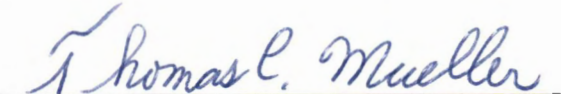
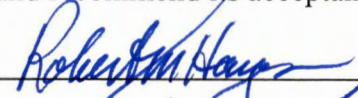
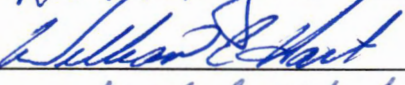
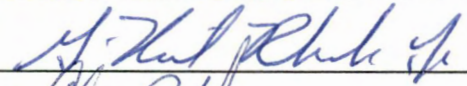
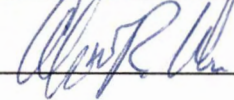


To the Graduate Council:

I am submitting herewith a dissertation written by Robert E. Etheridge entitled "Venturi Drift Reduction Nozzles: Spray Pattern Characteristics, Efficacy of Postemergence Herbicides, and Accuracy of Herbicide Placement." I have examined the final copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Plant and Soil Science.


Thomas C. Mueller, Major Professor

We have read this dissertation
and recommend its acceptance:

Accepted for the Council:


Associate Vice Chancellor and
Dean of The Graduate School

**VENTURI DRIFT REDUCTION NOZZLES: SPRAY PATTERN
CHARACTERISTICS, EFFICACY OF POSTEMERGENCE HERBICIDES, AND
ACCURACY OF HERBICIDE PLACEMENT**

A Dissertation
Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

Robert E. Etheridge

December, 1999

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Thesis
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DEDICATION

I dedicate this dissertation to my wife Elizabeth, whose love, encouragement, and patience made this endeavor possible and to my parents, Bobby and Joan, who have continually supported me in every step of my personal and professional development.

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ABSTRACT

Laboratory and field studies were conducted to evaluate the drift potential and efficacy of commonly used postemergence herbicides applied through venturi-type drift reduction nozzles as compared to a standard flat fan nozzle. Laboratory studies were conducted utilizing a Malvern laser droplet/particle size analyzer to determine the droplet spectra produced by a given nozzle. Spray solutions of glufosinate, glyphosate, and paraquat were applied through all combinations of five nozzle types (four venturi), three tip sizes, and four application pressures. Nozzles were also evaluated for pattern uniformity utilizing water plus surfactant at one pressure. When averaged over herbicide, tip size, and pressure the venturi nozzles collectively produced larger volume median diameter droplets than the standard nozzle. The percent of spray volume in droplets $< 205\ \mu\text{m}$ was less for the venturi nozzles (17%) than for the standard nozzle (65%) when averaged across all factors. The order of herbicides producing the largest droplets was paraquat ($470\ \mu\text{m}$) $>$ glyphosate ($460\ \mu\text{m}$) $>$ glufosinate ($400\ \mu\text{m}$), as measured by volume median diameter. The venturi nozzles were more variable in their spray volume distribution than the standard nozzle.

Field studies were conducted to compare nozzle effects on the efficacy of postemergence herbicides applied to common cocklebur (*Xanthium strumarium*) and broadleaf signalgrass (*Brachiaria platyphylla*). Spray solutions of commercial formulations of glufosinate, glyphosate, and paraquat were applied through all combinations of three nozzles (two venturi) and two application volumes. Nozzle type had the most consistent effect on common cocklebur control. The Delavan Raindrop

Ultra venturi nozzle provided the least control ($\leq 93\%$) and least biomass reduction (87%). The Spraying Systems AI Teejet venturi nozzle and the Spraying Systems XR Teejet flat fan nozzle provided similar levels of control (94 to 96%) and biomass reduction (92 and 93%). Nozzle type also affected broadleaf signalgrass control, but herbicide had the most consistent effect. Glyphosate controlled broadleaf signalgrass less ($\leq 88\%$) than either glufosinate or paraquat (92 to 98%).

Field studies were conducted to measure nozzle effects on the accuracy of herbicide deposition in a target area and to identify the nozzle parameters responsible for accurate herbicide placement. The Delavan Raindrop Ultra and Spraying Systems AI Teejet venturi nozzles deposited a larger percentage of applied herbicide in the target area than the flat fan nozzle. However, the uniformity of herbicide deposition was similar for the venturi and flat fan nozzles. Increasing application volume increased the uniformity of herbicide deposition in the target area with all nozzles. Correlation analysis indicated that the percentage of spray volume contained in droplets smaller than approximately 200 μm was most important in determining herbicide deposition.

