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APPLICATION CARRIER VOLUME: A COMPREHENSIVE EVALUATION OF AN ULTRA-LOW VOLUME SPRAYER COMPARED TO A CONVENTIONAL SPRAYER FOR ROW-CROP AND TURFGRASS PRODUCTION SYSTEMS

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APPLICATION CARRIER VOLUME: A COMPREHENSIVE EVALUATION OF AN
ULTRA-LOW VOLUME SPRAYER COMPARED TO A CONVENTIONAL
SPRAYER FOR ROW-CROP AND TURFGRASS PRODUCTION SYSTEMS

by

J. Connor Ferguson

A THESIS

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Greg R. Kruger

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APPLICATION CARRIER VOLUME: A COMPREHENSIVE EVALUATION OF AN
ULTRA-LOW VOLUME SPRAYER COMPARED TO A CONVENTIONAL
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University of Nebraska, 2013

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An Ultra-Low Volume (ULV) sprayer was developed to decrease carrier volume required for pesticide applications in row and turfgrass cropping systems. The ULV sprayer can make spray applications at or below 19 L ha^{-1} , which is far lower than a conventional sprayer in row crop or turfgrass production systems. Field studies were conducted at the University of Nebraska West Central Research and Extension Center Dryland Farm near North Platte, NE and the John Seaton Anderson Turfgrass Research Facility near Mead, NE to compare the ULV sprayer to a conventional sprayer. Studies were conducted to compare the two sprayers with herbicide applications, fungicide applications, and foliar fertilizer applications.

The row crop studies were applied over plots planted to six different species. Plant species used were non-glyphosate-resistant (*Zea mays* L.) non-glyphosate-resistant soybeans (*Glycine max* (L.) Merr.), amaranth (*Amaranthus hypochondriacus* L.), quinoa (*Chenopodium quinoa* Willd.), velvetleaf (*Abutilon theophrasti* Medik.), and green foxtail (*Setaria viridis* (L.) Beauv.). Each of these species were harvested and dried to compare dry weight reductions from the herbicide applications. The row crop studies were conducted in the summer of 2011 and the summer of 2012. The row crop studies also compared droplet size and distribution on a laser diffraction instrument to correlate droplet size and efficacy in the comparison of the two sprayers. In general the ULV sprayer had a different droplet spectrum from the conventional sprayer, but differences in the droplet size did not reveal a difference in the dry weight reductions across the row crop studies over both years.

The turfgrass studies were conducted in one of three different turfgrass systems: a mixed stand of Kentucky bluegrass (*Poa pratensis* L.) and perennial ryegrass (*Lolium perenne* L.); a uniform stand of tall fescue (*Festuca arundinacea* Schreb.); or a creeping bentgrass 'L-93' (*Agrostis stolonifera* L.) system managed to fairway height. The turfgrass studies were conducted in the spring and summer of 2012. Differences were not observed between the two sprayers across all of the turfgrass studies.

The ULV sprayer appears to be a useful option for a variety of spray applications in row crop and turfgrass production systems.

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TABLE OF CONTENTS

ACKNOWLEDGMENTS	i
TABLE OF CONTENTS.....	ii
LIST OF TABLES	iii
LIST OF FIGURES	v
CHAPTER 1: Effect of Application Carrier Volume on a Conventional Sprayer System and an Ultra-Low Volume Sprayer	1
CHAPTER 2: A Study of Polyethylene Oxide Concentrations and Efficacy of a 1,061 g ae ha ⁻¹ Glyphosate Solution between a Conventional Sprayer and an ULV Sprayer.....	14
CHAPTER 3: Comparison of Herbicide Efficacy and Adjuvants Using a Conventional Sprayer and an Ultra-Low Volume Sprayer	23
CHAPTER 4: Additional Laser Diffraction Tests with an ULV Sprayer	43
CHAPTER 5: Pre and Postemergence Herbicides on Weed Suppression in Established Turfgrass with a Conventional Sprayer and an Ultra-Low Volume Sprayer	54
CHAPTER 6: Effect of Application Carrier Volume on Crop Input and Fungicide Applications in Turfgrass with a Conventional Sprayer and an Ultra-Low Volume Sprayer.....	67
LITERATURE CITED.....	82

LIST OF TABLES

Table 1: Dry weight data for six species in 2011 and two species in 2012 by carrier volume and sprayer type.....	8
Table 2: Droplet size spectra from a laser diffraction instrument of conventional sprayer and ULV sprayer treatments by carrier volume tank mixes.....	11
Table 3: Dry weight reductions with PEO additions to a 1,061 g ae ha ⁻¹ solution with a conventional sprayer and an ULV sprayer.....	18
Table 4: Droplet size spectra from a laser diffraction instrument of PEO additions with a conventional sprayer and an ULV sprayer.....	20
Table 5: Dry weight data for three species in 2011 by active ingredient that resulted in sprayer type differences in dry weight reductions.....	33
Table 6: AI study herbicides with dry weight differences and its respective droplet sizes as analyzed by a laser diffraction instrument.....	36
Table 7: Adjuvant study treatments across pressures and its respective droplet sizes as analyzed by a laser diffraction instrument.....	36
Table 8: Adjuvant study adjuvant additions across pressures and their respective droplet sizes as analyzed by a laser diffraction instrument.....	38
Table 9: A selected fixture at a sampling of pressures across all three pump speeds and the droplet spectra from a laser diffraction instrument.....	48
Table 10: Fixture 105M its droplet spectrum across three different solutions at selected pressures across three pump speeds.....	50
Table 11: Selected fixtures and their droplet spectrum in three positions with water and a constant pump speed of 450 RPM.....	51
Table 12: Effect of four herbicide control methods of dandelion, ground ivy and large crabgrass in a turfgrass cropping system across both sprayer types at Mead, NE.....	63
Table 13: Effect of foliar treatments on chlorophyll content, NDVI percentage and dry weights on a creeping bentgrass green between the two sprayers in 2011 and 2012.....	74

LIST OF TABLES CONTINUED

Table 14: Weather conditions at the John Seaton Anderson Turf Research Facility near Mead, NE during the foliar fertilizer trial in 2011 and 2012.....	76
Table 15: Brown patch infection on a creeping bentgrass fairway when treated with propiconazole and azoxystrobin with a conventional and ULV sprayer.....	77

LIST OF FIGURES

Figure 1: Kamterter ULV Sprayer for Row Crop Spray Applications.....	2
Figure 2: Kamterter ULV Fixture Diagram.....	3
Figure 3: Kamterter ULV Sprayer for Agronomic Spray Applications.....	26
Figure 4: Kamterter ULV Sprayer Fixture Diagram.....	27
Figure 5: Kamterter ULV Sprayer Fixture Diagram.....	56
Figure 6: Dandelion counts at 0, 14, 28, and 56 DAT.....	62
Figure 7: Crabgrass control at 0, 14,28 and 56 DAE.....	65

Chapter 1.

Effect of Application Carrier Volume on a Conventional Sprayer System and an Ultra-Low Volume Sprayer

Introduction

Spray application technology continues to improve pesticide applications through new developments in formulation, adjuvant, sprayer, and nozzle technologies. A spraying system with pressurized liquid lines that force the liquid through a small orifice on the nozzle has been the convention in application technology since its development almost 70 years ago (Arle 1954). Most developments in application technology have improved on issues within the pressure-through-orifice spraying system rather than to engineer a new method of spray applications. Benefits of low-volume spray technologies in agronomic situations first appeared in publications in 1985 (Bode et al. 1985). Bode et al. (1985) described the drawbacks of conventional sprayer technology in how nozzle orifices can become blocked with viscous spray solutions. The ultra-low-volume technology tested in the study was an electrostatic sprayer system and a rotary atomizer. They further observed that an effective ultra- low-volume sprayer would have tremendous benefits for pesticide applications. Prior to this time, ultra-low-volume applications were used primarily for insect control in horticultural cropping systems (Sayer 1959). An ultra-low-volume sprayer was first patented in 1969 (Blue et al. 1969), but was not widely adopted, as most of the research after this patent focused on improving the already accepted pressure-through-orifice model.

Kamterter Products LLC in Waverly, NE, has developed an ultra-low-volume (ULV) sprayer to attempt to improve pesticide application efficiency through sprayer engineering (Figure 1). The system uses the interaction of two kinetic energy fluids – a gas and a liquid, to atomize and apply ultra-low-volumes of spray solutions. The system was designed to handle rates as low as 9.5 L ha^{-1} (Eastin and Vu 2012). The sprayer takes a column of liquid and meters it on a spray fixture surface. The liquid is fed by a linear peristaltic positive displacement pump which then combines with an air column at the spray fixture surface that shears the liquid to form droplets.



Figure 1: The Kamterter ULV sprayer for agronomic spray applications was installed on a Massey-Ferguson 135 tractor. The sprayer has three component parts: the peristaltic pump, the air blower and the fixtures. The pump sits directly behind the left rear tire with separate lines that are placed inside of unpressurized bottles that sit in a rack below the white wash-out tank. The blower is located underneath the 2-cycle motor that sits right above the pump and provides the air pressure for the sprayer system. The fixtures are on the boom, which is covered with a hood to compare to the hooded conventional sprayer (not shown) in the study. The liquid lines and air from the blower enter the fixtures separately and interact together at the fixture orifice where they are sheared to form droplets.

The ULV sprayer has the ability to meter liquids with high extensional viscosity and shear thinning fluid characteristics that are incompatible due to the small orifice nozzles used on currently adopted sprayer technologies (Bode et al. 1985, Eastin and Vu 2012) (Figure 2).

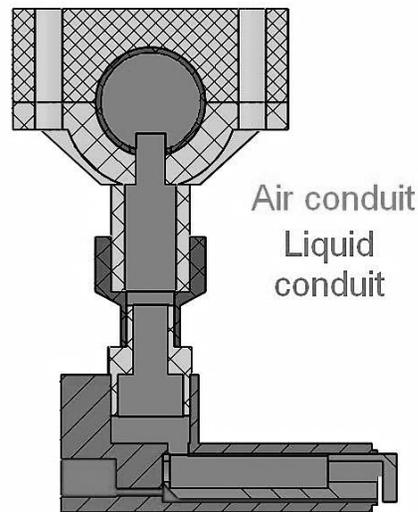


Figure 2: The Kamterter ULV Sprayer fixture diagram showing how the air component and the liquid component interact at the spray fixture surface to form droplets. The liquid conduit enters the fixture through a line in the back of the fixture. The air conduit enters the fixture from the boom through the top of the fixture. The fluids are completely separate until they interact and are sheared off at the fixture orifice to form droplets

Given the larger orifice of the ULV sprayer fixture, spray solutions with certain chemical and colloidal properties can be further investigated that currently would not be feasible with the small orifices used in conventional sprayer technology. Another feature of the system involves a single linear peristaltic pump designed to deliver liquid to each individual spray fixture (Eastin and Vu 2012). The liquid metering is connected to the ground speed of the sprayer, allowing for a constant volume over (per unit area covered) a tenfold range of speeds (Eastin and Vu 2012). The system, unlike a conventional pressure-through-orifice system, does not have pressure on the liquid lines.

The objective of the research was to test how various carrier volumes of a conventional sprayer and the ULV sprayer will impact glyphosate efficacy across six different plant species. Prior studies have identified drift reducing methods during application including lowering the operating pressure during an application (Derksen et al. 1999) or increasing the carrier volume decreases spray drift occurrence (Salyani and Cromwell 1992). The hypothesis for the study is that application carrier volumes will not have an effect on herbicide efficacy for the ULV sprayer, but will have differences for the conventional sprayer in terms of efficacy.

Materials and Methods

A field study at the University of Nebraska-Lincoln: West Central Research and Extension Center Dryland Farm near North Platte, NE was conducted compare a conventional sprayer and an ULV sprayer across nine carrier volumes with 1,061 g ae ha⁻¹ glyphosate (Roundup PowerMax, Monsanto, St. Louis, MO 63167) and a 5% v/v ammonium sulfate (Bronc, Wilbur-Ellis Company, Fresno, CA, 93755) solution. The study was sprayed on July 22nd in 2011 and August 22nd in 2012. Four carrier volumes with the conventional sprayer, five carrier volumes with the ULV sprayer, and an untreated check were arranged in a randomized complete block design with four replications. Treatments with the conventional sprayer were tested at 19, 38, 76, and 152 L ha⁻¹; and treatments with the ULV sprayer were tested at 2.5, 5, 9, 19 and 38 L ha⁻¹. The 19 l ha⁻¹ treatment was applied with an XR11001 nozzle (Teejet Technologies, Wheaton, IL 60187) at a pressure of 103 kPa for and a speed of 10 km h⁻¹. The 38 L ha⁻¹ treatment was applied with an XR110015 nozzle (Teejet Technologies, Wheaton, IL 60187) at a

pressure of 207 kPa and a speed of 10 km h⁻¹. The 76 L ha⁻¹ treatment was applied with an XR110025 nozzle (Teejet Technologies, Wheaton, IL 60187) at a pressure of 241 kPa and a speed of 9 km h⁻¹. The 152 L ha⁻¹ treatment was applied with an XR11004 nozzle (Teejet Technologies, Wheaton, IL 60187) at a pressure of 290 kPa and a speed of 7 km h⁻¹. The ULV sprayer treatments were applied at each of the respective volumes using the same proprietary fixtures at an air pressure of 6 kPa. The 2.5 L ha⁻¹ treatment was applied at a speed of 21 km h⁻¹. The 5 L ha⁻¹ treatment was applied at a speed of 11 km h⁻¹. The 9 L ha⁻¹ treatment was applied at a speed of 9 km h⁻¹. The 19 and 38 L ha⁻¹ treatments were applied at a speed of 8 km h⁻¹. The field study was applied over a 12 row plot planted to six different plant species in two row increments at 76 cm spacing. Plant species used were non-glyphosate-resistant corn (*Zea mays* L.) non-glyphosate-resistant soybeans (*Glycine max* (L.) Merr.), amaranth (*Amaranthus hypochondriacus* L.), quinoa (*Chenopodium quinoa* Willd.), velvetleaf (*Abutilon theophrasti* Medik.), and green foxtail (*Setaria viridis* (L.) Beauv.). At four weeks after treatment, five plants of each species per plot were harvested and dried at 60°C for 48 hours and dry weights were recorded. Only plants that were still living at the time of harvest were collected. Plant populations in each plot that underwent full necrosis from the glyphosate application were not harvested but recorded as zero grams per plant for dry weight measurements.

Laser diffraction comparison of spray droplet size

Each treatment was analyzed on a laser diffraction instrument (Sympatec Varios KF Sympatec Inc., Pennington, NJ 08534) to measure relative particle size and compared each volume and solution to an XR11003 nozzle (Teejet Technologies, Wheaton, IL

60187) at 300 kPa. The spraying parameters selected for discussion were the Dv50 which is the median droplet size in the spectrum, the percentage of droplets less than 210 μm , and the relative span. The relative span is defined as the $(Dv90 - Dv10) / Dv50$, which is better defined as the 10th percentile droplet size in μm subtracted from the 90th percentile droplet size and divided by the Dv50.

Statistical Parameters

The dry weight data were converted to one plant per plot and analyzed using a general linear mixed model with replication as the random variable and sprayer type and carrier volume as the fixed variables. Each species was analyzed separately. The main effect variables analyzed were sprayer type and carrier volume with carrier volume by sprayer type as the simple effect variable. The Tukey-Kramer adjustment was implemented to insure that differences were correctly reported. The two years of data were different ($p < 0.0001$). Thus we analyzed the data from each year separately. Soybean did not have a difference in year so it was analyzed together. The spray droplet size data were analyzed using a mixed model with replication as the random variable and sprayer type and carrier volume as the fixed variables. The main and simple effect variables were the same as the dry weight data. The Tukey-Kramer adjustment was also implemented. The data for both studies were analyzed in SAS (Statistical Analysis System (SAS) software, Version 9.2. SAS Institute, Inc., Cary, NC 27513) with a significance of $\alpha=0.05$.

