/A

a VMD or $D_{V0.5}$ is the volume median diameter which is the diameter of droplet such that 50% of the total volume of droplets is in droplets of smaller diameter; values were estimated using the USDA-ARS Spray Quality model (Kirk, 2007).
b VRU is the variable rate unit for the Micronair au-5000 and is used to adjust flowrate to the nozzle. Max is the full open setting.

reflectance values at the 680 nm wavelength in the red region and the 800 nm wavelength in the NIR region were used to calculate the narrowband NDVI for each spectral measurement (Castro-Esau et al., 2006). An ANOVA test was also carried out based on the NDVI data measured with the FieldSpec®. All the field tests were conducted between 12:00 to 14:00 at 1, 8, and 17 days following aerial treatment (DAT).

3. Results and discussion

3.1. *Greenseeker® NDVI*

The ANOVA test results on DAT 1 and DAT 8 did not show any significant difference among treatment means. The ANOVA test on DAT 17 is shown in Table 2. Nozzle type had a significant effect on glyphosate efficacy ($p = 0.0315$ at $\alpha = 0.05$). The normal plot of residuals and the residuals vs predicted value plot were checked and there was no severe indication of non-normality, nor was there any evidence pointing to possible outliers.

The analysis indicated a significant difference in treatment means, so the comparisons between paired treatments were conducted using Tukey's HSD (Honestly Significant Difference) in *R* (Table 3). Only treatment 3 was significantly different from treatment 5 at $\alpha = 0.1$ level. There was no significant difference between the other two treatments.

3.2. *FieldSpec® spectral reflectance*

The ANOVA test results for DAT 1 and DAT 8 did not show any significant difference among treatment means. The ANOVA test results on DAT 17 are presented in Table 4. Nozzle type had a significant effect on glyphosate efficacy ($p = 0.0002$ at $\alpha = 0.01$ level). The result of Tukey's HSD (Table 5) reported that treatment 2, 3 and 4 were significantly different from treatment 5 at $\alpha = 0.01$ level; treatment 1 was significantly different from treatment 3 and 5 at $\alpha = 0.05$ level; and treatment 1 was significantly different from treatment 4 at $\alpha = 0.1$ level. The result did not show any difference between treatments 1 and 2, 2 and 3, 2 and 4, and 3 and 4. Therefore, conventional flat-fan nozzles and rotary atomisers had better performance than the electrostatic nozzles with charging off. There was no evidence that the electrostatic nozzle with charging on was better than the electrostatic nozzles with charging off.

Table 3 – Tukey's HSD (Greenseeker® data).

Treatment[a]	Mean difference	d.f.	Standard error	t for H_0 Coeff = 0	Prob > |t|
1 vs 2	0.066	1	0.029	2.26	0.2505
1 vs 3	0.083	1	0.029	2.87	0.1117
1 vs 4	0.065	1	0.029	2.24	0.2579
1 vs 5	−0.015	1	0.029	−0.53	0.9821
2 vs 3	0.018	1	0.029	0.61	0.9698
2 vs 4	−6.667E-004	1	0.029	−0.023	0.9999
2 vs 5	−0.081	1	0.029	−2.78	0.1250
3 vs 4	−0.018	1	0.029	−0.63	0.9657
3 vs 5	−0.099	1	0.029	−3.39	**0.0545***
4 vs 5	−0.080	1	0.029	−2.76	0.1289

* Significant at $\alpha = 0.1$ level.
a Treatment 1: electrostatic (off); treatment2: electrostatic (on); treatment 3: CP-11TT; Treatment 4: AU-5000; treatment 5: control.

The average spectral reflectance values obtained by the FieldSpec® spectroradiometer for each treatment plot from three replicates at DAT 1, DAT 8 and DAT 17 are shown in Fig. 3, Fig. 4 and Fig. 5, respectively. Overall changes within the study field were observed from the shapes of the reflectance curves. Overall decreases in healthy weed area due to herbicidal control resulted in an increase in the blue and red reflectance and a decrease in the NIR reflectance. Since the soil type of the study field was the same, the effect of soil property was not a factor. As shown in Fig. 3, the spectral reflectance responses from five treatment plots were similar at DAT 1. Treatment 3 had higher reflectance both in the visible and NIR wavelength regions at DAT 8 (Fig. 4). At 17 days after treatment, there was a significant increase in the visible reflectance under treatment 3 (Fig. 5). Compared to DAT 1, the reflectance at DAT 17 increased from about 8% to 20% in the blue region, 15%–38% in the green region, and 15%–30% in the red region. Basically, changes in the reflectance in the NIR region were not significant. Treatment 2 and 4 were comparable. It should be noted that at DAT 17, the untreated control (TRT5) had the smallest reflectance in the visible region but the largest reflectance in the NIR. It was concluded that glyphosate herbicide efficacy under different aerial spray treatments could be differentiated from spectral responses over the visible and NIR spectrum regions.

Table 2 – Analysis of variance test result on DAT 17 (Greenseeker®).

Source	Degree of freedom	F-Value	P-value (Prob > F)
Block	2		
Model	4	4.62	0.0315 significant
A-Treatment	4	4.62	0.0315
Residual	8		
Cor total	14		
Std. Dev.	0.036	R^2	0.6981
Mean	0.26	R^2_{adj}	0.5471

Table 4 – Analysis of variance test result on DAT 17 (FieldSpec® data).