Venturi nozzles produce larger droplets which are less susceptible to drift than droplets produced by conventional flat fan nozzles. However, venturi nozzles vary in the size of droplets produced and the level of weed control they provide. Venturi nozzles which produce droplets of approximately 450 μm can provide weed control similar to that provided by a flat fan nozzle, whereas, venturi nozzles which produce 650 μm droplets provide less weed control than a flat fan nozzle. Venturi nozzles can reduce the drift potential of herbicide sprays and, depending on the specific nozzle, can be as effective as

flat fan nozzles with a variety of postemergence herbicides. Due to their overall reduction in drift potential of herbicide sprays, venturi nozzles can provide producers with increased flexibility with respect to the timing and location of herbicide applications. Also, utilization of venturi nozzles will allow producers to tailor herbicide application parameters, such as herbicide choice and application volume, to optimize weed control while minimizing drift potential.

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PART I
INTRODUCTION

BACKGROUND

Weed control systems have undergone tremendous changes in the past few years. The introduction of crops tolerant to non-selective products, such as glufosinate and glyphosate, has facilitated a shift in grower reliance from predominately preemergence (PRE) programs to postemergence (POST) programs. Because of their broad spectrum of activity, these POST programs are often simpler and less expensive than traditional combinations of PRE and POST products. However, accurate application of these products is critical to maintain weed control and reduce drift potential and subsequent damage to sensitive vegetation. Historically, drift has not been a major concern because most non-selective product applications were made early in the spring, prior to emergence of sensitive vegetation. Also, most in-season POST applications consisted of selective products. There is a need to minimize drift potential while maintaining adequate control with the new non-selective POST programs.

Herbicide drift potential and subsequent damage to sensitive species is predominately affected by droplet size produced by the sprayer (Yates et al. 1976) and environmental conditions such as wind speed. Larger droplets are heavier and will not remain in air currents as long as smaller droplets, thus reducing their likelihood and range of drift. Similarly, droplet size plays a key role in efficacy since adequate coverage of the target plant is necessary. At a constant volume of spray output, more smaller droplets can be produced relative to larger droplets thus increasing the potential for plant coverage and subsequent control. Obviously, some compromise between droplet sizes optimized for weed control and drift reduction will be required and will likely differ based on the target

HERBICIDE CHARACTERISTICS

Glyphosate is a non-selective, broad spectrum herbicide (Figure 1)¹ that is currently labeled to be applied POST to Roundup Ready^{®2} crops which have been genetically altered to tolerate glyphosate. In the US, Roundup Ready[®] cotton and soybeans were planted on approximately 3.5 and 40 million acres, respectively, in 1999 (Anonymous 1999). Non-tolerant crops and over 90 weed species are susceptible to glyphosate (Anonymous 1998a). Glyphosate inhibits EPSP synthase in susceptible plants which leads to depletion of the amino acids tryptophan, tyrosine, and phenylalanine. Subsequent inhibition of protein production and build up of shikimate result in death (Amrhein et al. 1980). Injury symptoms on highly susceptible species, such as annual grasses, may appear within a week after application while less susceptible species may not be fully controlled for 15 to 20 days following application. Glyphosate has no soil activity because it is quickly and tightly adsorbed by soil. This adsorption is a function of vacant phosphate sorption sites on the soil and not soil organic matter, clay content, and other soil parameters usually associated with herbicide adsorption (Anonymous 1994). Glyphosate is absorbed across the cuticle of plants and is transported primarily symplastically to underground tissues, immature leaves, and meristems (Boerboom and Wyse 1988, Marshall et al. 1987, Martin and Edgington 1981). Al-Khatib et al. (1993) found that indirect deposition of glyphosate at 1/30 the labeled rate of 0.43 kg ai/ha could produce visible injury symptoms on bean plants. While glyphosate is unlikely to move

¹ All figures and tables may be found in Appendix A and Appendix B, respectively.

² Roundup Ready[®]. Monsanto Company, St. Louis, MO 63167.

weed and possibly application volume.

Droplet size is primarily affected by nozzle design, orifice size, application pressure, and solution characteristics such as surface tension. Herbicides have been traditionally applied with hydraulic flat fan nozzles in an application volume of 150 to 200 L/ha of water at approximately 275 kPa spray pressure. Economic savings afforded by transporting less water and covering more acreage with a given volume of water has prompted applicators to reduce application volume in recent years. Also, the previously discussed concerns of drift with the new non-selective herbicide systems has led to a new generation of spray tips designed to produce a higher percentage of large drops.