Results

In 2011, there were no overall sprayer differences, though there were interactions at the simple effects level with differences between sprayer by treatment. The p values for sprayer type in 2011 ranged from 0.28 to 1.00. For corn, all treatments were similar except for the 5 L ha⁻¹ treatment with the ULV sprayer (Table 1). For corn in 2012, there was an overall main effect difference in sprayer type (p value = 0.03). Soybean data were combined for both years and showed had a main effect difference in sprayer type (p value = 0.0040). That difference was observed in the conventional sprayer treatments in 2012. The ULV treatments were similar across both years (Table 1). The reductions in dry weight from 2011 were not correlated to sprayer type and differed in each species. For amaranth and foxtail, the only treatment that was different was the 152 L ha⁻¹ treatment with the conventional sprayer. For velvetleaf the two different treatments were the 38 L ha⁻¹ treatment with the conventional sprayer and the 5 L ha⁻¹ treatment with the ULV sprayer but these treatments were similar to one another (Table 1). No differences were observed in dry weight reductions with quinoa. Since only corn and soybeans emerged consistently across the plots in 2012, data on amaranth, quinoa, foxtail and velvetleaf data were not collected. Due to a change in the peristaltic positive displacement pump, the 2.5 L ha⁻¹ carrier volume treatment was not applied in 2012.

Table 1: Dry weight data for six species in 2011 and two species in 2012 by carrier volume and sprayer type.

Carrier Volume	Sprayer Type	Corn	Soybean	Amaranth	Quinoa	Velvetleaf	Foxtail	Corn	Soybean
L ha ⁻¹		2011						2012	
		g						g	
Check		16.24	2.33	1.67	1.70	3.51	20.41	62.06	9.93
152	Conventional	1.63 a	1.10	2.17 b	0.16	1.15 ab	4.30 b	31.13	5.12 b
76	Conventional	0 a	1.42	0.63 a	0	0.54 a	0 a	30.51	5.21 b
38	Conventional	0 a	1.35	0.86 ab	0	1.48 b	0 a	27.10	4.60 b
19	Conventional	9.15 ab	1.83	0.40 a	0	0.07 a	0 a	13.50	4.39 b
38	ULV	1.94 a	0.50	1.03 ab	0.43	0.18 a	0 a	25.55	1.89 a
19	ULV	4.19 a	1.15	1.38 ab	0	0.92 a	0 a	49.73	1.72 a
9.5	ULV	2.88 a	0.91	0.76 ab	0	0.85 a	0 a	23.87	1.67 a
5	ULV	19.00 b	1.28	1.85 ab	0	1.54 b	0 a	22.92	1.12 a
2.5	ULV	0 a	1.03	1.42 ab	0	0.92 a	0 a	-*	-*

The dry weights were equalized to one plant per plot and analyzed across treatments. The dry weights are separated by letters (simple effect differences) if no main effect differences were observed. Quinoa had no differences of any kind and is thus not separated with letters. Soybean differences in 2011 and corn differences in 2012 were observed as a main effect difference and are not thus broken out by letter designation.

* - The 2.5 l ha⁻¹ treatment was not applied in 2012 due to a change in peristaltic pump that prevented the application of that carrier volume.

Laser diffraction results

There was a positive linear correlation with droplet size and carrier volume for the conventional and ULV sprayers. The relative span is the only main effect difference between the droplet spectra of the two sprayers where the ULV sprayer had a relative span with a value twice that of the conventional sprayer across treatments. The largest Dv50 was with the 152 L ha⁻¹ treatment with the conventional sprayer with a 241 µm median droplet size, which was 130 µm larger than the smallest Dv50 (the 2.5 L ha⁻¹ treatment with the ULV sprayer) at 111 µm (Table 2). At the 38 L ha⁻¹ carrier volume the ULV sprayer had a Dv50 that was 60 µm larger than the conventional sprayer (199 µm to 136µm respectively). At the 19 L ha⁻¹ treatment the ULV sprayer had a Dv50 of 162 µm which was similar to the conventional sprayer which had a Dv50 of 163 µm. The percent of droplets less than 210 µm was linearly correlated with carrier volume for both sprayers. Higher carrier volumes had a lower percentage of fine droplets than the lower carrier volumes. The ULV sprayer had a lower percentage of droplets less than 210 µm than the conventional sprayer at the 38 and the 19 L ha⁻¹ treatments. The 38 L ha⁻¹ carrier volume treatment was the exception throughout with respect to the Dv50 and the percent of droplets less than 210µm. This is most likely due to the XR110015 nozzle run at 207 kPa. The small orifice at the higher pressure created a smaller Dv50 and percent of droplets less than 210 µm when compared to other carrier volumes within the conventional sprayer treatments. The 19 L ha⁻¹ treatment with the conventional sprayer had a larger Dv50 and fewer fine droplets than the 38 L ha⁻¹ even with the smaller orifice size of the XR11001 nozzle. The lower pressure for the 19 L ha⁻¹ treatment applied at only 103 kPa as opposed

to the 38 L ha⁻¹ treatment applied at 207 kPa resulted in a similar median droplet size for both sprayers as expressed as the Dv50 in Table 2. The reference nozzle at 300 kPa and 94 L ha⁻¹ across all treatments had a Dv50 of 145 µm, which was similar to the ULV fixture at 6 kPa and 9.5 L ha⁻¹ with a Dv50 of 144 µm. Additionally, the percentage of droplets smaller than 210 µm was similar between the reference nozzle at 300 kPa and 94 L ha⁻¹ across all treatments and the ULV fixture at 6 kPa and 5 L ha⁻¹. The relative span indicates that the two sprayers are not identical with respect to droplet spectra even though similarities exist within the previously described droplet spectra parameters.

Table 2: Droplet size spectra from a laser diffraction instrument of conventional sprayer and ULV sprayer treatments by carrier volume tank mixes.

Carrier volume L ha ⁻¹	Nozzle	Sprayer type	Spray Pressure		Dv50 µm	RS	% < 210 µm %
			kPa	(psi)			
94	XR11003	Reference	300	(43.5)	145 e-h	1.67 d	72 ijk
152	XR11004	Conventional	290	(42)	241 a	1.31a	41 a
76	XR110025	Conventional	241	(35)	162 c	1.58 cd	66 d
38	XR110015	Conventional	207	(30)	136 h	1.49 bc	79 l
19	XR11001	Conventional	103	(15)	163 c	1.43 ab	67 def
38	Proprietary	ULV	6	(1)	199 b	2.46 e	53 b
19	Proprietary	ULV	6	(1)	162 c	2.89 fg	62 c
9.5	Proprietary	ULV	6	(1)	144 e-h	2.78 f	66 d
5	Proprietary	ULV	6	(1)	123 i	2.85 f	71ghi
2.5	Proprietary	ULV	6	(1)	111 j	3.06 g	74 jk

The letters represent differences between the treatments and their corresponding droplet parameters with an $\alpha=0.05$

The difference in relative span of the two spray droplet spectra might reveal performance variations in a drift study, but such research has yet to be conducted at this point.

Discussion and Conclusions

Carrier volume is a key factor to maximize efficacy in spray applications of some pesticides (Whisenant et al. 1993). The RoundUp Powermax label specifies that ground applications be applied with a carrier volume of at least 28 L ha⁻¹ for field applications (anonymous 2012a). The results show that carrier volume does not influence the efficacy of glyphosate between 2.5 and 38 L ha⁻¹ with the ULV sprayer and between 19 and 152 L ha⁻¹ with the conventional sprayer. Results from 2012 show that ULV sprayer treatments had greater reduction in dry weights than the conventional sprayer treatments even at reduced carrier volumes. Further research is needed to determine if droplet size or droplet concentration increases the efficacy of glyphosate. Though the ULV sprayer treatments were applied at a lower carrier volume, the amount of glyphosate applied per area was the same across carrier volumes. The concentration of glyphosate per droplet was higher in the lower carrier volumes to maintain the 1,061 g ae ha⁻¹ glyphosate rate maintained in each treatment. The differences in carrier volume did not affect the application rate of glyphosate, but did change the droplet size characteristics in both sprayers. Glyphosate efficacy has been shown to be effective even at reduced carrier volumes (Jordan 1981) which confirm the findings from the study.

There has yet to be research conducted as to the drift potential of the ULV sprayer as compared to the conventional sprayer and this question must be addressed in future

research before widespread adoption of this new technology. Current drift models are not sufficient to predict drift with the ULV sprayer as algorithms and parameters are designed for the conventional sprayer and are not yet available for this technology. AgDISP[®], AgDRIFT[®], DropKick[®], and SpraySafe Manager[®] are currently accepted drift models for aerial application, and have been used previously for ground-based application (Hewitt 2000). AgDRIFT[®] 1.0 developed a basic model for ground application as well. The models though are based on conventional spraying technology and assume flow-rates that are above that used by ULV sprayer technology (Schleier et al. 2012). ULV sprayer technology is not suited for these models so drift has to be analyzed using a large field trial (Schleier et al. 2012). Absent of a large scale field drift study, drift predictions can only be surmised based on the droplet data from the laser diffraction instrument collected in this study. The technology will increase the possibilities for new adjuvant and formulation development to be undertaken by industry and independent researchers to further hone this new spray technology. The ULV sprayer is comparable to the conventional sprayer even with a different droplet formation system and general application engineering throughout. An ULV sprayer with reduced carrier volumes will provide growers and applicators an effective tool for weed control. The efficiency of application with the ULV sprayer will improve weed control regimes.

Chapter 2.

A study of polyethylene oxide concentrations and efficacy of a 1,061 g ae ha⁻¹ glyphosate solution between a conventional sprayer and an ULV sprayer

Introduction

Polyethylene oxide (PEO) is a water soluble resin that is used in agriculture, construction materials, cosmetics, mining, and the pharmaceutical industry (anonymous 2002). PEO is used in the agricultural industry primarily as an adjuvant to increase spray particle size and reduce drift in a spray solution. It is well established that spray particle size influences spray drift (Hewitt 1997, Yates et al. 1976, Bouse et al. 1988, Bird et al. 1996, Carlsen et al. 2006), so the study will measure how this water soluble drift reduction agent affects glyphosate efficacy and median droplet size. Drift reducing adjuvants reduce spray drift as they increase spray solution viscosity (Nuyttens et al. 2011). The hypothesis is that the PEO at a given concentration will increase mean droplet size but will not lessen the efficacy of the 1,061 g ae ha⁻¹ glyphosate solution.

Materials and Methods

A field study at the University of Nebraska-Lincoln: West Central Research and Extension Center Dryland Farm near North Platte, NE was conducted to compare dry weight reductions from glyphosate between an ULV sprayer and a conventional sprayer. The study compared four concentrations polyethylene oxide (POLYOX WSR N-750, Dow Chemical Company, Midland, MI) mixed to a 2% solution in ethanol and then added at 50, 100, 200, and 400 ml creating solutions of 5, 10, 20 and 40% PEO v/v respectively to

a 1,061 g ae ha⁻¹ glyphosate (Roundup PowerMax, Monsanto, St. Louis, MO 63167) and a 5% v/v ammonium sulfate (Bronc, Wilbur-Ellis Company, Fresno, CA, 93755) solution. The study contained five treatments for each sprayer and an untreated check (11 total treatments) arranged in a randomized complete block design with four replications. Treatments with the conventional sprayer were applied at 76 L ha⁻¹ with XR11003 nozzles (Teejet Technologies, Wheaton, IL, 60187) at a pressure of 255 kPa and a speed of 8 km h⁻¹. Treatments with the ULV sprayer were applied at 19 L ha⁻¹ with proprietary nozzles at an air pressure of 6 kPa and a speed of 8 km h⁻¹. The ULV sprayer has negligible liquid pressure which differs from the conventional sprayer. The field study was applied over 12 row plots planted to six different plant species in two row increments at 76 cm spacing. Plant species used were non-glyphosate-resistant corn (*Zea mays* L.) non-glyphosate-resistant soybeans (*Glycine max* (L.) Merr.), amaranth (*Amaranthus hypochondriacus* L.), quinoa (*Chenopodium quinoa* Willd.), velvetleaf (*Abutilon theophrasti* Medik.), and green foxtail (*Setaria viridis* (L.) Beauv.). Five plants of each species in each plot were harvested at four weeks after treatment and dried for 48 hours at 60°C. Additionally, each treatment was analyzed on a laser diffraction instrument (Sympatec Varios KF, Sympatec Inc., Pennington, NJ 08534) for its relative particle size. Treatments were compared to a reference treatment at 94 L ha⁻¹ with an XR11003 Nozzle (Teejet Technologies, Wheaton, IL 60187) at 300 kPa.

Statistical Parameters

The dry weight data were converted to one plant per plot and analyzed using a general linear mixed model with replication as the random variable and sprayer type and active ingredient as the fixed variables. Each species was analyzed separately. The main effect variables analyzed were sprayer type and PEO concentration with PEO concentration by sprayer type as the simple effect variable. The Tukey-Kramer adjustment was implemented to insure that differences were correctly reported. The two years of data were different ($p < 0.0001$). Thus we analyzed the data from each year separately. The spray droplet size data were analyzed using a mixed model with replication as the random variable and sprayer type and PEO concentration as the fixed variables. The main and simple effect variables were the same as the dry weight data. The Tukey-Kramer adjustment was also implemented. The data for both studies were analyzed in SAS (Statistical Analysis System (SAS) software. Version 9.2. SAS Institute, Inc, Cary, NC 27513) with a significance of $\alpha = 0.05$.

Results

The two years of data differed in corn where year was significant for corn but was not different in soybeans. For the other four species that did not emerge in 2012, only the 2011 data will be presented. The corn data will be presented separately for each year, but the soybean data will be pooled and reported together.

In three species: amaranth, foxtail, and velvetleaf no main effect or simple effect differences were observed. In quinoa, there were no main effect differences, but a simple

effect difference was noted. The 20% PEO treatment was different between sprayer type where the ULV sprayer had a greater reduction in dry weight than the conventional sprayer (Table 3). In corn, main effect differences were also not observed, but simple effect differences between sprayer type and treatment were noted. The 5% PEO treatment was different between sprayer type where the ULV sprayer had a greater reduction in dry weight than the conventional sprayer (Table 3). The 40% PEO treatment with the conventional sprayer had a greater reduction in dry weight than the ULV sprayer treatment.

In corn in 2012, there was no main effect or simple effect differences observed. In soybean from both 2011 and 2012, there was a main effect in sprayer type where the ULV sprayer treatments decreased dry weight more than the conventional sprayer treatments.

Table 3: Dry weight reductions with PEO additions to a 1,061 g ae ha⁻¹ solution with a conventional sprayer and an ULV sprayer.

PEO Concentration	Sprayer Type	2011						2012	
		Corn	Soybean	Amaranth	Quinoa	Velvetleaf	Foxtail	Corn	Soybean
%		g							
Untreated Check		18.54	1.21	2.17	2.70	8.12	11.90	55.38	8.59
40	Conventional	4.38 ab	1.70	1.57	1.48 bc	3.48	5.00	32.82	4.34
	ULV	22.64 d	1.31	1.38	0.13 ab	2.16	6.07	21.14	0.90
20	Conventional	17.63 bcd	1.80	0.95	1.84 c	2.54	4.04	36.44	2.97
	ULV	1.11 a	2.01	1.08	0 a	0.38	1.16	32.90	0.75
10	Conventional	17.90 bcd	2.58	1.93	1.14 abc	5.10	7.09	28.74	2.92
	ULV	6.37 abc	1.55	0.61	0 a	2.08	0	37.88	1.80
5	Conventional	19.17 cd	2.28	2.26	0.75 abc	4.23	9.08	43.57	4.67
	ULV	4.15 ab	1.72	1.61	0 a	3.31	0	30.72	1.72
0	Conventional	6.98 abc	0.87	1.87	0.66 abc	2.27	0	36.02	1.78
	ULV	10.12 a-d	1.80	0.58	0 a	1.78	0	50.48	3.02

The dry weights were equalized to one plant per plot and analyzed across treatments. The dry weights are separated by letters (simple effect differences) if no main effect differences were observed. Amaranth, velvetleaf, and foxtail in 2011 and corn in 2012 had no differences of any kind and is thus not separated with letters. Soybean differences in 2011 and 2012 were a main effect difference in sprayer type where the ULV sprayer treatments reduced dry weights more than the conventional sprayer treatments and are thus not separated by a letter.

Laser diffraction instrument results

With respect to droplet size and distribution, there were main effect differences observed between the two sprayers with the D_{v50} , percent of droplets less than $210\ \mu\text{m}$ and the relative span. The ULV sprayer had an overall larger D_{v50} than the conventional sprayer. The D_{v50} was PEO concentration dependent, where the largest D_{v50} was observed with the 40% PEO treatment and the smallest D_{v50} was with the 0% PEO treatment (Table 4). The trend observed was that at each respective PEO concentration, the ULV sprayer had a larger D_{v50} than the conventional sprayer. The lone exception was where the 0% PEO treatment had a smaller D_{v50} for the ULV sprayer than the conventional sprayer.