Source	Degree of freedom	F-Value	P-value (Prob > F)
Block	2		
Model	4	21.38	0.0002 significant
A-Treatment	4	21.38	0.0002
Residual	8		
Cor total	14		
Std. Dev.	0.029	R^2	0.9145
Mean	0.17	R^2_{adj}	0.8717

Table 5 – Tukey's HSD (FieldSpec® data).

Treatment[a]	Mean Difference	df	Standard error	t for H_0 Coeff = 0	Prob > |t|
1 vs 2	0.044	1	0.024	1.86	0.4046
1 vs 3	0.098	1	0.024	4.15	0.0198**
1 vs 4	0.076	1	0.024	3.22	0.0690***
1 vs 5	−0.097	1	0.024	−4.12	0.0206**
2 vs 3	0.054	1	0.024	2.28	0.2427
2 vs 4	0.032	1	0.024	1.36	0.6685
2 vs 5	−0.14	1	0.024	−5.98	0.0022*
3 vs 4	−0.022	1	0.024	−0.93	0.8784
3 vs 5	−0.19	1	0.024	−8.27	0.0002*
4 vs 5	−0.17	1	0.024	−7.34	0.0005*

* Significant at $\alpha = 0.01$ level.
** Significant at $\alpha = 0.05$ level.
*** Significant at $\alpha = 0.1$ level.
a Treatment 1: electrostatic (off); treatment2: electrostatic (on); treatment 3: CP-11TT; Treatment 4: AU-5000; treatment 5: untreated check.

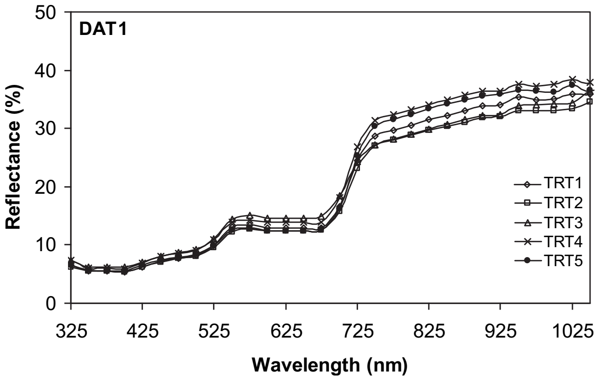

Fig. 3 – Average spectral reflectance curves for each treatment plot from three replicates at DAT 1.

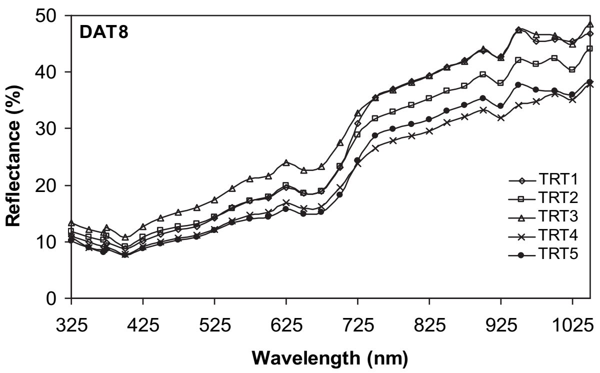

Fig. 4 – Average spectral reflectance curves for each treatment plot from three replicates at DAT 8.

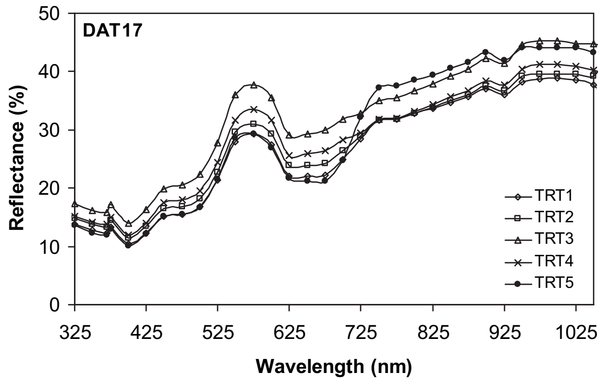

Fig. 5 – Average spectral reflectance curves for each treatment plot from three replicates at DAT 17.

4. Conclusions

The ANOVA test results of NDVI measurements from the Greenseeker® and Fieldspec® collected data on DAT 1 and DAT 8 did not show any difference among treatments; however, a significant difference among treatment means on DAT 17 was observed. All the glyphosate application treatments provided effective weeds control as compared to untreated areas at DAT 17. The Tukey's HSD result of the Greenseeker® data shows that there was no significant difference between any other two treatments except for treatment 3 and untreated area. The Tukey's HSD test result of NDVI measurements from the FieldSpec® shows that applications using CP-11TT flat-fan nozzles and AU-5000 rotary atomisers were more efficacious in controlling weed populations than the electrostatic nozzles with charging off; but no evidence was available to show that electrostatic nozzles with charging on was better than the electrostatic nozzles with charging off. Based on the analysis of spectral reflectance measurements with the FieldSpec® spectroradiometer, the overall changes within the study field were observed from the shapes of the reflectance curves. Glyphosate herbicidal efficacy under different aerial spray treatments could be differentiated from spectral responses over the visible and NIR spectrum regions. At DAT 17, treatment 3 had the highest spectral reflectance in the visible wavelength bands.

Overall, the ground-based spectral reflectance data could be used to assess the glyphosate efficacy applied with different aerial spray technologies. This research showed that reflectance data obtained from ground-based platform can be used to compare treatment performance for aerial herbicide application using different nozzle technologies. For this study, aerial herbicide applications performed within product label recommendations and were efficacious, regardless of the nozzle technology employed.

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