This research will focus on three non-selective herbicides, two of which are registered for postemergence use on their respective genetically engineered crops; four venturi drift reducing spray nozzles and one conventional flat fan nozzle; and three spray application volumes as achieved by varying tip size. Laboratory analysis with a Malvern laser will be conducted to characterize spray droplet size distribution for each combination of herbicide, nozzle type, tip size (spray volume), and pressure. This data will be analyzed and corresponding efficacy values will be determined in the field for the three herbicides, the two lower carrier volumes, and the nozzles which produce the largest, smallest, and intermediate droplet sizes, as measured by the Malvern analysis. Herbicide deposition within a target area will also be evaluated with one herbicide only.

due to volatilization (Anonymous 1994), drift losses can occur under certain conditions.

Glufosinate is a non-selective, broad spectrum herbicide (Figure 1) that has more contact activity than glyphosate. Glufosinate has little to no soil activity due to rapid microbial breakdown and is only moderately mobile in plant xylem or phloem (Anonymous 1994). It acts by inhibiting glutamine synthase in susceptible plants (Lea et al. 1984), resulting in a buildup of ammonia and glyoxylate in susceptible plants.

Ammonia acts locally to destroy cell membranes, whereas the accumulation of glyoxylate inhibits the activation of RUBP carboxylase (Wild and Wendler 1990). Glufosinate acts directly to destroy cell membranes and indirectly to reduce photosynthesis. Visible signs of injury usually occur within 3 to 5 days of application and death within 1 to 2 weeks.

Glufosinate is rainfast in 4 hours and activity is enhanced by bright sunlight, high humidity, and moist soil conditions (Anonymous 1998a). Glufosinate is labeled to apply POST to Liberty Link^{®3} corn which has been genetically altered to tolerate glufosinate.

Tolerance was imparted to Liberty Link[®] corn by cloning a gene from a soil bacteria which codes for the enzyme that converts glufosinate into a non-phytotoxic metabolite and inserting the gene into crop species (De Block et al. 1987, Thompson et al. 1987).

Non-tolerant crops and a wide range of weeds are susceptible to glufosinate. Glufosinate is as effective or more effective than glyphosate at controlling barnyardgrass, morningglory, prickly sida, and hemp sesbania (Lanie et al. 1994) and other annual broadleaf and grass weeds (Kapusta and Bates 1982, Kapusta 1981).

Paraquat is a non-selective, broad spectrum, contact herbicide (Figure 1). It is

³ Liberty Link[®]. AgrEvo USA Company, Wilmington, DE 19808.

quickly and tightly bound to clay particles and subsequently has no soil activity. It is primarily used preplant or PRE to control existing vegetation in reduced tillage production systems but can also be applied POST-directed in various crops and as a dessicant. Paraquat is rapidly absorbed into plants and can cause wilting and desiccation within one hour of application. Necrosis of affected plant tissue occurs within 1 to 3 days. Paraquat is transported apoplastically and remains in the leaves under normal conditions causing localized activity only. It acts by accepting electrons from photosystem I and reacting with oxygen in the cells to form a superoxide radical. Subsequent cellular reactions produce hydroxyl which readily attacks unsaturated fatty acids such as membrane fatty acids and chlorophyll. Intermediate products in this reaction react with hydroxyl to create a self-perpetuating reaction of lipid degradation which destroys cell membranes and results in rapid leaf wilting and desiccation (Anonymous 1994). Paraquat is not metabolized in plants and is highly effective on most species. It is not volatile, but its rapid and broad spectrum activity create concerns about drift damage. This is especially true when paraquat is utilized in situations where non-target vegetation may be present and actively growing such as in preplant applications for late-planted crops or in desiccation applications.

DROPLET SIZE AND APPLICATION VOLUME EFFECTS

There is increased interest in reducing application volumes. Research has focused on the effects of varying carrier volume on herbicide efficacy (Brewster and Appleby 1990, Cranmer and Linscott 1990, McMullen 1995, Whisenant et al. 1993) and results

vary with some chemicals. Increasing carrier volume increased the efficacy of imazamethabenz (Brewster and Appleby 1990), while fenoxaprop-p-ethyl efficacy remained constant over a wide range of volumes (McMullen 1995). Activity of glyphosate (Ambach and Ashford 1982), sethoxydim (McMullen 1995), and paraquat (McKinlay et al. 1972) increased as application volume decreased. A recent review of the literature by Knoche (1994) indicated a wide variation in efficacy with different application volume and herbicide combinations. This work also illustrated differences among weed species at given volumes and droplet sizes. The angle of spray incidence on the leaf varies among species and was indicated as a major cause of this variation. Glyphosate activity on velvetleaf was increased by applying the same quantity of glyphosate in fewer, more concentrated drops as compared to more, less concentrated drops (Cranmer and Linscott 1990). Clopyralid activity on honey mesquite was greater with less concentrated droplets applied in greater numbers (Whisenant et al. 1993). Droplet size is also an important factor in efficacy of POST herbicides (Ambach and Ashford 1982, Boerboom and Wyse 1988, McKinlay et al. 1974, McKinlay et al. 1972), with small droplets generally producing greater levels of control than large droplets. Whisenant et al. (1993) concluded that larger carrier volumes were necessary to maximize efficacy when large spray droplets were utilized.