Table 4: Droplet size spectra from a laser diffraction instrument of PEO additions with a conventional sprayer and an ULV sprayer.

PEO Addition	Nozzle	Sprayer Type	Spray Pressure		Dv50	Droplets < 210 μm	RS
			kPa	psi	μm	%	
40	XR11003	Conventional	255	37	333 b	28 b	1.50 ab
	Proprietary	ULV	6	0.87	461 a	19 a	1.37 a
20	XR11003	Conventional	255	37	243 c	42 c	1.65 bc
	Proprietary	ULV	6	0.87	339 b	33 b	1.79 c
10	XR11003	Conventional	255	37	206 cde	51 de	1.64 bc
	Proprietary	ULV	6	0.87	226 cd	48 cd	2.26 d
5	XR11003	Conventional	255	37	184 def	58 ef	1.65 bc
	Proprietary	ULV	6	0.87	193 def	53 de	2.58 e
0	XR11003	Conventional	255	37	171 ef	63 f	1.57 ab
	Proprietary	ULV	6	0.87	151 f	64 f	2.78 f

The letters represent differences between the treatments and their corresponding droplet parameters with an $\alpha=0.05$

The results for the percent of droplets less than 210 μm mirror the D_{v50} results where there was an overall difference between the sprayer types. The ULV sprayer had a lower percentage of droplets less than 210 μm than the conventional sprayer at each respective PEO concentration with the exception of the 0% PEO treatment (Table 4). The results for the relative span were sprayer dependent where the conventional sprayer had a smaller relative span than the ULV sprayer. There was one exception with this data was that the 40% PEO treatment with the ULV sprayer had a smaller relative span than the conventional sprayer at 40% PEO (Table 4). The relative span for the 40% PEO treatment for the ULV sprayer had the smallest observed relative span in the entire study.

Discussion and Conclusions

The dry weight data from the two years of the study indicates that the ULV sprayer does not differ in dry weight reductions with glyphosate when compared to the conventional sprayer, but may be more effective based on the results highlighted in soybean for both years. Among the other species, there was neither main effect nor simple effect differences observed. The percentage of PEO did not lessen dry weight reductions with glyphosate, even at a 40% v/v addition. It appears that PEO additions should equal at least 20% v/v to see a significant improvement in the reduction of fine droplets, because this drastically enhances the spray quality and drift reduction characteristics of the tank mix. There was no difference in dry weight reductions with glyphosate at any PEO concentration.

The droplet size data shows a clear difference between the sprayers where the ULV sprayer has a smaller D_{v50} without the addition of PEO, but a larger D_{v50} with any addition of PEO. The data mirrors that of the comparison between the conventional sprayer and the ULV sprayer with respect to the percentage of droplets less than 210 μm . At PEO additions at or greater than 20% v/v, the ULV sprayer has a lower percentage of fine droplets than the conventional sprayer. There is a twofold increase in the carrier volume between the conventional sprayer and the ULV sprayer, yet the ULV sprayer has fewer driftable fines than the conventional sprayer.

The reason for the larger droplet size of the ULV sprayer when PEO is present in the solution is due to PEO's viscoelastic properties that allow individual droplets to maintain cohesion to one another during the atomization process. Given the larger orifice of the ULV sprayer fixture and the lower air pressure exerted on the solution, the results support what would be expected given the viscoelastic properties of PEO. The conventional sprayer uses a smaller orifice and a greater pressure exerted on the solution which causes a break up of droplets and why absent of PEO, creates an overall larger droplet throughout the spectrum than the ULV sprayer.

Data from the relative span comparison shows a difference between the conventional sprayer and the ULV sprayer. In all but one case, the ULV sprayer has a larger relative span than that of the conventional sprayer, due most likely to larger droplets in the ninetieth to the hundredth percentile area and smaller droplets up to the tenth percentile of the droplet spectrum. The one difference was that the overall lowest relative span was the ULV sprayer treatment with the 40% PEO addition. The relative span gets

much larger for the ULV sprayer treatments as the PEO percentages decrease throughout the study.

Based on the improved droplet spectrum produced by the ULV sprayer with various PEO additions, the new sprayer technology appears to be a useful tool for growers and applicators alike. The fact that dry weight reductions with glyphosate were different, but in a few cases enhanced, gives further credence to the adoption of this new technology. Beyond the sprayer comparison, the data suggests that PEO at any addition up to 40% v/v in glyphosate applications can improve the droplet spectrum by reducing the percentage of fine droplets while maintaining efficacy across a wide range of species.

Chapter 3.

Comparison of Herbicide Efficacy and Adjuvants Using a Conventional Sprayer and an Ultra-Low Volume Sprayer

Introduction

Carrier volume is a key factor to maximize efficacy in spray applications of some pesticides (Whisenant et al. 1993). Pesticides are an integral part of large scale agricultural production with an average annual use rate of over 2.2 billion kg worldwide (Kiely et al. 2004). Spray drift impacts off-target sites, thus it must be considered prior to application (Sciumbato et al. 2005). Pesticide spray drift is defined by the EPA as the physical movement of a pesticide through the air at the time of application or soon thereafter, to any site other than the one intended for application (EPA 1999). The

consequences of pesticide spray drift are well documented. Pesticide spray drift can negatively impact adjoining crops and decrease yield in off-target sites (Reddy et al. 2010). In order to better understand drift, the EPA established a task force to address the topic of pesticide drift and set some basic spraying standards when replicating pesticide drift studies. The EPA's Spray Drift Task Force (SDTF) discovered that particle size is a significant factor that influences spray drift (Hewitt et al. 2002). Spray droplets less than 200 μm are more prone to drift than droplets greater than 200 μm (Zhu et al. 1994).

Different formulations applied with the same pressure, nozzle, and volume can differ in their performance due to differences in physical properties (Reichard et al. 1996). The physical properties of a spray solution can impact the performance of a treatment applied to a field (Hewitt 2007). For example, formulations of glyphosate differ in their physical properties including AI concentration, viscosity, molecular weight, and surface tension, yet maintain a similar drift potential (Kirk 2000). Herbicide manufacturers and applicators utilize spray adjuvants to help increase herbicide efficacy and decrease drift potential of a given spray solution (Sharma and Singh 2001, Woznica et al. 2003). Crop response to a given adjuvant in the biological activity of an identical spray solution can vary from species to species (Spanoghe et al. 2007). Adjuvants can enhance the properties of a spray solution (Lan et al. 2008) and the properties of the selected adjuvants can differ in their physical properties in the solution. Drift reduction adjuvants are intended to increase droplet size (Kirk 2003), and thus a reduction in drift. Drift control agents fundamentally reduce the off-target drift of a given pesticide, however efficacy can be improved as the amount of deposited herbicide can increase with less off-target movement

of spray particles (McMullan 2000). Glyphosate decreases the average particle size of a given spray solution (Mueller and Womac 1997), which favors an increase in spray drift. Adjuvants change droplet size through a given sprayer-nozzle configuration (Miller and Ellis 2000). Dynamic surface tension and other physical properties like viscosity, shear thinning properties, and molecular weight also influence droplet size and can affect spray drift (Hewitt 2007, Miller and Ellis 2000). It has been demonstrated that the droplet size spectrum influences spray drift (SDTF 1997), thus increasing the average spray particle size is the most logical starting point to address spray drift.

Kamterter Products LLC in Waverly, NE, has developed an ultra-low volume sprayer to attempt to improve pesticide application efficiency through sprayer engineering. The system creates an interaction of two kinetic energy fluids a gas and a liquid, to atomize and apply ultra-low volumes of spray solution in an agronomic setting (Figure 3).



Figure 3: The Kamterter ULV sprayer for agronomic spray applications was installed on a Massey-Ferguson 135 tractor. The sprayer has three component parts: the peristaltic pump, the air blower and the fixtures. The pump sits directly behind the left rear tire with separate lines that are placed inside of unpressurized bottles that sit in a rack below the white wash-out tank. The blower is located underneath the 2-cycle motor that sits right above the pump and provides the air pressure for the sprayer system. The fixtures are on the boom, which is covered with a hood to compare to the hooded conventional sprayer (not shown) in the study. The liquid lines and air from the blower enter the fixtures separately and interact together at the fixture orifice where they are sheared to form droplets.

The system was designed to handle rates as low as 9.5 L ha^{-1} (Eastin and Vu 2012). The sprayer takes a column of liquid and meters it on a spray fixture surface. The liquid is fed by a linear peristaltic positive displacement pump which then interacts with an air column at the spray fixture surface that shears the liquid to form droplets (Figure 4).

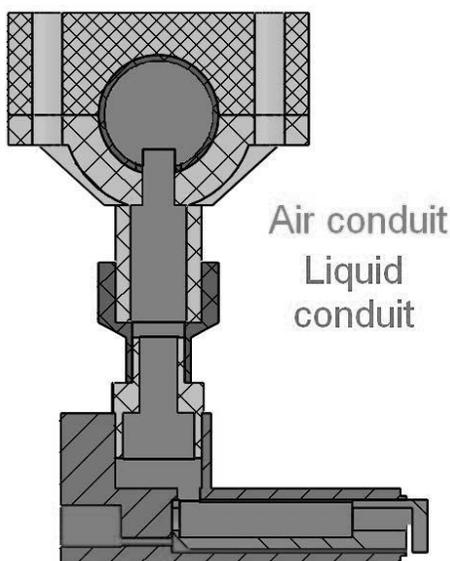


Figure 4: The Kamterter ULV Sprayer fixture diagram showing how the air component and the liquid component interact at the spray fixture surface to form droplets. The liquid conduit enters the fixture through a line in the back of the fixture. The air conduit enters the fixture from the boom through the top of the fixture. The fluids are completely separate until they interact and are sheared at the fixture orifice to form droplets.

Given the larger orifice of the ULV sprayer fixture, spray solutions with certain chemical and colloidal properties can be further investigated that currently would not be feasible with the small orifices used in conventional sprayer technology (Eastin and Vu 2012, Bode et al.1985). Another feature of the system involves a single linear peristaltic pump designed to deliver liquid to each individual spray fixture (Eastin and Vu 2012). The liquid metering is connected to the ground speed of the sprayer, allowing for a constant volume over a tenfold range of speeds (Eastin and Vu 2012). The system, unlike a conventional pressure against an orifice system, does not have pressure on the liquid lines.

The hypothesis of the active ingredient study is that the difference in application carrier volume from the two sprayers across active ingredients will cause a difference in

efficacy and measured droplet size. The adjuvant study hypothesis is that efficacy and droplet size differences will be observed across all four adjuvants and both pressures with the ULV sprayer.

Materials and Methods

Active Ingredient Study

A field study at the University of Nebraska-Lincoln: West Central Research and Extension Center Dryland Farm near North Platte, NE was conducted to compare an ULV sprayer and a conventional sprayer. The study contained ten active ingredients for each sprayer and an untreated check arranged in a randomized complete block design with four replications. The ten herbicides chosen were glyphosate (Roundup PowerMax, Monsanto, St. Louis, MO 63167) at 1,061 g ae ha⁻¹, glufosinate (Liberty, Bayer Crop Sciences, Research Triangle Park, NC 27709) at 449 g ai ha⁻¹, 2,4-D ester (Weedone, Nufarm, Burr Ridge, IL 60527) at 562 g ae ha⁻¹, dicamba (Clarity, BASF Ag Products, Research Triangle Park, NC 27709) at 281 g ae ha⁻¹, atrazine (Atrazine 4L, Tenkoz, Alpharetta, GA 30022) at 1,234 g ai ha⁻¹, saflufenacil (Sharpen, BASF Ag Products, Research Triangle Park, NC 27709) at 50 g ai ha⁻¹, mesotrione (Callisto, Syngenta Crop Protection, Greensboro, NC 27419) at 281 g ai ha⁻¹, chloransulam-methyl (First Rate, Dow AgroSciences, Indianapolis, IN 46268) at 10 g ai ha⁻¹, sodium salt of bentazon (Basagran, Arysta Life Sciences, Cary, NC 27513) at 1,120 g ai ha⁻¹, and clethodim (Select Max, Valent, Walnut Creek, CA 94596) at 136 g ai ha⁻¹. Treatments with the conventional sprayer were applied at 76 L ha⁻¹ with XR11003 nozzles (Teejet Technologies, Wheaton,

IL, 60187) at a pressure of 255 kPa and a speed of 8 km h⁻¹. Treatments with the ULV sprayer were applied at 19 L ha⁻¹ with proprietary fixtures at an air pressure of 6 kPa and a speed of 8 km h⁻¹. The ULV sprayer has no liquid pressure which differs from the conventional sprayer. The field study was applied over 12 row plots planted to six different plant species in two row increments at 76 cm spacing. Plant species used were non-glyphosate-resistant corn (*Zea mays* L.) non-glyphosate-resistant soybeans (*Glycine max* (L.) Merr.), amaranth (*Amaranthus hypochondriacus* L.), quinoa (*Chenopodium quinoa* Willd.), velvetleaf (*Abutilon theophrasti* Medik.), and green foxtail (*Setaria viridis* (L.) Beauv.). Five plants of each species in each plot were harvested at four weeks after treatment and dried for 48 hours at 60°C. Additionally, each treatment was analyzed on a laser diffraction instrument (Sympatec Varios KF, Sympatec Inc., Pennington, NJ 08534) to determine relative particle size and each solution was compared to a reference treatment at 94 L ha⁻¹ with an XR11003 Nozzle (Teejet Technologies, Wheaton, IL 60187) at 300 kPa.

ULV Adjuvant Study

A trial of four drift reducing adjuvants added to a 1,061 g ae ha⁻¹ glyphosate (Roundup PowerMax, Monsanto, St. Louis, MO 63167) and a 5% v/v ammonium sulfate (Bronc, Wilbur-Ellis Company, Fresno, CA, 93755) solution was performed to determine efficacy of these drift reduction materials. The adjuvant trial was only tested with the ULV sprayer using proprietary fixtures at air pressures of 5 and 10 kPa. Treatments were applied at 19 L ha⁻¹ at a speed of 8 km h⁻¹. The study had four adjuvant treatments, a glyphosate only treatment, and an untreated check arranged in a randomized complete

block design with four replications. The adjuvants selected for the study were polyethylene oxide (PEO) (POLYOX WSR N-750, Dow Chemical Company, Midland, MI 48674), hydroxyethyl cellulose (HEC), glycerin, and methylated soybean oil (MSO). The glycerin and methylated soybean oil were both 100% v/v solutions prior to adding at the 10% v/v rate for the treatment. The PEO was mixed at a 25% v/v rate, while all the other adjuvants in the study were mixed at a 10% v/v rate. The PEO was mixed to a 2% v/v solution with water prior to adding at the 25% v/v rate. The HEC was mixed to a 10% v/v solution with water prior to adding at the 10% v/v rate. Treatments were applied over 12 row plots planted to six different plant species (the same as the AI study) in two row increments at 76 cm spacing. Five plants of each species in each plot were harvested at four weeks after treatment and dried for 48 hours at 60°C. Treatments were also analyzed on the laser diffraction instrument for droplet spectra to be identified for the study.

Active Ingredient Study Statistical Parameters

The dry weight data were converted to one plant per plot and analyzed using a general linear mixed model with replication as the random variable and sprayer type and active ingredient as the fixed variables. Each species was analyzed separately. The differences between active ingredients were ignored unless the difference was due to sprayer type as would be expressed in the simple effect variable. The main effect variables analyzed were sprayer type and active ingredient with active ingredient by sprayer type as the simple effect variable. The Tukey-Kramer adjustment was implemented to insure that differences were correctly reported. The two years of data were different ($p < 0.0001$). Thus we analyzed the data from each year separately. The spray droplet size data were

analyzed using a mixed model with replication as the random variable and sprayer type and active ingredient as the fixed variables. The main and simple effect variables were the same as the dry weight data. The Tukey-Kramer adjustment was also implemented. The data for both studies were analyzed in SAS (Statistical Analysis System (SAS) software. Version 9.2. SAS Institute, Inc, Cary, NC 27513) with a significance of $\alpha=0.05$.