As discussed earlier, spray droplet size is a major determinant of the drift potential of a herbicide spray (Mueller and Womac 1997, Whisenant et al. 1993, Yates et al. 1976). Specifically, droplets smaller than 200 μm are most susceptible to drift. Droplet size is commonly adjusted by changing the size of the spray nozzle orifice and/or the operating

pressure, with smaller orifices and higher pressure producing smaller drops. Nordby and Skuterud (1975) reported that increasing pressure from 250 to 1000 kPa reduced droplet size mass median diameter from 306 to 196 μm and increased the total drift of spray from 1.4 to 2.9%. Nozzle manufacturers are currently marketing nozzles in orifice sizes capable of producing a higher percentage of large drops over a wide range of operating pressures (Mueller and Womac 1997). There may be a conflict between maximizing droplet size to control drift and minimizing droplet size and carrier volume to increase efficacy and efficiency.

Numerous studies have evaluated the individual influences of nozzle type, tip size, and pressure on spray droplet characteristics. However, little work has been done to evaluate the effects of herbicide formulation and how it interacts with other factors in terms of spray droplet parameters. Furthermore, few studies have allowed for comparisons between measured spray pattern characteristics and herbicide deposition and weed control under field conditions.

PART II

**CHARACTERIZATION OF THE SPRAY DROPLET SPECTRA AND
PATTERNS OF FOUR VENTURI DRIFT REDUCTION NOZZLES¹**

¹Published in Weed Technology 13(4):xx. Authors: R. E. Etheridge, A. R. Womac, and T. C. Mueller. Res. Assoc., Dept. of Plant and Soil Sciences; Assoc. Prof., Dept. of Agric. and Biosystems Eng.; and Assoc. Prof., Dept. of Plant and Soil Sciences, Univ. of Tennessee, Knoxville.

ABSTRACT

Laboratory studies were conducted utilizing a Malvern laser droplet/particle size analyzer to determine the droplet spectra of several venturi-type drift reduction nozzles as compared to a standard single-, elliptical-orifice flat fan nozzle. Spray solutions of glufosinate, glyphosate, and paraquat were applied through all combinations of five nozzle types (four drift reduction), three tip sizes, and four application pressures. Nozzles were also evaluated for pattern uniformity utilizing water plus surfactant at one pressure. When averaged over herbicide, tip size, and pressure the venturi nozzles collectively produced larger volume median diameter droplets than the standard nozzle. The percent of spray volume in droplets $< 205\ \mu\text{m}$ was less for the venturi nozzles (17%) than for the standard nozzle (65%) when averaged across all factors. The order of herbicides producing the largest droplets was paraquat ($470\ \mu\text{m}$) $>$ glyphosate ($460\ \mu\text{m}$) $>$ glufosinate ($400\ \mu\text{m}$), as measured by volume median diameter. The venturi nozzles were more variable in their spray volume distribution than the standard nozzle. Utilization of venturi-type nozzles may minimize the drift potential of the herbicides evaluated but could also lead to uneven herbicide application and subsequent erratic weed control.

Nomenclature: glufosinate, 2-amino-4-(hydroxymethylphosphinyl)butanoic acid; glyphosate, isopropylamine salt of N-(phosphonomethyl)glycine; paraquat, 1,1'-dimethyl-4,4'-bipyridinium ion.

Additional Index Words: Glufosinate, glyphosate, paraquat, Malvern, venturi nozzle.

Abbreviations: AI, Spraying Systems AI Teejet; CV, coefficient of variation; HSD,

Tukey's Honest Significant Difference; LM, Lurmark Ultra Lo-Drift; NIS, nonionic surfactant; POST, postemergence; PRE, preemergence; RU, Delavan Raindrop Ultra; TD, Greenleaf TurboDrop; VMD, volume median diameter; V205, volume of spray in droplets less than 205 μm in diameter; XR, Spraying Systems XR Teejet.

INTRODUCTION

The use of herbicides such as glyphosate and glufosinate in tolerant crops has shifted grower reliance from predominately preemergence (PRE) herbicide programs to postemergence (POST) programs. Because of their broad spectrum of activity, these POST herbicides are often simpler and less expensive than traditional combinations of more selective PRE and POST herbicides. However, proper application of these products is critical due to potential off-site spray drift and damage to non-tolerant crops and other sensitive vegetation. Historically, most non-selective herbicides were applied early in the spring, prior to emergence of sensitive crops. Due to liability concerns over drift damage, there is a need to minimize drift potential with the new POST programs.