Adjuvant Study Statistical Parameters

The dry weight data were converted to one plant per plot and analyzed using a general linear mixed model with replication as the random variable and pressure and adjuvant as the fixed variables. Each species was analyzed separately. The main effect variables analyzed were pressure and adjuvant with pressure by adjuvant as the simple effect variable. The Tukey-Kramer adjustment was implemented to insure that differences were correctly reported. The two years of data were different ($p < 0.0001$). Thus we analyzed the data from each year separately. The spray droplet size data were analyzed using a mixed model with replication as the random variable and pressure and adjuvant as the fixed variables. The main and simple effect variables were the same as the dry weight data. The Tukey-Kramer adjustment was also implemented. The data for both studies were analyzed in SAS (Statistical Analysis System (SAS) software. Version 9.2. SAS Institute, Inc, Cary, NC 27513) with a significance of $\alpha=0.05$.

Results

Active Ingredient Study Dry Weight Results

The dry weight comparison for the active ingredient study in 2011 yielded a difference in sprayer type in soybean (p value = 0.049) where the conventional sprayer treatments showed greater reduction in dry weights than the ULV sprayer treatments. There were no main effect differences across the other four species (p values ranged from 0.09 to 0.85). Corn and quinoa had no main or simple effect differences observed in 2011. In 2012 main effect differences in sprayer type were observed in corn (p value = 0.003) where the conventional sprayer reduced dry weight more than the ULV sprayer across all active ingredients. No differences in sprayer type (p value = 0.59) or simple effect differences of sprayer type by active ingredient were observed in soybean in 2012. Since only corn and soybeans emerged consistently across the plots in 2012, data on amaranth, quinoa, foxtail and velvetleaf data were not collected.

Table 5: Dry weight data for three species in 2011 by active ingredient that resulted in sprayer type differences in dry weight reductions.

Active ingredient	Sprayer type	Rate	Amaranth	Velvetleaf	Foxtail
		g ai ha ⁻¹		2011 g	
Check					
Atrazine	Conventional	1,234	0.86 a	1.96 a	25.05 b-g
	ULV	1,234	1.13 a	8.86 c	9.89 abc
Chloransulam-methyl	Conventional	10	6.69 c	2.73 a	21.32 a-g
	ULV	10	1.98 ab	3.43 a	15.13 a-e
Clethodim	Conventional	136	1.90 ab	8.51 c*	14.14 a-d
	ULV	136	2.20 ab	3.55 a*	39.06 efg

The dry weights were equalized to one plant per plot and analyzed across treatments. Quinoa had no differences of any kind. Soybean differences for 2011 were a main effect difference in sprayer type where the conventional sprayer reduced dry weights more than the ULV sprayer. There were no differences in soybean in 2012. Corn differences in 2012 were observed as a main effect difference and no differences were observed in 2011. Only the active ingredients that resulted in differences were included in the table.

* Clethodim differences in velvetleaf were due to plant variability in plots as clethodim is not active on velvetleaf.

In 2011, differences emerged at the simple effects level with treatment by sprayer differences for the other three species with at least one herbicide. Clethodim efficacy was different in foxtail between the two sprayers, with the conventional sprayer decreasing the dry weight more than the ULV sprayer (Table 5). Atrazine was different in velvetleaf with the conventional sprayer treatment reducing dry weight more than the ULV sprayer. The ULV sprayer had greater efficacy with chloransulam-methyl in amaranth as compared to the conventional sprayer. No differences between sprayer type were observed across all six species for 2,4-D, bentazon, dicamba, glufosinate, glyphosate, mesotrione and saflufenacil.

Adjuvant Study Dry Weight Results

The adjuvant study yielded no difference in dry weight reductions across all six species in all treatments and pressures in 2011. There were no main effect or simple effect differences in corn 2012. In soybean there were no main effect differences but one simple effect difference of pressure by treatment appeared where HEC at 5 kPa reduced dry weight more than HEC at 10 kPa. The HEC treatment at 5 kPa was 3.49 g and the 10 kPa HEC treatment was 8.57 g respectively. The four adjuvant additions to glyphosate did not decrease the efficacy of glyphosate even at the reduced carrier volume of 19 L ha⁻¹

Active Ingredient Study Laser Diffraction Instrument Results

The conventional sprayer and the ULV sprayer had different droplet spectra overall, where there were main effect differences at $\alpha = 0.05$ in sprayer type for Dv50,

percent of droplets less than 210 μm , and relative span. The herbicides that resulted in dry weight differences between the two sprayers: atrazine, chloransulam-methyl, and clethodim also resulted in differences between the two sprayers also for Dv50, percent of droplets less than 210 μm , and relative span (Table 6).

Table 6: AI study herbicides with dry weight differences and its respective droplet sizes as analyzed by a laser diffraction instrument

Active ingredient	Nozzle	Sprayer type	Spray pressure		Dv50	Droplets < 210 µm	RS
			kPa	(psi)	µm	%	
atrazine	XR11003	Conventional	255	(37)	223 ab	46 ab	1.22 a
	Proprietary	ULV	6	(1)	139 hij	68 jk	2.78 b
chloransulam-methyl	XR11003	Conventional	255	(37)	223 ab	46 abc	1.28 a
	Proprietary	ULV	6	(1)	159 f	62 gh	2.82 b
clethodim	XR11003	Conventional	255	(37)	233 ab	42 ab	1.20 a
	Proprietary	ULV	6	(1)	126 j	75 l	2.39 b

The letters represent differences between the treatments and their corresponding droplet parameters with an $\alpha=0.05$

Table 7: Adjuvant study treatments across pressures and its respective droplet sizes as analyzed by a laser diffraction instrument.

Treatment pressure	Nozzle	Sprayer type	Spray Pressure		Dv50	Droplets < 210 µm	RS
			kPa	(psi)	µm	%	
Reference	XR11003	Reference	300	(43.5)	208 a	53 b	1.59 a
5 kPa	Proprietary	ULV	5	(0.72)	211 a	52 a	2.42 b
10 kPa	Proprietary	ULV	10	(1.45)	124 b	73 c	2.58 c

The letters represent differences between the treatments and their corresponding droplet parameters with an $\alpha=0.05$

The herbicides not listed in the table: 2,4-D, bentazon, dicamba, glufosinate, glyphosate, mesotrione, and saflufenacil also resulted in main effect differences between the sprayer types in all three droplet data categories. Those differences though, did not result in dry weight differences between the two sprayers across all six species as referenced in the dry weight data results (Table 5).

Adjuvant Study Droplet Data

The adjuvant study yielded main effect differences in pressure and adjuvant type with respect to the Dv50, percent of droplets less than 210 μm , and relative span. Treatments at 5 kPa had a Dv50 that was twice as large as the 10 kPa pressure, and a lower percent of droplets less than 210 μm compared to the treatments at 10 kPa (Table 7).

The treatments with PEO had the largest Dv50 and the lowest percentage of droplets less than 210 μm compared with the other adjuvant treatments (Table 8). The glyphosate check and the treatments with glycerin were statistically similar in all three measurements. Since this study was just comparing pressures within the ULV sprayer, simple effect results are not going to be addressed. It was observed however, that the treatments with PEO at 5 kPa had the largest Dv50, the lowest percentage of fine droplets and a relative span below 2.

Table 8: Adjuvant study adjuvant additions across pressures and their respective droplet sizes as analyzed by a laser diffraction instrument.

Adjuvant addition	Nozzle	Sprayer type	Spray pressure		Dv50 µm	Droplets < 210 µm %	RS
			kPa	(psi)			
No Adjuvant	Proprietary	ULV	7.5*	(1.08)	142 d	69 d	2.29 c
Glycerin	Proprietary	ULV	7.5*	(1.08)	146 cd	68 d	2.29 c
HEC	Proprietary	ULV	7.5*	(1.08)	189 b	56 b	2.36 c
MSO	Proprietary	ULV	7.5*	(1.08)	157 c	65 c	2.14 b
PEO	Proprietary	ULV	7.5*	(1.08)	271 a	40 a	1.91 a

The letters represent differences between the treatments and their corresponding droplet parameters with an $\alpha=0.05$

Discussions and Conclusions

Active Ingredient Study

Differences observed in dry weight reductions and the droplet size, appear to be linked. The smaller droplet produced by the ULV sprayer (Table 6) reduced efficacy among some active ingredients as compared to the conventional sprayer. The difference though was not observed in more than one broadleaf species for any given active ingredient. No active ingredient resulted in differences between sprayer type in more than one species. Tables 1 and 2 reveal that clethodim efficacy in foxtail was reduced with the lower carrier volume and smaller droplet size from the ULV sprayer. The ULV sprayer clethodim treatments had the smallest Dv50 and the greatest percentage of fine droplets (126 μm and 75 % respectively) observed of any of the treatments. This is contrasted with the conventional sprayer where the clethodim treatment had the largest Dv50 and the fewest fine droplets (233 μm and 42 % respectively) of all treatments. Droplet size differences between the sprayers were consistent throughout the study. Active ingredients that resulted in no sprayer type differences do not appear to be droplet size or carrier volume dependent: 2,4-D, bentazon, dicamba, glufosinate, glyphosate, mesotrione, and saflufenacil.

There were no clear differences between sprayer types with contact active herbicides or systemic herbicides in the study. The three herbicides that resulted in simple effect differences between the two sprayers are all systemic herbicides. Two of those herbicides (atrazine and clethodim) resulted in greater reduction in dry weights for the conventional sprayer treatments in velvetleaf and foxtail respectively. One herbicide

(chloransulam-methyl) resulted in a greater reduction of dry weights for the ULV sprayer in amaranth. The other systemic herbicides: 2,4-D, dicamba, glyphosate and mesotrione did not result in any differences across species between the sprayers in both years.

Bentazon and saflufenacil are contact active herbicides and resulted in no differences between the sprayers across the species. This means that the ULV sprayer did not result in lessened coverage, as these two herbicides are coverage dependent to maximize their efficacy. Glufosinate is not a contact herbicide or systemic herbicide exclusively, and did not result in differences between the sprayers. The active ingredient efficacy difference between these two sprayers appears negligible, thus revealing the usefulness of this new technology.

Adjuvant Study

The adjuvant study revealed that a change in air pressure with this sprayer alters the ULV sprayers' droplet formation system. Though droplet size was decreased with the increase in pressure, dry weight differences were not observed among weed species tested. The dry weight results with respect to the droplet size data for glyphosate compliments the data observed in the active ingredient study where differences in spray droplet size did not result in dry weight differences with some active ingredients including glyphosate.

The adjuvant additions proved to not be a hindrance in glyphosate efficacy when compared to the glyphosate treatment with no adjuvant across all six species in 2011 and in corn and soybean in 2012. The adjuvant addition differences can help to fine tune the application parameters for the ULV sprayer to help to reduce drift without lessening

active ingredient efficacy. Though glyphosate was the only active ingredient tested in this study, we were able to observe that PEO was the most effective adjuvant addition to increase the $Dv50$ of the droplet spectra and reduce fine droplets. The other two useful adjuvant additions were HEC followed by MSO. The glycerin revealed no difference in droplet size when compared to the glyphosate with no adjuvant treatment, thus it is unlikely to reduce drift of glyphosate in a ULV sprayer. It would require further testing to see how these adjuvants affect the deposition and uptake of various active ingredients as glycerin could be useful in minimizing droplet evaporation and increasing canopy penetration and would thus still be a useful addition to the tank mix. Adjuvants can enhance the performance of spray droplets (Lan et al. 2008, Kirk 2003) and can also increase the surface tension and viscosity of the spray which can improve its drift reduction and deposition characteristics (Hewitt 2007, Miller and Ellis 2000).

By selecting the 5 kPa pressure and PEO as the adjuvant, the drift potential would decrease for the ULV sprayer and will allow it to be a useful tool for making pesticide spray applications. For the active ingredient study, the ULV sprayer fixtures were operated at 6 kPa and thus were within the range of optimal effectiveness as determined from the adjuvant study. From another study that tested various concentrations of PEO in a $1,061 \text{ g ae ha}^{-1}$ glyphosate solution, it was determined that that by adding at least 20 percent PEO v/v reduced the percentage of fine droplets from 50 percent to 25 percent (Ferguson et al. 2011). A further observation is that when PEO was doubled again, at a 40 percent v/v concentration, the percentage of fine droplets fell to nearly 15 percent (Ferguson et al. 2011). Neither of these PEO additions lessened the glyphosate efficacy

across all six species in 2011 or between corn and soybeans in 2012 with both the conventional and the ULV sprayers. Increasing the volume of drift reduction adjuvants in a tank mix increases droplet size and reduces drift (Kirk 2003). Further testing comparing PEO and its effects on efficacy of other active ingredients has yet to be conducted.

Overall Conclusion

Active ingredient efficacy as determined by dry weight reductions were not reduced at a lower carrier volume with the ULV sprayer in 2011. A reduced efficacy on corn when treated with the ULV sprayer was the only observed difference in 2012. Though individual sprayer type by active ingredient differences were observed, the overall difference between the two sprayers is negligible. The adjuvant additions were useful to improve droplet size for the ULV sprayer while maintaining glyphosate efficacy. Glyphosate efficacy does not appear to be carrier volume or droplet size specific, at least within the application parameters observed in this study. The active ingredient formulations used in the study were designed for use in a conventional sprayer. Thus the potential to further improve the technology can be addressed with improvements in formulation technology specific to ULV sprayers. With the lower carrier volumes of the Kamterter ULV sprayer, the efficiency with which to make pesticide applications improves and could provide applicators and growers with another option for making these applications in the future.

Chapter 4.

Additional Laser Diffraction Tests with an ULV Sprayer

Introduction

As a component of each field study, tests were run on a laser diffraction instrument (Sympatec Varios KF, Sympatec Inc., Pennington, NJ 08534) with the treatment mix that was applied in the field to determine relative droplet size and distribution. The reasoning behind these tests was to identify the spray quality produced by each sprayer from the treatment mix to get a better idea of how this affected each spray application. The data obtained from these tests have helped to provide a baseline to address ways to improve spray applications through the identification of the droplet size and distribution across a wide spectrum of spray solutions. In order to identify the droplet spectrum of the ULV sprayer used throughout the comparisons with the conventional sprayer, additional tests were run using different fixtures and positions of the ULV sprayer fixtures on the laser diffraction instrument. These studies were conducted in the summer of 2011 with three different solutions at various concentrations with 9 different fixtures. Changes in air pressure and pump speed in the ULV sprayer were altered during these tests to determine how much effect each operating parameter component had on the spray quality with identical solutions and fixtures.

Materials and Methods

Three studies were conducted at the University of Nebraska-Lincoln: West Central Research and Extension Center in North Platte, NE to determine spray quality with the ULV sprayer across different operating parameters and solutions.

Kamterter Large Study

The first study compared the spray quality of five different ULV fixtures at six different air pressures and three different pump speeds (180 total treatments) with water to determine the droplet size and distribution with a constant solution. The fixtures selected were all proprietary fixtures, and those selected were 102M, 105A, 105M, 112M, and 119M (Kamterter Products LLC, Waverly Nebraska, 68462). The fixtures were tested at air pressures of 5, 6, 8, 10, 15, and 20 kPa. Pump speeds selected were 300, 450, and 600 RPM. Each fixture by pressure by pump speed combination was replicated three times for accuracy of data collection. The D_{v50} (median droplet size), percentage of droplets less than $210\ \mu\text{m}$ (driftable fine droplets), and relative span $((D_{v90} - D_{v10}) \div D_{v50})$ of each fixture by pressure by pump speed combination were analyzed using a mixed model with replication as the random variable and fixture, pressure and pump speed as the fixed variables. The main effect variables were the fixture, pressure, and pump speed respectively. The simple effect data were the fixture by pressure, fixture by pump speed, pressure by pump speed and fixture by pressure by pump speed. The Tukey-Kramer adjustment was also implemented. The data were analyzed in SAS (Statistical Analysis System (SAS) software. Version 9.2. SAS Institute, Inc, Cary, NC 27513) with a significance of $\alpha=0.05$.

105M Study

The second study compared how a single fixture's spray quality can vary across solutions and operating parameters. Three solutions at five different air pressures and

three different pump speeds (45 total treatments) were tested to determine droplet size and distribution. The fixture selected for the study was the proprietary fixture 105M (Kamterter Products LLC, Waverly Nebraska, 68462). Solutions selected for the study were water, hydroxyethyl cellulose (HEC) at 10% v/v in water, and polyethylene oxide (PEO) at 15% v/v in water. Both the HEC and PEO were concentrated solutions that were previously premixed and then added to the water prior to spraying. Air pressures selected for the study were 6, 8, 10, 15, and 20 kPa. The three pump speeds selected were 300, 450, and 600 RPM. Each solution by pressure by pump speed combination was replicated three times for accuracy of data collection. The D_{v50} (median droplet size), percentage of droplets less than 210 μm (driftable fine droplets), and relative span $((D_{v90} - D_{v10}) \div D_{v50})$ of each solution by pressure by pump speed combination were analyzed using a mixed model with replication as the random variable and solution, pressure and pump speed as the fixed variables. The main effect variables were the solution, pressure, and pump speed respectively. The simple effect data were the solution by pressure, solution by pump speed, pressure by pump speed and solution by pressure by pump speed. The Tukey-Kramer adjustment was also implemented. The data were analyzed in SAS (Statistical Analysis System (SAS) software. Version 9.2. SAS Institute, Inc, Cary, NC 27513) with a significance of $\alpha=0.05$.