Cost of transporting water has prompted applicators to reduce carrier volume and cover more area with less water. Knoche (1994) indicated wide variation in efficacy with different carrier volume and herbicide combinations. Glyphosate activity on velvetleaf (*Abutilon theophrasti*) was increased by applying the same quantity of glyphosate in fewer, more concentrated droplets as compared to more, less concentrated droplets (Cranmer and Linscott 1990). Clopyralid activity on honey mesquite (*Prosopis glandulosa*) was greater with less concentrated droplets applied in greater numbers

(Whisenant et al. 1993). Whisenant et al. (1993) concluded that increased carrier volumes were necessary to maximize efficacy when large spray droplets were utilized. Small droplets generally produce greater levels of control than large droplets (Ambach and Ashford 1982, Boerboom and Wyse 1988, McKinlay et al. 1974, McKinlay et al. 1972).

Droplet size is the major determinant of drift potential of herbicide sprays (Mueller and Womac 1997, Whisenant et al. 1993, Yates et al. 1976). Droplets smaller than 200 μm are most susceptible to drift. Droplet size can be adjusted by changing the nozzle orifice size and/or the operating pressure, with smaller orifices and higher pressures producing smaller droplets. Nordby and Skuterud (1975) increased the spray pressure from 250 to 1000 kPa and reduced droplet size mass median diameter (MMD) from 306 to 196 μm and increased total drift of spray from 1.4 to 2.9%. Nozzle manufacturers are currently marketing nozzle designs capable of producing larger droplets over a wide range of operating pressures (Mueller and Womac 1997). New venturi nozzles consist of a flow-metering pre-orifice, an air-fluid venturi and mixing chamber, and a flat fan orifice to define the pattern.

Little published data exists defining the spray droplet spectra and pattern characteristics of venturi-type drift reduction nozzles. Some studies have reported the individual effects of nozzle type and pressure on spray droplet spectrum (Combella et al. 1996, Nordby and Skuterud 1975), yet few have examined herbicide solution or carrier volume effects on atomization. Moreover, little work has been reported on the interaction of nozzle type, carrier volume, spray pressure, and herbicide on spray droplet spectrum

characteristics. The objectives of this research were to: (1) characterize the droplet spectra of the newest venturi nozzles as compared to a single-, elliptical-orifice flat fan nozzle, (2) evaluate how three POST herbicides and carrier volumes affect spray droplet characteristics over a range of spray pressures, and (3) quantify the variation in spray pattern for the venturi nozzles.

MATERIALS AND METHODS

Four venturi-type drift reduction nozzles were analyzed and compared to a single-, elliptical-orifice flat fan nozzle. The venturi nozzles included a Delavan Raindrop Ultra (RU)², Greenleaf TurboDrop (TD)³, Lurmark Ultra Lo-Drift (LM)⁴, and Spraying Systems AI Teejet (AI)⁵. The flat fan nozzle was a Spraying Systems XR Teejet (XR)⁵. For each nozzle type, tips were fan sprays of 110° spray angle with nominal discharge rates of 0.57, 1.14, and 1.51 L/min at 276 kPa to simulate field application volumes of 50, 100, and 150 L/ha, respectively, assuming field application speeds of 11.9 to 13.4 km/h and a nozzle spacing of 51 cm. The tip sizes producing 0.57, 1.14, and 1.51 L/min application volumes are hereafter referred to as 110015, 11003, and 11004, respectively.

² Raindrop Ultra®. Delavan Spray Technologies, Monroe, NC 28110.

³ TurboDrop®. Greenleaf Technologies, Covington, LA 70434.

⁴ Ultra Lo-Drift®. Lurmark LTD, Long Stanton, Cambridge. Distributed by Precision Fitting and Valve Co. Inc., Farmington, MN 55024.

⁵ AI Teejet® and XR Teejet®. Spraying Systems Co., Wheaton, IL 60188.

Droplet Spectra Analysis. Commercial formulations of glufosinate⁶, glyphosate⁷, and paraquat⁸ were added to water carrier to maintain constant application rates of 0.43, 0.84, and 0.71 kg ai/ha, respectively, at all application volumes. To accomplish this, separate mixes of each herbicide were prepared in 11-L stainless steel containers and delivered to the nozzles by compressed air at controlled pressure. These represent normal use rates for these herbicides (Anonymous 1998a). A nonionic surfactant⁹ (NIS) at 0.25% v/v was included with the paraquat solutions.