Positions Study

The third study sought to measure the position of the fixture relative to the laser diffraction instrument to determine the spray quality at a fixed location of the droplet pattern. Five fixtures at a constant pump speed and solution were tested at three positions

(Center, Left and Right) at three different pressures (45 total treatments) with each fixture by pressure by position treatment replicated three times. The fixtures selected for the study were 103A, 105M, 117M, 122M, and 126M (Kamterter Products LLC, Waverly Nebraska, 68462). The pressures selected for the study were 6, 8, and 10 kPa at a pump speed of 450 RPM. The D_{v50} (median droplet size), percentage of droplets less than 210 μm (driftable fine droplets), and relative span $((D_{v90} - D_{v10}) \div D_{v50})$ of each fixture by pressure by position combination were analyzed using a mixed model with replication as the random variable and solution, pressure and position as the fixed variables. The main effect variables were the fixture, pressure, and position respectively. The simple effect data were the fixture by pressure, fixture by position, pressure by position and fixture by pressure by position. The Tukey-Kramer adjustment was also implemented. The data were analyzed in SAS (Statistical Analysis System (SAS) software. Version 9.2. SAS Institute, Inc, Cary, NC 27513) with a significance of $\alpha=0.05$.

Results

Kamterter Large Study

There were overall main effect differences across the fixture types, pressure and pump speed for the D_{v50} , percent of droplets less than 210 μm and the relative span. All of these main effect parameters were significant (p value < 0.0001) so no simple effect differences were broken out (Table 9). Changes in pressure resulted in the greatest change in the droplet spectrum across all of the fixtures. Table 9 shows one of the five fixtures and how pressure and pump speed changed the droplet spectrum. With the fixture

112M, as pressure was doubled across pump speeds, the median droplet size was decreased by half. At the 450 RPM pump speed, when pressure was doubled from 5 kPa to 10 kPa the median droplet size went from 256 μm to 123 μm . This was also observed when the pressure was increased from 5 kPa to 20 kPa the median droplet size decreased by a fourth from 256 μm to 72 μm . Table 9 does not include all of the pressures or fixtures tested, but the selected fixture was representative of the performance of the other fixtures under identical parameters. The results for the percent of droplets less than 210 μm and the relative span also followed the same pattern, though not to the same degree. At the 450 RPM pump speed, when the pressure was doubled from 5 kPa to 10 kPa, the percent of driftable fine droplets increased by 1.5 times (44% to 71% respectively). The percent of driftable fines doubled when the pressure was quadrupled from 5 kPa to 20 kPa (Table 9). The largest median droplet size was produced when the pump speed was at 450 RPM and the pressure at 5 kPa. This was not consistent across other pressures though. When pump speed was increased to 600 RPM, the median droplet size was the largest at the 10, 15, and 20 kPa pressures.

Table 9: A selected fixture at a sampling of pressures across all three pump speeds and the droplet spectra from a laser diffraction instrument.

Fixture	Solution	Pressure		Pump speed	Dv50	RS	% < 210 μm
		kPa	(psi)	RPM	μm		%
112M	Water	5	(0.75)	300	223	2.33	48
112M	Water	10	(1.5)	300	113	2.71	76
112M	Water	15	(2.25)	300	83	2.49	87
112M	Water	20	(3)	300	64	2.36	94
112M	Water	5	(0.75)	450	256	2.39	44
112M	Water	10	(1.5)	450	123	2.86	71
112M	Water	15	(2.25)	450	90	2.80	83
112M	Water	20	(3)	450	72	2.80	88
112M	Water	5	(0.75)	600	205	2.78	51
112M	Water	10	(1.5)	600	130	3.01	67
112M	Water	15	(2.25)	600	97	2.85	80
112M	Water	20	(3)	600	79	3.22	84

There were main effect differences between fixtures, pressure and pump speeds, so no statistical separation is shown at the simple effect level.

105M Study

Main effect differences between solution types, pressure and pump speed were observed in all three droplet spectrum categories (p value <0.0001 for all three respectively). Changes in solution type had the greatest effect on the droplet spectrum, which has been consistent in other studies. PEO produced the largest median droplet size and fewest driftable fine droplets across all pressures and pump speeds (Table 10). HEC had a larger median droplet size and fewer driftable fine droplets than water across all pressures and pump speeds. The largest Dv50 and fewest droplets less than 210 μm were produced when the pump speed was 600 RPM and the pressure was at 5 kPa (Table 10). When pressure was doubled, the median droplet size was decreased by half as shown in Table 10 with two selected pressures from the study.

Position Study

There were overall main effect differences in the Dv50, percent of droplets less than 210 μm and the relative span across the changes in position, fixtures and pressure (p value <0.0001 for all three respectively). Table 11 shows the effect of position and pressure changes with two fixtures, where in general, the droplet spectrum is different depending on the fixtures position with respect to the laser. The largest median droplet size and fewest driftable fine droplets were observed with the 6 kPa pressure regardless of position or fixture (Table 11).

Table 10: Fixture 105M its droplet spectrum across three different solutions at selected pressures across three pump speeds.

Fixture	Solution	Pressure		Pump speed RPM	Dv50 μm	RS	% < 210 μm %
		kPa	(psi)				
105M	Water	10	(1.5)	300	90	2.44	86
105M	HEC	10	(1.5)	300	135	2.68	67
105M	PEO	10	(1.5)	300	297	1.80	37
105M	Water	20	(3)	300	54	2.45	96
105M	HEC	20	(3)	300	71	2.45	92
105M	PEO	20	(3)	300	143	2.34	65
105M	Water	10	(1.5)	450	118	2.48	77
105M	HEC	10	(1.5)	450	154	2.71	62
105M	PEO	10	(1.5)	450	361	1.73	30
105M	Water	20	(3)	450	64	2.48	93
105M	HEC	20	(3)	450	82	2.45	88
105M	PEO	20	(3)	450	171	2.27	58
105M	Water	10	(1.5)	600	136	2.48	70
105M	HEC	10	(1.5)	600	164	2.52	59
105M	PEO	10	(1.5)	600	367	1.65	30
105M	Water	20	(3)	600	74	2.57	90
105M	HEC	20	(3)	600	93	2.35	85
105M	PEO	20	(3)	600	215	2.25	49

There were main effect differences between solutions, pressure and pump speeds, so no statistical separation is shown at the simple effect level.

Table 11: Selected fixtures and their droplet spectrum in three positions with water and a constant pump speed of 450 RPM.

Fixture	Position	Pressure		Pump speed RPM	Dv50 μm	RS	% < 210 μm %
		kPa	(psi)				
103A	Left	6	(0.9)	450	182	2.14	57
103A	Center	6	(0.9)	450	143	2.67	66
103A	Right	6	(0.9)	450	229	2.65	47
103A	Left	8	(1.2)	450	157	2.05	67
103A	Center	8	(1.2)	450	115	2.64	76
103A	Right	8	(1.2)	450	170	2.16	62
103A	Left	10	(1.5)	450	134	2.16	74
103A	Center	10	(1.5)	450	100	2.64	81
103A	Right	10	(1.5)	450	173	2.19	62
105M	Left	6	(0.9)	450	167	2.78	58
105M	Center	6	(0.9)	450	167	2.63	59
105M	Right	6	(0.9)	450	182	2.84	55
105M	Left	8	(1.2)	450	139	2.16	71
105M	Center	8	(1.2)	450	141	2.79	66
105M	Right	8	(1.2)	450	150	3.07	62
105M	Left	10	(1.5)	450	102	2.54	80
105M	Center	10	(1.5)	450	115	2.75	75
105M	Right	10	(1.5)	450	135	3.61	65

There were main effect differences between solutions, pressure and pump speeds, so no statistical separation is shown at the simple effect level.

Discussion and Conclusions

Across all three studies, the operating pressure had the greatest effect on the median droplet size and the percentage of driftable fine droplets. This is consistent with what has been observed in other studies with the ULV sprayer to determine droplet size and distribution (Ferguson et al. 2013a). Since the ULV sprayer has negligible liquid pressure, the main atomizing pressure exerted on the system is from the air pressure that shears the droplets at the fixture surface opening. This is the case even with the relatively low pressures used in the system because the physics of droplet formation in the fixture is very sensitive to changes in air pressure as observed in previous studies (Ferguson et al. 2011, 2013a, 2013b). Changes in the pump speed affected the droplet spectrum, though not to the degree observed with the change in the pressure. This is due mostly to the mechanics of the sprayer itself because pump speed affects the flow of the liquid through the lines, but the atomization process to form droplets is influenced more by the pressure exerted down from the air pressure. Pump speed though did affect droplet size by as much as 50 μm which could change the spray quality from a fine to a very fine or fine to a medium droplet classification.

Differences observed across the droplet spectra across different fixtures is also to be expected, since each fixture differs in the shape, size, and positions of air chambers and other parts of the fixture itself. These studies helped to quantify the known differences in the design of the fixtures to determine how much each design feature affects the overall droplet spectrum produced under identical operating parameters and solutions. The differences observed in droplet size and distribution in the position study would need to be

replicated to ensure that actual differences exist in the droplet spectrum of a given fixture. This study was conducted to understand if the measurement point of a fixture can affect the overall droplet spectrum, but no work was conducted with a conventional nozzle with which to compare. In short, the three studies conducted have helped to improve the Kamterter ULV sprayer by identifying the best operating parameters and fixture designs to fine tune the technology moving forward.

Chapter 5: Pre and Postemergence Herbicides on Weed Suppression in Established Turfgrass with a Conventional and an Ultra-Low Volume Sprayer

Introduction

Weeds may cause economic and aesthetic losses by competing for limited resources against the crop (Beckett et al. 1988, Crook and Renner 1990, Kudsk and Streibig 2003). In turfgrass management, dandelion, large crabgrass, and ground ivy compete with turfgrass species for resources and can dominate landscapes. In cropping situations absent disturbance from tillage, dandelion can be a particularly troublesome weed (Franssen and Kells 2007). Dandelion is a perennial; it may be problematic for turfgrass managers every year without proper control. Previous research has demonstrated that 2,4-D and mesotrione are effective at reducing dandelion stands in no-tillage corn systems (Franssen and Kells 2007).

Ground ivy is a common stoloniferous perennial weed that can disrupt a turfgrass system (Kohler et al. 2004a). Ground ivy has the ability to spread into a dense canopy and out-compete established turfgrass creating thin stands and reduce turf vigor (Kohler et al. 2004b). Hatterman-Valenti et al. (1996) identified that ground ivy control can be inconsistent, where control from the same treatments can range from 66% to 91% thereby making successful control regimes hard to predict. Patton and Weisenberger (2012) observed consistent ground ivy control in established turf using 2,4-D, dicamba, mecoprop, sulfentrazone, triclopyr or mesotrione.

Large crabgrass is a competitive annual warm season grass that is commonly found in established turfgrass systems throughout the US. Pendimethalin is a commonly used PRE herbicide in turfgrass to control large crabgrass (Johnson 1997, Bhowmik and Bingham 1990, Johnson 1993a, Johnson 1993b), but prior studies have not researched variations in carrier volumes and their effects on large crabgrass control with pendimethalin. Carrier rates in these studies ranged from 375 L ha⁻¹ to 470 L ha⁻¹.

Mesotrione was released in 2008 for use in turfgrass (anonymous 2008), and has been reported to be effective at controlling dandelion and ground ivy (Franssen and Kells 2007, Patton and Weisenberger 2012).

Most labels for turfgrass herbicides recommend a carrier volume of at least 187 L ha⁻¹ in order to provide effective weed control (anonymous 2012, 2009a, 2009b, 2008). Previous research on the control of weeds in turfgrass has focused on alternative methods for herbicide application, but the convention is to use carrier volumes of 187 L ha⁻¹ or greater (Johnson 1997, Bhowmik and Bingham 1990, Johnson 1993a, Johnson 1993b). This results in a reduced application efficiency as applicators and golf course superintendents can only cover a limited area per tank load. The use of ultra-low volume (ULV) technology has been documented in other cropping systems (Bode et al. 1985) but is not widely used in turfgrass.

Kamterter LLC in Waverly, NE, has developed an ULV sprayer to improve the efficiency of pesticide applications. The system uses the interaction of two kinetic energy fluids – a gas and a liquid, to atomize and broadcast low volumes of spray solutions. The

system was designed to handle rates as low as 9.5 L ha^{-1} . The sprayer takes a column of liquid and meters it on a spray fixture surface. The liquid is fed by a linear peristaltic positive displacement pump which then combines with an air column at the spray fixture surface that shears the liquid to form droplets (Eastin and Vu 2012). The ULV sprayer has the ability to meter liquids with high extensional viscosity and shear thinning fluid characteristics that cannot be atomized with small orifice nozzles on conventional sprayers (Figure 5).

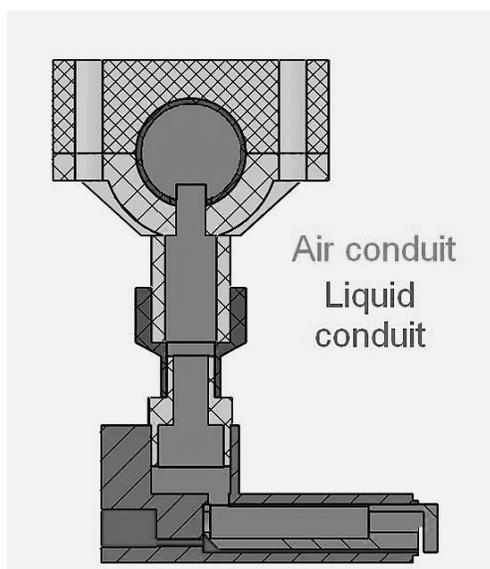


Figure 5: Kamterter ULV Sprayer fixture showing how the air component and the liquid component enter the fixture and interact at the spray fixture surface to form droplets.

Given the larger orifice of the ULV sprayer fixture, spray solutions with certain chemical and colloidal properties can be further investigated that currently would not be feasible with the conventional pressure-against-an-orifice nozzle. The liquid metering is connected to the ground speed of the sprayer, allowing for a constant volume over a ten-

fold range of speeds (Eastin and Vu 2012). The system, unlike a conventional pressure against an orifice system, has negligible pressure on the liquid lines.

The objectives of these studies were to identify if this new sprayer system can effectively apply herbicide active ingredients in a turfgrass system comparable to a conventional sprayer system.

Materials and Methods

Four field studies at the University of Nebraska-Lincoln: John Seaton Anderson Turfgrass Research Facility near Mead, NE were conducted in the spring and summer of 2012 to determine weed control regimes correlated between an ULV sprayer and a conventional sprayer (Toro Multi-Pro 1200, The Toro Company, Bloomington, MN, 55420). All treatments with the conventional sprayer were applied at 561 L ha⁻¹ with XR11006 nozzles (Spraying Systems Co., P.O. Box 7900, Wheaton, IL 60189) at 310 kPa and a speed of 5 km hr⁻¹, and treatments with the ULV sprayer were applied at 19 L ha⁻¹ with proprietary fixtures at 6 kPa air pressure and a speed of 5 km hr⁻¹. All treatments were arranged in a randomized complete block design with four replications consisting of 0.9 x 1.5 m plots.

Dandelion and Ground Ivy Study-1

The first two studies were conducted on two separate stands of turf containing dandelion (dandelion study) or ground ivy (ground ivy study-1) Both studies contained two treatments by two sprayer types and an untreated check. The treatments selected were a 2,326 g ae ha⁻¹ 2,4-D + 248 g ae ha⁻¹ dicamba + 622 g ae ha⁻¹ mecoprop treatment

(Trimec Classic[®], PBI/Gordon Corporation, Kansas City, MO 64101) and a 224 g ai ha⁻¹ mesotrione treatment (Tenacity[®], Sygenta Crop Protection Inc, Greensboro, NC, 27419). The mesotrione treatments were made in split applications of 112 g ha⁻¹. The first application was made at the time of the 2,4-D + dicamba + mecoprop application on June 8, 2012 and then the second application was made three weeks later on June 28, 2012 . The dandelion study was applied over a mixed stand of Kentucky bluegrass (*Poa pratensis* L.) and perennial ryegrass (*Lolium perenne* L.). Dandelion counts were taken at 0, 14, 28, and 56 days after treatment. Dandelion or ground ivy counts were taken at the time of application, 14, 28, and 56 days after treatment. Counts for dandelion were taken using a 1.81 m² grid and converted to plants /m².