All nozzle evaluations were made at pressures of 100, 276, 450, and 625 kPa. A pressure reading was taken at the nozzle body and controlled to within +/- 2 kPa of the target pressure. No tip screens were used to maximize the accuracy of the pressure readings at the nozzle.

A Malvern 2605 Lc droplet/particle size analyzer¹⁰ fitted with a 1000-mm lens was utilized to quantify the spray droplet spectrum. Droplets produced by venturi-type nozzles contain air bubble pockets that may bias the measurements of some instruments that view droplets and droplet content. The Malvern measures droplets and does not view droplet content. Further, the Malvern measures number density weighted values (often

⁶ Liberty® herbicide. AgrEvo USA Company. Wilmington, DE 19808.

⁷ Roundup Ultra® herbicide. Monsanto Company, St. Louis, MO 63167.

⁸ Gramoxone Extra® herbicide. Zeneca Ag Products, Wilmington, DE 19850-2500.

⁹ X-77® nonionic surfactant, which is a mixture of alkylaryl polyoxyethylene, glycols, free fatty acids, and isopropanol. Loveland Industries Inc., Greeley, CO 80632.

¹⁰ Malvern Instruments, Malvern England.

referred to as spatial) and can overestimate numbers of small droplets, which have a slower settling velocity relative to larger droplets. However, instrument effects on measurement are well documented and acceptable (Womac et al. 1999). Spray droplets were directed through the path of the Malvern's collimated laser beam causing light rays to be diffracted onto a multi-element detector. Small droplets diffract light at a greater angle than large droplets, causing light rays to strike the detector further along the detection radius. The computer mathematically converts the pattern of the diffracted light scatter into a droplet size distribution.

The Malvern instrument was mounted on an adjustable stand so that the laser beam was horizontal to the ground, just above a stainless steel table that functioned as a catch basin for applied solutions. A nozzle was mounted on a carriage 30 cm above the laser beam and manually traversed allowing the spray to be directed down into and across the beam. The data collection software allowed the detected energy levels to be constantly observed and these data were used to verify that the entire spray pattern intersected the laser beam on each pass. A constant back-and-forth movement of about 20 passes of the nozzle over the beam was maintained during data acquisition (24-s period). Fiberglass filter media was placed on the table directly under the path of the nozzle to minimize droplet bounce which could contaminate the detector lens and result in inaccurate measurements. The test procedures, as previously described by Mueller and Womac (1997) were (1) align laser, (2) update data gathering software, (3) measure background light intensity, (4) establish nozzle + tip size + herbicide + pressure condition, (5) initiate data collection, (6) manually traverse spray pattern across laser

beam until measurement period ends, and (7) stop spray output and inspect data for validity. The Malvern instrument polled 10,000 light diffraction events during the 24-s measurement period and converted the energy pattern into a corresponding droplet size distribution.

Each run of an experimental unit produces a tremendous amount of information, consisting of the percentage of spray volume in each of 32 ranges of droplet size from 5 to 1880 μm . The volume median diameter (VMD), which is the point where one-half of the spray volume is in smaller droplets, and the percentage of spray volume in droplets less than 205 μm (V205) are presented. Instrument lens selection and corresponding divisions of droplet sizes resulted in the instrument producing a division in the droplet spectrum at 205 μm , which is near the well-accepted 200 μm level used for describing a “driftable” droplet. While there is no clear definition of a “driftable” droplet, Nordby and Skuterud (1975) reported an increase in total drift of spray solution from 1.4% to 2.9% as MMD droplet size was reduced from 306 to 196 μm . Thus the V205 data may provide a reasonable measure of the amount of small or driftable droplets present. Due to time requirements for establishing each treatment combination, the experiment was conducted over a 14-day period. An internal standard of glyphosate applied through the XR11003 nozzle was evaluated at the beginning and end of each day to ensure consistent operation of the equipment. The data were consistent and resulted in a coefficient of variation (CV) less than 5%, which was in agreement with work by Womac et al. (1999) characterizing the sources of variation in laser-derived droplet spectrum measurements. Due to the precision of the test system and repeatability of results over time, the study was conducted

in a completely randomized design with three replicates and data subjected to an analysis of variance (ANOVA). For all significant treatment effects, means were compared using Tukey's Honest Significant Difference (HSD) test at the 5% significance level. Tukey's HSD was utilized to reduce the chance of type I errors since there were such a large number of comparisons (Steele and Torrie 1980).