Counts were taken with a 1.5 x 1.2 m transect with 67 subunits and plant counts were recorded if the cross section of the subunit intersected a plant. The ground ivy counts were converted to percent ground cover for each plot by dividing the number of plants per subunit in the grid by the total number of intersects before statistical analysis was performed.

Ground ivy study-2

A third study (ground ivy study-2) was conducted to compare the efficacy of a 2,4-D + dicamba + sulfentrazone + triclopyr solution (T-Zone[®], PBI/Gordon Corporation, Kansas City, MO 64101) on ground ivy in a separate but adjacent site to the ground ivy study-1 between a conventional sprayer and an ULV sprayer. The treatments were a 1427 g ae ha⁻¹ 2,4-D + 109 g ae ha⁻¹ dicamba + 33 g ai ha⁻¹ sulfentrazone + 377 g ai ha⁻¹

triclopyr solution with each sprayer type and an untreated control. Treatments were applied on April 16, 2012. Counts were taken as described previously at 7, 14, 28 and 56 days after treatment.

Crabgrass study

The fourth study (crabgrass study) was conducted to compare the efficacy of a 1736 g ai ha⁻¹ pendimethalin (Pendulum Aqua Cap[®], BASF Corporation, Research Triangle Park, NC 27709) solution applied as a PRE for large crabgrass control in established turfgrass between a conventional sprayer and an ULV sprayer. The treatments were pendimethalin at 1736 g ai ha⁻¹ with each sprayer type and an untreated control. The established turfgrass was a Kentucky bluegrass and perennial ryegrass mix. Treatments were applied on April 16, 2012. Plots were visually rated for percent crabgrass ground cover at two months after application when large crabgrass began to emerge. Subsequent ratings were made every two weeks for a total of four ratings. The percentage of crabgrass cover in each plot was converted as a percent control by dividing the percent cover in the treated plot by the percent cover in the untreated control in each replicate prior to the statistical analysis was performed.

Statistical Methods

The two ground ivy studies and the large crabgrass study data were analyzed using a general linear mixed model with replication as the random variable and sprayer type, and treatment as the fixed variables. Across all four studies, sprayer type did not produce a statistical difference, and was eliminated from the final analysis. Each study

was separated at $\alpha=0.05$ using a repeated measures analysis. The main effect variables analyzed were sprayer type and treatment with treatment by sprayer type as the simple effect variable. For the dandelion study, the Poisson adjustment was included to prevent over dispersion which can occur with count data. For the ground ivy and crabgrass studies, the Tukey-Kramer adjustment was implemented to insure that differences were correctly reported. The data were analyzed in SAS (Statistical Analysis System (SAS) software. Version 9.2. SAS Institute, Inc., Box 8000, SAS Circle, Cary, NC 27513).

RESULTS

Dandelion and Ground Ivy Study Results

The count data was different for the herbicide type ($p = 0.0045$) timing ($p = <.0010$) and timing by herbicide ($p= 0.0442$). Statistical analysis was a repeated measures analysis that grouped herbicide across both sprayers given differences between sprayer type was non-significant across the study. The mesotrione treatments reduced the dandelion populations more than the 2,4-D + dicamba + mecoprop treatments. The 28 DAT counts resulted in the lowest number of dandelion plants for both treatments with both sprayers (Figure 6). The mesotrione treatments reduced dandelion counts more than the 2,4-D + dicamba + mecoprop treatments. This is likely due to the activity of the active ingredients of the two herbicides, where mesotrione is more efficacious under warmer conditions as would be expected in the middle of the summer. The 2,4-D + dicamba + mecoprop herbicide is used mostly in the spring and fall for control of broadleaf weeds in turf and as such did not show as much activity in dandelion control in

the summer months (anonymous 2012). The herbicides suppressed dandelion counts for up to 28 days after treatment (Table 12). The second application of mesotrione at 14 days after treatment reduced dandelion counts more than the single application of 2,4-D + dicamba + mecoprop. Both treatments had an increase in counts after 28 days after treatment indicating a reduction in control, a month after application. The 2,4-D + dicamba + mecoprop treatments with both sprayers returned to their pre-application levels at 56 days after treatment and the mesotrione treatments continued to show dandelion control through the duration of the study. It would be likely that 56 days after the second mesotrione application that the dandelion counts would have returned to their pre-application levels as well, thus both herbicides would be comparable in regard to a single application.

The ground ivy data had no significant main effect or simple effect differences in the study. Data (Table 12) is presented as the average of each herbicide at each timing, across both sprayers. The conventional sprayer provided better control of ground ivy for the first mesotrione application and the ULV sprayer provided better control for the second mesotrione application. None of the treatments provided ground ivy control that exceeded 40 percent control compared to the untreated control, although both sprayers provided equal control.

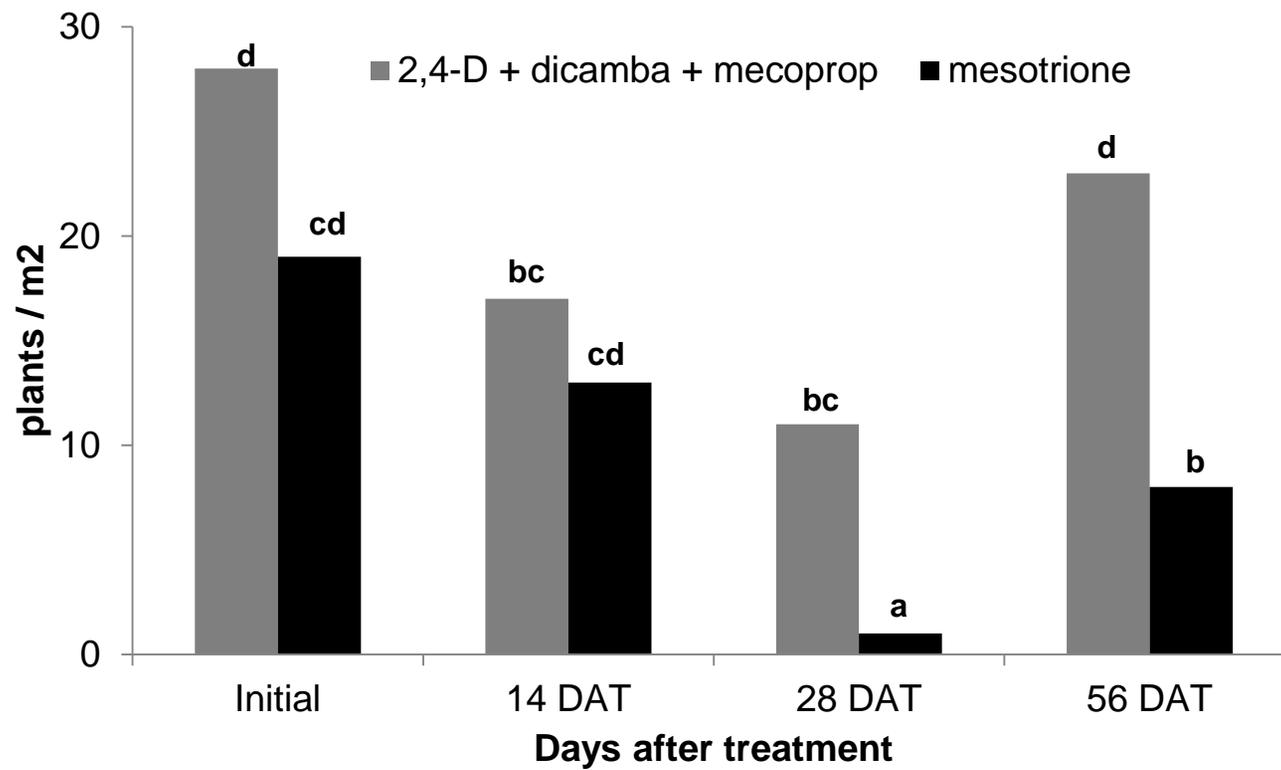


Figure 6: Dandelion counts at 0, 14, 28, and 56 days after treatment with 2,4-D + dicamba + mecoprop and mesotrione. Statistical separation was made with a repeated measures analysis grouped by herbicide as there was no difference in sprayer type. Treatments with the same letter are not different.

Table 12: Effect of four herbicide control methods of dandelion, ground ivy and large crabgrass in a turfgrass cropping system across both sprayer types at Mead, NE.

Treatment	Rate kg ai ha ⁻¹	Dandelion control				Ground ivy control				Large crabgrass control			
		Initial	Counts 14 DAT	28 DAT	56 DAT	7 DAT	14 DAT	28 DAT	56 DAT	% 7 DAE ^a	14 DAE ^a	28 DAE ^a	56 DAE ^a
Untreated		19	19	16	14	0*	0	0	0	0	0	0	0
2,4-D + dicamba + mecoprop	2.3 + 0.25 + 0.62	28 d	17 cd	11 bc	23 d	0*	31	15	15	-	-	-	-
mesotrione	0.11	19 cd	13 bc	1 a	8 b	0*	25	39	39	-	-	-	-
2,4-D + dicamba + sulfentrazone + triclopyr	1.43 + 0.11 + 0.03 + 0.38	-	-	-	-	6 b	34 a	37 a	34 a	-	-	-	-
pendimethalin	1.74	-	-	-	-	-	-	-	-	89 a	64 b	44 c	33 c

Each study was analyzed separately and separated as a repeated measures analysis of sampling over time in each plot.

* The 7 days after treatment control values were recorded as zero for the ground ivy study with 2,4-D + dicamba + mecoprop and mesotrione because these counts were taken as initial counts, not as counts 7 days after treatment.

^a DAE = days after emergence.

Values without a letter were not statistically significant.

Ground ivy study-2

The 2,4-D + dicamba + sulfentrazone + triclopyr resulted in application timing difference and no significant differences between sprayer type. Ground ivy control was improved at 14 DAT as compared to 7 DAT, but did not statistically improve at 28 or 56 DAT. The two treatments suppressed the ground ivy growth as compared to the untreated control throughout the study and up to 56 days after treatment. Both sprayers equally provided a reduction in ground ivy (Table 12).

Crabgrass study

Statistical separations were observed across the four timings, but there was no significant a difference between sprayer types. The repeated measures analysis reports the difference in crabgrass control over the four timings. The treatments with each sprayer helped to suppress crabgrass emergence for up to two months after application and maintain control until the 1st of July (Table 12). Large crabgrass control was above 60 % until 14 days after emergence, when control of crabgrass was reduced and continued that trend through the duration of the study (Figure 7). This was true in the treatments applied with both sprayer types.

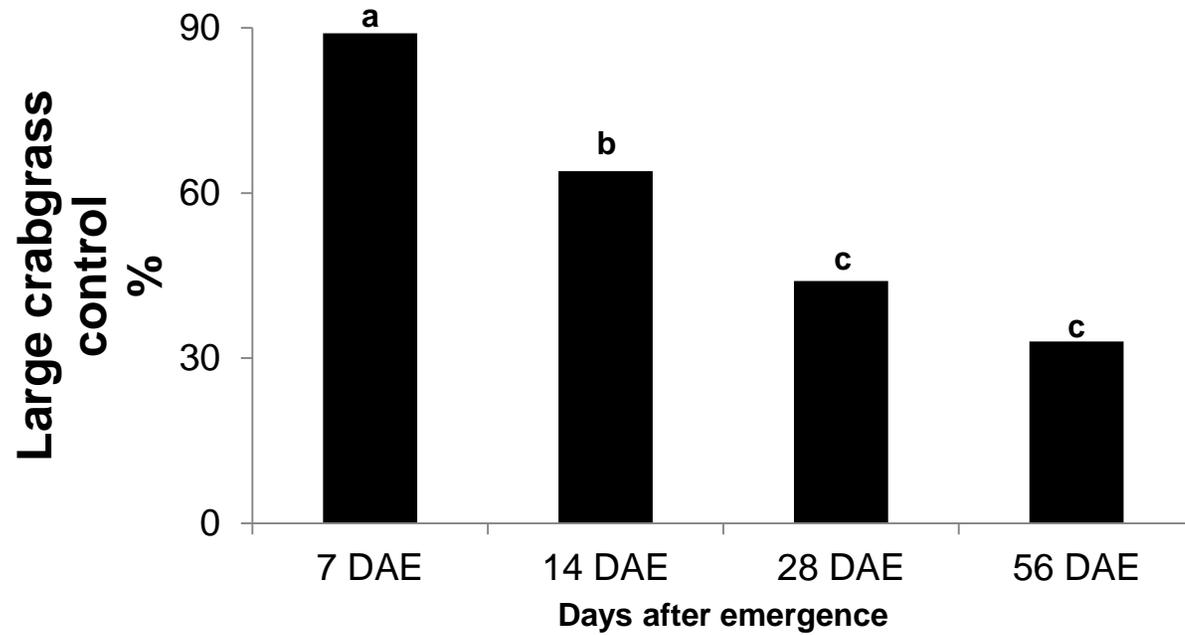


Figure 7: Large crabgrass control at 7, 14, 28, and 56 days after emergence. There was no difference between sprayer types and the separations were made using a repeated measures analysis. Treatments with the same letter are not statically significant.

Discussion and Conclusions

Based on the data from four studies, no statistical differences were identified between the conventional sprayer and the ULV sprayer, and minimal differences were found between active ingredients and timings. The mesotrione did not bleach the turf as has been observed in some mesotrione applications (anonymous 2008, Goddard et al. 2010) which further highlights the usefulness of this herbicide as a dandelion control in established turfgrass even at ULV carrier volumes.

These active ingredients are not carrier volume dependent, as the ULV treatments at a 15 fold decrease in carrier volume did not reduce weed control as reported on the label.

Spray drift has yet to be investigated with this system but prior research with this sprayer system reveals a different droplet spectrum than the conventional sprayer/nozzle configuration (Ferguson et al. 2013). A study of ten herbicide active ingredients was performed on a laser diffraction system with the ULV sprayer and conventional sprayer and across the active ingredients investigated the ULV sprayer demonstrated an overall smaller droplet spectrum than the conventional sprayer. Previous research suggests that a smaller droplet is more effective for deposition of herbicide active ingredients (Knoche 1994), though it's more prone to drift (Kudsk and Streibig 2003). The spray droplet spectrum is one of the most crucial factors influencing spray drift (Zhu 1994 and Hewitt 1997), resulting in the need for extensive work to determine droplet size and distribution with the ULV sprayer. Other research has revealed that when adjuvants are incorporated

into the tank mix, the ULV sprayer has a larger droplet than the conventional sprayer (Ferguson et al. Unpublished).

The ULV sprayer improves application efficiency without decreasing weed control versus a conventional sprayer. Since turfgrass pesticide applications traditionally have used a large carrier volume, this technology would appear to be a useful alternative for turf managers as a means to improve application efficiency. With no differences between sprayer types observed across an array of herbicides applied over different weed species, the Kamterter ULV sprayer appears to be an additional option for herbicide applications in a turfgrass system.

Chapter 6: Effect of application carrier volume on foliar fertilizer and fungicide applications in turfgrass with a conventional and an ultra-low volume sprayer

Introduction

Crop input applications are commonly made in turfgrass systems to enhance turf growth and quality. Creeping bentgrass (*Agrostis stolonifera* L.) is a common cool-season turfgrass in Nebraska and the Midwest used primarily on golf courses and other highly managed playing surfaces. Golf greens are intensively managed turfgrass systems requiring an annual nitrogen application of 100 to 250 kg ha⁻¹ per growing season (Carrow et al. 2001). Recent studies have identified the benefits of using foliar nutrients to enhance turf growth and quality especially in creeping bentgrass (Gaussoin et al. 2009,

Stiegler et al. 2011). Golf course superintendents and turf managers are implementing the application of nitrogen and other micronutrients as part of their management program to improve turf growth. Research on the use of trinexapac-ethyl in creeping bentgrass identified an increase in nitrogen use efficiency and a reduction in drought stress during summer months (Kreuser and Soldat 2012, McCann and Huang 2007, Goss et al. 2002). Trinexapac-ethyl has also demonstrated an increase in turf quality by reducing plant stress. (Heckman et al. 2001, McCollough et al. 2007).