Pattern Variation Analysis. A Lurmark patternator table¹¹ was used to determine the variation in output pattern from each nozzle + tip size combination. The patternator table consists of 60 troughs that are 5 cm wide at the top and arranged adjacent to each other so output from a 305-cm wide spray boom can be collected. The table was mounted with the troughs horizontal with the ground on a wheeled frame to allow it to be moved in and out of a spray pattern. The table can be tilted to allow the captured spray solution to accumulate in graduated cylinders mounted at the end of each trough and provide a measure of spray output at 5 cm increments across the spray pattern. Measurements from the individual graduated cylinders were then utilized to compute a CV across the pattern of each nozzle + tip size combination. Sample standard deviations and CV values were computed according to procedures detailed by Sokal and Rohlf (1981).

A spray boom was mounted 41 cm above the table and nozzles were placed 51 cm apart along the boom such that they sprayed down upon the table. Boom height and nozzle spacing were selected to represent the recommendations of most of the nozzle manufacturers for 110° angle nozzles (Anonymous 1995, Anonymous 1998d). Literature

¹¹ Lurmark LTD, Long Stanton, Cambridge. Distributed by Precision Fitting and Valve Co. Inc., Farmington, MN 55024.

from Delavan (Anonymous 1998b) and Greenleaf Technologies (Anonymous 1998c) did not directly provide boom-height recommendations for the RU and TD nozzles, respectively, on a 51-cm nozzle spacing. A boom height of 41 cm was chosen to represent the lowest practical height for use in most POST herbicide application situations. The only factors evaluated were nozzle type (RU, TD, LM, AI, XR) and tip size (110015, 11003, 11004). All measurements were made at a spray pressure of 276 kPa with a spray solution of water plus NIS at 0.25% v/v mixed in stainless steel cans and delivered to the nozzles with compressed CO².

The test procedures were (1) align table under boom, (2) establish nozzle type + tip size combination, (3) initiate spray application, (4) stop spray application after measurement period, (5) raise table vertically so spray accumulates in graduated cylinders, (6) measure and record accumulated spray solution in each cylinder, and (7) invert table to empty each cylinder. To minimize visual measurement variability and to compare similar accumulated volume, the measurement period was 45, 30, and 20 s for the 110015, 11003, and the 11004 tips, respectively. The study was conducted in a completely randomized design with three replicates and data subjected to an ANOVA. For all significant treatment effects, means were compared using Tukey's HSD test at the 5% significance level (Steele and Torrie 1980). Tukey's HSD was utilized to reduce the chance of type I errors.

RESULTS AND DISCUSSION

The interaction of nozzle, herbicide, tip size, and pressure was significant

(ANOVA not shown). Due to the large number of treatment combinations (180), only a few discrete datum will be discussed. Glufosinate applied through the RU110015 nozzle-tip size combination at 100 kPa produced larger VMD droplets (1242 μm) and fewer small droplets ($V_{205} = 1.4\%$) than any other treatment combination. Glufosinate applied under these conditions has less drift potential than any other application scenario evaluated. Paraquat applied through the XR110015 nozzle-tip size combination at 625 kPa produced the smallest VMD droplets (120 μm), the most small droplets ($V_{205} = 90.3\%$), and has the greatest drift potential of any treatment combination evaluated. Data pooled over nozzle, herbicide, tip size, and pressure are shown in Table 1. The pooled data will be primarily utilized to simplify the discussion.

Nozzle Type. When averaged over herbicide, tip size, and pressure, the venturi nozzles produced larger droplets than the XR nozzle (Table 1). Nozzles producing from largest to smallest droplets, as measured by VMD, were $\text{RU} > \text{AI} > \text{TD} > \text{LM} > \text{XR}$, respectively. Similarly, the venturi nozzles resulted in less spray volume containing small droplets as compared to the XR nozzle (Table 1). Nozzles producing from fewest to most small droplets were $\text{RU} < \text{TD} < \text{AI} = \text{LM} < \text{XR}$, respectively, as measured by V_{205} . The smallest and largest mean V_{205} values for each herbicide were produced by the RU and XR nozzles, respectively (Table 2). The other venturi nozzles (AI, LM, TD) performed similarly and resulted in mean V_{205} values ranging from 17.2% to 17.8% using glyphosate. The AI and TD nozzles performed similarly with glufosinate (24.0 and 23.0%, respectively) and paraquat (13.7 and 13.5%, respectively). Based on this data, the venturi nozzles may reduce drift potential by producing large droplets and minimizing

small droplets. These nozzles should minimize drift potential when applying broad spectrum herbicides in close proximity to non-target, sensitive vegetation.

Herbicide. Herbicides producing from largest to smallest mean VMD were paraquat > glyphosate > glufosinate, respectively (Table 1). Herbicides producing from smallest to largest mean V205, or percentage of spray in small droplets, was paraquat < glyphosate < glufosinate, respectively. If the interaction of nozzle type with herbicide is examined (Table 2), glufosinate consistently produced the smallest mean VMD and largest V205 (indicating many small droplets) across all nozzles, though not always significant.