Brown patch (*Rhizoctonia solani* Kuhn) is a common warm-season pathogen of creeping bentgrass which can be a serious disease if not treated (Martin and Lucas 1984). The disease primarily affects the plant tissues at or above the soil surface (Burpee and Martin 1992). Fungicide applications on creeping bentgrass greens are regularly made to prevent and suppress brown patch from June to September in the mid-west (Settle et al. 2001). It is a widely accepted practice by golf course superintendents to make applications every 14 to 21 days during those months (Settle et al. 2001). Azoxystrobin is a strobilurin fungicide commonly used for the control of brown patch in creeping bentgrass and other turfgrasses. It inhibits fungal pathogens by interfering with cellular respiration through the disruption of electron transport in the mitochondria (Aspinall and Worthington 1999). Propiconazole is also a common fungicide for brown patch control in creeping bentgrass. Propiconazole is a dimethylation inhibitor that was first approved for the use in turfgrass in the early 1980's (Martin 2003).

Foliar applications in turfgrass are made with a carrier volume greater than 187 L ha⁻¹ as recommended on most labels to ensure coverage and crop safety of the application

(anonymous 2012, 2010, 2009, 2008a, 2008b). Couch (1985) researched the effects of application carrier volume on fungicide efficacy in the control of brown patch and other turf diseases. He also determined that a carrier volume of at least 407 L ha⁻¹ with contact fungicides and 814 L ha⁻¹ for systemic fungicides was required for proper disease management. Other research has demonstrated that a carrier volume of at least 407 L ha⁻¹ was necessary for proper disease suppression in turfgrass (Fidanza et al. 2009, Fidanza 2009). This is a reduction in application efficiency as applicators and golf course superintendents can only cover a limited area per tank load. The use of ultra-low volume (ULV) technology has been documented in other cropping systems (Bode et al. 1985) but is not widely used in turfgrass.

An ULV sprayer was engineered by Kamterter Products LLC in Waverly, NE. The sprayer was developed to improve application efficiency in multiple cropping systems. The sprayer interacts two kinetic energy fluids – a gas and a liquid, to atomize droplets to apply ultra-low volumes of spray solution in a turfgrass system. The ULV sprayer was developed to make applications as low as 9.5 l ha⁻¹ (Eastin and Vu 2012). The liquid column of the system is fed by the linear peristaltic positive displacement pump which meters the liquid on the spray fixture surface. This then interacts with an air column at the spray fixture surface that shears the liquid to form droplets.

The objective of these studies was to compare the described ULV sprayer system to a conventional sprayer for turfgrass foliar nutrition and fungicide applications.

Materials and Methods

Growth Regulator/Foliar Fertilizer Study

A field study at the University of Nebraska-Lincoln: John Seaton Anderson Turfgrass Research Facility near Mead, NE was conducted in 2011 and 2012 to determine turfgrass response to a fertilizer and growth regulator application between an ULV sprayer and a conventional sprayer (Toro Multi-Pro 1200, The Toro Company, Bloomington, MN, 55420). The study contained three treatments for each sprayer and an untreated check (7 total treatments) arranged in a randomized complete block design with three replications. The first study treatments were a 1 L ha⁻¹ trinexapac-ethyl (T-NEX 1 AQ Quali-Pro, Raleigh, NC 27609) treatment, a 29 L ha⁻¹ 13-2-3-0.12-1.4-0.2-0.2 (N-P-K-Cu-Fe-Mn-Zn fertilizer blend) (Gary's Green Ultra, Grigg Brothers, Albion, ID 83311) treatment and a 19 L ha⁻¹ 3-7-18-0.02-0.01-0.05-0.001 (N-P-K-B-Co-Cu-Mo fertilizer blend) (P-K Plus, Grigg Brothers, Albion, ID 83311) treatment. Treatments with the conventional sprayer were applied at 561 L ha⁻¹ with XR11006 nozzles (Teejet Technologies, Wheaton, IL 60187) at 310 kPa and a speed of 5 km hr⁻¹. Treatments with the ULV sprayer were applied at 48 L ha⁻¹ with proprietary nozzles at 6 kPa air pressure and a speed of 5 km hr⁻¹. The trial was applied over creeping bentgrass 'L-93' managed at fairway height (1.3cm). The turf was watered daily to replace 80% evapotranspiration and mowed every other day until the end of the first week of the study. Three measurements were taken in each plot

for chlorophyll content with a chlorophyll meter (FieldScout CM 1000 NDVI Chlorophyll Meter, Spectrum Technologies Inc. Plainfield, IL 60585) at 7 and 14 days after treatment in 2012 and 21 days after treatment in 2011. Three measurements in each plot were obtained for normalized difference vegetation index (NDVI) with a turf color meter (FieldScout TCM 500 NDVI Turf Color Meter, Spectrum Technologies Inc. Plainfield, IL 60585). Plots were mowed after the first week and then left unmanaged until they were harvested at 21 days after treatment. Each plot was harvested for clipping biomass at 21 days after treatment, by mowing a strip in the center of each plot measuring 0.6 x 3 m and collecting the clippings for each plot. The clippings were dried for 48 hours at 60°C and dry weights were recorded.

The ULV sprayer is normally applied at a carrier volume of 19 L ha⁻¹ or less. Due to the higher labeled rates of the foliar fertilizers, the carrier volume had to be increased to 48 L ha⁻¹ to keep equal application rates between the two sprayers. The tank mix treatments containing the foliar fertilizers with the ULV sprayer were mixed without any dilution and consequently were applied as pure product due to the low carrier volume required of the ULV sprayer.

Fungicide study

A field study at the University of Nebraska-Lincoln: John Seaton Anderson Turfgrass Research Facility near Mead, NE was conducted in 2012 to compare an ULV sprayer and a conventional sprayer in the control of brown patch in creeping bentgrass 'L-93'. The study contained two treatments for each sprayer and an untreated check (5 total

treatments) arranged in a randomized complete block design with four replications. Treatments selected were a 1,747 g ai ha⁻¹ propiconazole (Banner Maxx II, Syngenta Crop Protection, Greensboro, NC, 27419) treatment and a 538 g ai ha⁻¹ azoxystrobin (Heritage TL, Syngenta Crop Protection, Greensboro, NC, 27419) treatment. Treatments with the conventional sprayer were applied at 561 L ha⁻¹ with XR11006 nozzles (Teejet Technologies, Wheaton, IL 60187) at 310 kPa and a speed of 5 km hr⁻¹. Treatments with the ULV sprayer were applied at 19 L ha⁻¹ with proprietary nozzles at 6 kPa air pressure and a speed of 5 km hr⁻¹. Treatments were applied on June 28, 2012 and August 2, 2012. The creeping bentgrass was managed at fairway height of 1.3 cm for the study and plots were mowed every other day. The turf was also watered daily to replace 80 % ET. Plots were rated for visual estimations of brown patch at 14, 28, 7/35, and 28/56 days after treatment - the days with the slash represent days after the second application over the days since the first application.

The chlorophyll content and NDVI data were analyzed with a generalized linear mixed model with a repeated measures analysis. Each data set was analyzed separately. The main effect variables analyzed were sprayer type, timing and treatment with treatment by sprayer type as the simple effect variable. The Tukey-Kramer adjustment was implemented to insure that differences were correctly reported. Thus we analyzed the data from each year separately. The data were analyzed in SAS (Statistical Analysis System software. Version 9.2. SAS Institute, Inc, Cary, NC 27513.) at $\alpha=0.05$.

Fungicide Study Statistical parameters

The brown patch percentage data were analyzed using a general linear mixed model and a repeated measures analysis. Sprayer type was not included in the final analysis as it was not statistically different. The main effect variables analyzed were timing and treatment with treatment by sprayer type as the simple effect variable. The Tukey-Kramer adjustment was implemented to insure that differences were correctly reported. The data were analyzed in SAS (Statistical Analysis System software. Version 9.2. SAS Institute, Inc, Cary, NC 27513.) at $\alpha=0.05$.

Results

Fertilizer Trial Results

There was a main effect difference in timing in 2012 with the chlorophyll content and NDVI data where the 14 DAT timing resulted in improved turf quality (Table 13). In 2011 there was no main effect or simple effect differences from the study. The years were different ($p = < 0.0001$) so each year was analyzed differently. It was further observed that the turf was not damaged from the application of the pure foliar fertilizer treatments with the ULV sprayer. The two treatments with the fertilizer additions were applied as pure product with the ULV sprayer, but none of the treatments in either year of the study caused turf burn. This was also minimized through the daily watering regime to replace 80% evapotranspiration.

Table 13: Effect of foliar treatments on chlorophyll content, NDVI percentage and dry weights on a creeping bentgrass green between the two sprayers in 2011 and 2012.

Treatment	Rate	Chlorophyll content			NDVI			Dry weights	
		2011	2012		2011	2012		2011	2012
	L ha ⁻¹	relative chlorophyll content			% reflectance			g	
		21 DAT	7 DAT	14 DAT	21 DAT	7 DAT	14 DAT		
Untreated		414	322 b	388 a	81	74 bc	77 a	24	65
trinexapac-ethyl	1	418	341 b	397 a	80	76 ab	76 ab	20	69
N-P-K-Cu-Fe-Mn-Zn fertilizer blend	29								
+ N-P-K-B-Co-Cu-Mo fertilizer blend	19	454	319 b	409 a	81	73 bc	76 a	29	65
trinexapac-ethyl									
+ N-P-K-Cu-Fe-Mn-Zn fertilizer blend	29	423	315 b	383 a	79	73 c	77 a	19	62
+ N-P-K-B-Co-Cu-Mo fertilizer blend	19								

Timing differences were noted in the chlorophyll content and NDVI percentage in 2012. There were no differences between sprayer type in both years of the study. Chlorophyll content and NDVI were analyzed as a repeated measures analysis and the 2011 data and the dry weight data were analyzed with a generalized linear mixed model.

The trial was replicated over two years and applied in different conditions to exacerbate differences that might exist between the two sprayers. The trial was first applied on September 15, 2011 during a very cool and damp three weeks in the fall. In order to compare the sprayers in hotter and drier conditions, the trial was replicated in 2012 and sprayed on June 28, 2012. The summer of 2012 in Nebraska was one of the hottest and driest on record which allowed for a true range of conditions with which to compare this study between the two sprayers (Table 14). Since creeping bentgrass is very sensitive, the hot and dry conditions would be ideal to see if turf burn from the treatments to ensure crop health from these applications.

Fungicide Study Results

There was a main effect difference in treatment ($p = 0.0002$) where azoxystrobin decreased brown patch more than propiconazole. There was also a main effect difference in timing (p value <0.0001), where the brown patch ratings after the second application of azoxystrobin and propiconazole were lower than the after the first application respectively (Table 15). There was not a main effect difference between sprayer type and it was not included in the final repeated measures analysis.

Table 14: Weather conditions at the John Seaton Anderson Turf Research Facility near Mead, NE during the foliar fertilizer trial in 2011 and 2012.

Date	9/15/2011	10/06/2011	06/28/2012	07/19/2012
Event	Application	Harvest	Application	Harvest
Conditions				
High Temperature °C	17.2°C	28.8°C	38.9°C	38.3°C
Low Temperature	3.3°C	13.8°C	22.7°C	21.7°C
Dew Point	1.3°C	6.8°C	73°C	20°C
Wind Speed / Direction	10.3 / NW	30.6 / SW	9.8 / W	9.3 / W
Precipitation	16 mm*		0.00	

Conditions for the two years of the research are compiled for the date of application and the biomass harvest at 21 days after treatment. Wind speed is expressed as the average wind speed in kilometers per hour. Precipitation is the sum total during the three week period for each year of the study.

* The precipitation from 2011 occurred only in the 5 days following the application.

Table 15: Brown patch infection on a creeping bentgrass fairway when treated with propiconazole and azoxystrobin with a conventional and ULV sprayer.

Treatment	Rate g ai ha ⁻¹	Brown patch			
		14 DAT	28 DAT	%	
				7/35 DAT*	28/56 DAT*
Untreated		53 d	38 de	5 ab	0 a
propiconazole	1,747	31 c	48 d	0 a	0 a
azoxystrobin	538	18 a	7 ab	1 a	0 a

Treatments with the same letters were not different. The ratings were separated through a repeated measurement analysis. Treatments were grouped across sprayer types as there was no difference between them.

*The 7/35 and 28/56 days after treatment ratings represent 7 and 28 days after the second application and 35 and 56 days after the first application respectively.

The second application of propiconazole and azoxystrobin reduced brown patch occurrence. Between the 35 and 56 days after the first treatment ratings, the weather was noticeably cooler, which further reduced brown patch toward the end of the study. This can be seen in the untreated plots where the brown patch occurrence continued to decrease throughout the study (Table 15). The different sprayer types reduced brown patch similarly even with a 15-fold decrease in carrier volume between the two sprayers. The propiconazole treatments reduced brown patch occurrence for the first two weeks after application, but was not different from the untreated plots four weeks after treatment (Table 15). The azoxystrobin treatments showed quick reduction of brown patch occurrence out to 28 DAT proving to be an effective control option of brown patch in creeping bentgrass. No difference in treatment effect was observed at 35 and 56 DAT.

Discussion

Growth regulator and nutrient study

The study revealed minimal difference among treatments across both years of data. The foliar nutrient additions improved turf quality with both sprayers at 14 DAT. Turf quality improvements though were negligible which could be explained by the low total nutrient composition of each product and the absence of a pure nitrogen treatment in which to compare. This statement is also further quantified with the lack of turf burn observed in either year of the study. The conditions were quite different in both years of the study as referenced in Table 14, yet the hot and dry summer of 2012 did not produce a

different result from the cooler fall application in 2011. Uptake of nutrients was greater in the fall 2011 application as compared to the summer 2012, which confirms the findings from Gaussoin et al. (2009) which used a similar fertilization scheme and found reduced nutrient uptake from a summer application. Trinexapac-ethyl applications did not reduce the dry weight biomass harvested from each plot as compared to the untreated plots across both years of the study, though reduced dry weights in the combination treatment of fertilizer + trinexapac-ethyl. Trinexapac-ethyl did not appear to enhance turf quality in either year as chlorophyll and NDVI values were similar to untreated plots, but leaf tissues were not analyzed to quantify differences. Carrier volume was not a significant factor in the performance of the fertilizer or growth regulator additions, but further research would be required on a turfgrass that was not intensively managed to quantify this hypothesis.

Fungicide Study

Carrier volume did not affect the performance of the fungicides on brown patch control. The study revealed that a 19 L ha⁻¹ carrier volume with the ULV sprayer was effective on brown patch control similar to the 561 L ha⁻¹ carrier volume with the conventional sprayer. Propiconazole and azoxystrobin are systemic fungicides. Brown patch was suppressed with a carrier volume lower than Couch (1985) and Fidanza et al. (2009) identified as necessary for disease management with systemic fungicides. Azoxystrobin was not evaluated in the Couch study as it was not released until 1996, nine years after his research was conducted. Further research would be required to determine if the 814 L ha⁻¹ carrier volume would have provided greater brown patch control versus the 561 L ha⁻¹ carrier volume with the conventional sprayer or the 19 L ha⁻¹ carrier volume

with the ULV sprayer. Contact active fungicides were not evaluated in the study to determine if the ULV sprayer at a lower carrier volume could reduce disease pressure as revealed in its disease suppression with systemic herbicides. Previous research with herbicides on weed control showed that herbicides with contact active properties were not affected by carrier volume between the two sprayers (Ferguson et al. 2013a). Treatments with azoxystrobin provided better brown patch control than the propiconazole treatments. Both fungicides showed improved brown patch control with both sprayers after the second application, 14 days after the initial application.

Additional research has been conducted to analyze droplet size and distribution between a conventional sprayer and the ULV sprayer. Droplet size and distribution were analyzed using a laser diffraction instrument (Sympatec Varios KF, Sympatec Inc., Pennington, NJ 08534) in a study to compare different application carrier volumes using a 1,061 g ae ha⁻¹ glyphosate (Roundup PowerMax, Monsanto, St. Louis, MO 63167) + 5% v/v ammonium sulfate (Bronc, Wilbur-Ellis Company, Fresno, CA, 93755) solution. Results showed a different droplet spectrum for the conventional sprayer as compared to the ULV sprayer, but identical Dv50 (median droplet size) values at the 19 L ha⁻¹ carrier volume (Ferguson et al. 2013b). Dry weight reductions in the target species from this study also showed no differences between the sprayers from both years.

Conclusions

Results from this study and previous research reveal the effectiveness of the ULV sprayer in turfgrass. Given the ability to make crop input and fungicide applications at a fifteen-fold decrease in application carrier volume greatly improves the efficiency of application for golf-course superintendents and turf managers. While it would be impossible to state that all applications with the ULV sprayer would be similar to a conventional sprayer in turfgrass, enough data exists to suggest that multiple applications can be made with this new technology without reduction in disease management or turf quality.

Literature Cited

- Anonymous 2012a. Roundup PowerMax® herbicide label. St. Louis, MO: Monsanto Co. 51p. <http://www.cdms.net/LDat/ld8CC045.pdf>
- Anonymous. 2012b. Trimec Classic® herbicide label. Kansas City, MO: PBI/Gordon Corporation. 3p. <http://www.pbigordon.com/pdfs/TrimecClassic-SL.pdf>
- Anonymous. 2012. T-NEX® 1AQ herbicide label. Raleigh, NC: Makhteshim Agan North America Inc. 15p. http://fs1.agrian.com/pdfs/T-NEX_1AQ_Label2.pdf
- Anonymous. 2010. Heritage® TL fungicide label. Greensboro, NC: Syngenta Crop Protection Inc. 20p. <http://www.cdms.net/LDat/ld6NG006.pdf>
- Anonymous. 2009a. Pendulum Aqua Cap® herbicide label. Research Triangle Park, NC: BASF Corporation. 19 p. <http://www.cdms.net/ldat/ld3BO003.pdf>
- Anonymous. 2009b. T-Zone® herbicide label. Kansas City, MO: PBI/Gordon Corporation. 6p. <http://www.pbigordon.com/pdfs/T-Zone-SL.pdf>
- Anonymous. 2009. Banner Maxx® II fungicide label. Greensboro, NC: Syngenta Crop Protection Inc. 21p. <http://www.cdms.net/LDat/ld99L000.pdf>
- Anonymous. 2008a. Tenacity® herbicide label. Greensboro, NC: Syngenta Crop Protection Inc. 14 p. http://natseed.com/pdf/Tenacity%20Herbicide_Label.pdf
- Anonymous. 2008a. Gary's Green Ultra™ foliar nutrient label. Albion, ID: Grigg Bros. 1p. <http://www.griggbros.com/attachments/200-GarysGreenUltra.pdf>
- Anonymous. 2008b. P-K Plus™ foliar nutrient label. Albion, ID: Grigg Bros. 1p. <http://www.griggbros.com/attachments/285-PKPlus.pdf>
- Anonymous. 2002. Polyox water soluble resin. Form number: 326-00001-0302 AMS. Dow Chemical Company, Midland MI. http://msdssearch.dow.com/PublishedLiteratureDOWCOM/dh_0031/0901b80380031a4a.pdf?filepath=polyox/pdfs/noreg/326-00001.pdf&fromPage=GetDoc
- Arle, H. F. 1954. The sensitivity of Alcala 44 cotton to 2,4-D. Proc. West. Weed Control Conf. 14:20-25.
- Aspinall I.H., Worthington PA. 1999. Betamethoxyacrylates; synthesis of new types of strobilurin fungicides with extended side chains. Pestic Sci 55:197-218.

- Bhowmik, P C. and S. W. Bingham. 1990. Preemergence activity of dinitroaniline herbicides used for weed control in cool-season turfgrasses. *Weed Technol.* 4:387-393.
- Bird, S.L., D.M. Esterly, and S.G. Perry. 1996. Off-target deposition of pesticides from agricultural aerial spray applications. *J. Environ. Quality* 25, 1095.
- Blue, J., C. B. Riddle and D.B. Horton. 1969. U.S. Patent 3,427,454: Low volume sprayer system. U.S. Patent Office.
- Bode, L.E., B.J. Butler, and L.M. Wax. 1985. Use of electrostatics, rotary atomizers, and vegetable oils in low volume ground application. *ASTM STP 875*, pp. 78-87.
- Bouse, L.F., J.B. Carlton and P.C. Jank. 1988. Effect of water soluble polymers on spray droplet size. *Trans. ASAE* 31(6):1633-1641, 1648.
- Burpee LL, Martin B. 1992. Biology of *Rhizoctonia* species associated with turfgrasses. *Plant Dis* 76:112-117.
- Carlsen, S. C. K., N.H. Spliid, and B. Scensmark. 2006. Drift of 10 herbicides after tractor spray application: 2. Primary Drift (droplet drift). *Chemosphere* 64(5) 778-786.
- Carrow, R.N., D.V. Waddington, and P.E. Rieke. 2001. Turfgrass soil fertility and chemical problems: Assessment and management. Ann Arbor Press, Chelsea, NY.
- Couch, H.B. 1985. Turfgrass fungicides II: Dilution rates, nozzle size, nozzle pressure and disease control. *Golf Course Management* 52(8):73-76, 78-80.
- Derksen, R.C., H.E. Ozkan, R.D. Fox, and R.D. Brazee. 1999. Droplet spectra and wind tunnel evaluation of venturi and pre-orifice nozzles. *Trans. ASAE* 42(6) 1573-1580.
- Eastin, J.A. and D. Vu. 2012. U.S. Patent 8,091,272 B2: Systems for the control and use of fluids and particles. U.S. Patent Office.
- EPA.1999. Spray drift on pesticides. EPA Publication No. 735 F99024, Environmental Protection Agency.
- Franssen A.S., J.J. Kells. 2007. Common dandelion (*Taraxacum officinale*) control with postemergence herbicides in no-tillage glufosinate-resistant corn. *Weed Technol.* 21, 14-17.

- Ferguson, J.C., R.E. Gaussoin, R.S. Henry, J.A. Eastin, and G.R. Kruger. 2013a. Comparison of Herbicide Efficacy and Adjuvants Using a Conventional Sprayer and an Ultra-Low Volume Sprayer. IN PRESS.
- Ferguson, J.C., R.E. Gaussoin, R.S. Henry, J.A. Eastin, and G.R. Kruger. 2013b. Effect of Application Carrier Volume on a Conventional Sprayer System and an Ultra-Low Volume Sprayer. IN PRESS.
- Ferguson, J.C., R.E. Gaussoin, J.A. Eastin, and G.R. Kruger. 2011. Effect of polyethylene oxide additions on droplet size and glyphosate efficacy in a conventional sprayer and an ultra-low volume sprayer. UNPUBLISHED.
- Fidanza, M.A., J.E. Kaminski, M.L. Agnew, and D. Shepard. 2009. Evaluation of water droplet size and water-carrier volume on fungicide performance for anthracnose control on annual bluegrass. *Intl. Turfgrass Soc. Res. J.* 11: 195-205.
- Fidanza, M. 2009. Fairy ring 101. *USGA Green Section Record* Mar-Apr: 8-10.
- Gaussoin, R., C. Schmid, K. Frank, T. Butler, H. Liu, W. Jarvis, and C. Baldwin. 2009. Foliar uptake of nutrients applied in solution to creeping bentgrass (*Agrostis palustris* Huds.), annual bluegrass (*Poa annua* var. *reptans* (Hauskn.) Timm), and ultra-dwarf bermudagrass (*Cynodon dactylon* × *C. transvaalensis* Burtt-Davy). *In Proc. of the Int. Plant Nutrition Colloquium*, 16th. UC Davis. Available at <http://escholarship.org/uc/item/16j7j53q> (verified 4 Feb. 2011).
- Goddard, M. J., J.B. Willis, and S.D. Askew. 2010. Application placement and relative humidity affects smooth crabgrass and tall fescue response to mesotrione. *Weed Science*, 58(1), 67-72.
- Goss, R.M., J.H. Baird, S.L. Kelm, and R.M. Calhoun. 2002. Trinexapac-ethyl and nitrogen effects on creeping bentgrass grown under reduced light conditions. *Crop Sci.* 42:472–479.
- Hatterman-Valenti, H., M.D.K. Owen, and N.E. Christians. 1996. Ground ivy (*Glechoma hederacea* L.) control in a kentucky bluegrass turfgrass with borax. *J. Environ. Hort.* 14:101-104.
- Heckman, N.L., G.L. Horst, R.E. Gaussoin, and K.W. Frank. 2001. Storage and handling characteristics of trinexapac-ethyl treated Kentucky bluegrass sod. *HortScience* 36:1127–1130.
- Hewitt, A.J. 2007. Spray optimization through application and liquid physical property variables –I. *Environmentalist* 28:25-30.

- Hewitt, A.J., D. Johnson, J.D. Fish, C.G. Hermansky, and D.L. Valcore. 2002. The development of the spray drift task force database on pesticide movements for aerial agriculture spray applications. *Environ. Toxicol. Chem.* 21(3): 660-672.
- Hewitt, A.J. 2000. Spray drift: impact of requirements to protect the environment. *Crop Protection*.19:623-627.
- Hewitt, A.J. 1997. The importance of droplet size in agricultural spraying. *Atomization and Sprays*. 7(3):235-244.
- Hixson, A. C., T. W. Gannon, and F. H. Yelverton. 2007. Efficacy of application placement equipment for tall fescue (*Lolium arundinaceum*) growth and seedhead suppression. *Weed Technol.* 21:801–806.
- Johnson, B. J. 1997. Sequential application of preemergence and postemergence herbicides for large crabgrass control in tall fescue turf. *Weed Technology*. 11: 693-7.
- Johnson, B. J. 1993a. Sequential herbicide treatments for large crabgrass (*Digitaria sanguinalis*) and goosegrass (*Eleusine indica*) control in bermudagrass (*Cynodon dactylon*) turf. *Weed Technol.* 7:674-680.
- Johnson, B. J. 1993b. Differential large crabgrass control with herbicides in tall fescue and common bermudagrass. *HortScience* 28:1015-1016.
- Jordan, T. N. 1981. Effects of diluent volumes and surfactants on the phytotoxicity of glyphosate to bermudagrass (*Cynodon dactylon*). *Weed Sci.*29:79–83.
- Kiely, T., D. Donaldson, and A. Grube. 2004. Pesticides and Industry Sales and Usage: 2000 and 2001 market estimates. U.S. EPA.
- Kirk, I.W. 2003. Spray mix adjuvants for spray drift mitigation. ASAE Paper No. AA03003. St. Joseph, Mich.: ASAE.
- Kirk, I.W. 2000. Aerial spray drift from different formulations of glyphosate. *Trans. ASAE*, 43(3):555-559.
- Knoche, M. 1994. Effect of droplet size and carrier volume on performance of foliage-applied herbicides. *Crop Protection*, 13(3), 163-178.
- Kohler, E. A., C. S. Throssell, and Z. J. Reicher. 2004a. Ground ivy (*Glechoma hederacea*) populations respond differently to 2,4-D or triclopyr. *Weed Technol.* 18:566–574.

- Kohler, E. A., Throssell C. S., and Reicher, Z. J. 2004b. Cultural and chemical control of ground ivy (*Glechoma hederacea*). HortSci. 48:566-574.
- Kreuser, W.C. and D.J. Soldat. 2012. Frequent trinexapac-ethyl applications reduce nitrogen requirements of creeping bentgrass golf putting greens. Crop Sci. 52: 1348 – 1357.
- Kudsk P. and J.C. Streibig. 2003. Herbicides—a two-edged sword. Weed Research, 43(2), 90–102.
- Lan, Y., W.C. Hoffman, B.K. Fritz, D.E. Martin, J.D. Lopez Jr. 2008. Spray drift mitigation with spray mix adjuvants. Appl. Eng. in Agric. 24(1):5-10.
- Martin, B. 2003. A new strobilurin fungicide for turfgrass disease control. Golf Course Manag. 71: 188-191.
- Martin, S.B. and L.T. Lucas. 1984. Characterization and pathogenicity of *Rhizoctonia* spp. and binucleate *Rhizoctonia*-like fungi from turfgrasses in North Carolina. Phytopathology 74: 170-175.
- McCann, S.E. and B. Huang. 2007. Effects of trinexapac-ethyl foliar application on creeping bentgrass responses to combined drought and heat stress. Crop Sci. 47: 2121-2128.
- McCullough, P.E., H. Liu, L.B. McCarty, and J.E. Toler. 2007. Trinexapac-ethyl application regimens influence growth, quality, and performance of bermudagrass and creeping bentgrass putting greens. Crop Sci. 47:2138–2144.
- McMullan, P.M. 2000. Utility adjuvants. Weed Technology 14: 792-797.
- Miller, P.C.H. and M.C.B Ellis. 2000. Effects of formulation on spray nozzle performance for applications from ground-based boom sprayers. Crop Protect. 19:609-615.
- Mueller, T. C. and A.R. Womac. 1997. Effect of formulation and nozzle type on droplet size with isopropylamine and trietium salts of glyphosate. Weed Technol. 11:639-643.
- Nuyttens, D., M. De Schampheleire, K. Baetens, E. Brusselman, D. Dekeyser and P. Verboven. 2011. Drift from field crop sprayers using an integrated approach: results of a five-year study. Trans. ASABE 54(2): 403-408.
- Patton, A., and D. Weisenberger. 2012. Herbicide Selection and Timing Influences Ground Ivy Control. 2011 Annu. Rep. - Purdue Univ. Turfgrass Sci. Progr. p. 45-48.

- Reddy, K.N., W. Ding, R.M. Zablotowicz, S.J. Thomson, Y. Huang, and L.J. Krutz. 2010. Biological Responses to glyphosate drift from aerial application in non-glyphosate resistant corn. *Pest Mgmt. Sci.* 66(10) 1148-1154.
- Reichard, D.L., H. Zhu, R.A. Downer, R. D. Fox, R.D. Brazee, H.E. Ozkan and F.R. Hall. 1996. A system to evaluate shear effects on spray drift retardant performance. *Trans ASAE* 39(6) 1993-1999.
- Salyani, M. and R.P. Cromwell. 1992. Spray drift from ground and aerial applications. *Trans. ASAE* 35(4):1113-1120.
- Sayer, H.J. 1959. An ultra-low-volume spraying technique for the control of desert locust, *Schistocera gregaria* (Forsk.). *B. Entomol. Res.* 50: 371-386.
- Sciumbato, A.S., S.A. Senseman, J.Ross, T.C. Mueller, J.M. Chandler, J.T. Cothren, and I.W. Kirk. 2005. Effects of 2,4-D formulation and quinclorac on spray droplet size and deposition. *Weed Technol.* 19:1030-1036.
- Schleier III, J.J., R. K. D. Peterson, K.M. Irvine, L.M. Marshall, D.K. Weaver, C.J. Preftakes. 2012. Environmental fate model for ultra-low-volume insecticide applications used for adult mosquito management. *Sci.of the Tot. Env.* 438:72-79.
- SDTF (Spray Drift Task Force) 1997. A summary of ground spray application studies. Macon, MO.: Stewart Agricultural Research Services Inc.
- Settle, D., J. Fry, and N. Tisserat. 2001. Dollar spot and brown patch fungicide management strategies in four bentgrass cultivars. *Crop Sci* 41: 1190-1197.
- Sharma, S.D. and M. Singh. 2001. Surfactants increase toxicity of glyphosate and 2,4-D to Brazil pulse. *Hort. Sci.* 36:726-728.
- Spanoghe, P., M. De Schampheleire, P. Van der Meeren and W. Steurbaut. 2007. Influence of agricultural adjuvants on droplet spectra. *Pest Manag Sci* 63: 4-16.
- Stiegler, J.C., M.D. Richardson, and D.E. Karcher. 2011. Foliar nitrogen uptake following urea application to putting green turfgrass species. *Crop Sci* 51: 1253-1260.
- Whisenant, S. G., L. F. Bouse, R. A. Crane, and R. W. Bovey. 1993. Droplet size and spray volume effects on honey mesquite mortality with clopyralid. *J. Range Manag.* 46:257-261.

- Woznica, Z., J. D. Nalewaja, C.G. Messersmith and P. Milkowski. 2003. Quinclorac efficacy as affected by adjuvants and spray carrier water. *Weed Technol.* 17:582-588.
- Yates, W.E., N.B. Akesson, and D. Bayer. 1976. Effects of spray adjuvants on drift hazards. *Trans. ASAE*, 19:41-46.
- Zhu, H., D.L. Reichard, R.D. Fox, R.D. Brazee and H.E. Ozkan. 1994. Simulation of drift of discrete sizes of water droplets from field sprayers. *Trans ASAE* 37(5):1401-1407.