Herbicides producing from largest to smallest mean V205 values (Table 2) were glufosinate > glyphosate > paraquat, respectively, with the AI, RU, and TD nozzles.

Glyphosate and paraquat resulted in similar values with the LM and XR nozzles. These results indicate that glufosinate may result in a higher percentage of smaller, potentially more “driftable” droplets than either glyphosate or paraquat, independent of nozzle type.

Tip Size and Pressure. Decreasing tip size increased the mean V205 (Table 1) since reducing tip size within the same nozzle type generally results in smaller droplets produced (Womac et al. 1997). Additionally, an unexpected effect on VMD was discovered. Mean VMD values of 448, 421, and 454 μm were produced by the 110015, 11003, and 11004 tips, respectively, when averaged over all factors. Increasing tip size generally increased the mean VMD and decreased the mean V205 produced by each nozzle, except for the RU and TD nozzles (Table 3). The RU nozzles exhibited the opposite trend, with mean VMD decreasing and mean V205 increasing as tip size increased, which likely accounts for the unexpected response in VMD when averaged

over all factors. These unexpected results are likely due to flow turbulence within the nozzle. The XR nozzle exhibited the greatest response to increasing tip size, resulting in mean V205 values of 79.0, 62.2, and 53.2% for the 110015, 11003, and 11004 tips, respectively. This emphasizes the need for effective drift control practices in low application volume systems. As expected, increasing pressure decreased the mean VMD and increased the mean V205 (Nordby and Skuterud 1975) produced by each tip (Table 1).

Pattern Variability. At 100 kPa some of the venturi nozzles produced spray patterns which were narrow and poorly defined (data not shown). At 276 kPa and above, all nozzles produced satisfactory spray patterns.

Pattern variability refers to the evenness of spray volume distribution across the width of spray pattern produced by nozzles on a boom. Coefficient of variation is commonly used to measure this variability and Figure 1 illustrates the relative distribution of output across a 305-cm boom represented by CV values of 24.2 and 12.1 %. These values were the second-highest and the lowest CV values measured in the study and resulted from the TD + 11004 and XR + 11004 nozzle + tip size combinations, respectively. The venturi nozzles were generally more variable in spray pattern distribution than the XR nozzle (Table 4). The high CV values were caused by a disproportionate accumulation of spray volume between the nozzles which was probably due to larger droplet formation at the outermost edges of each nozzle spray pattern. This increased variation in spray distribution by the venturi nozzles could result in inconsistent weed control due to uneven herbicide application as compared to standard single-,

elliptical-orifice nozzles, especially when spraying large weeds and/or reduced herbicide application rates. Pattern variability was also affected by tip size with the venturi nozzles. The XR nozzle exhibited similar variation across all tip sizes (12.1 to 13.3%). The AI and RU nozzles exhibited the greatest variability (largest CV) with the smallest tip size (22.6 and 27.2%). This is an important finding since reduced application volumes are being used which risk poor spray coverage and uneven spray distribution with certain nozzle types. This could possibly be reduced by altering boom height or the nozzle spacing along the boom. However, increasing the boom height increases drift potential (Nordby and Skuterud 1975) and may offset any reduced drift potential gained by utilizing nozzles which produce larger droplets.

Recent concerns about spray drift have prompted applicators to focus on improved methods to reduce off target pesticide movement (Combellack et al. 1996). The data reported herein indicate that utilization of venturi-type drift reduction nozzles can result in spray patterns with larger, less drift-prone droplets than standard single-, elliptical-orifice flat fan nozzles. Venturi nozzle technology may provide applicators with the flexibility to apply non-selective herbicides in areas or conditions not possible with conventional nozzles. This is essential as producers increasingly rely on timely POST applications for acceptable weed control. However, it is clear that no single nozzle will perform best under all conditions, as evidenced by variable nozzle performance with different herbicides or tip sizes. Performance variation illustrates the necessity to document nozzle performance under different application scenarios and provide applicators with the resulting information necessary to make informed decisions

regarding drift control. The efficacy of potential products applied with these venturi-type nozzles under a wide range of conditions has not been fully addressed. Increased carrier volumes are necessary to maximize the efficacy of certain herbicides applied in large droplets (Whisenant et al. 1993) and similar responses could be expected from the venturi nozzles, especially when contact herbicides such as paraquat are utilized.

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PART III

EFFECT OF VENTURI DRIFT REDUCTION NOZZLES AND APPLICATION

VOLUME ON POSTEMERGENCE HERBICIDE EFFICACY¹

¹ To be submitted for publication in Weed Technology.

ABSTRACT

Field studies were conducted to compare venturi-type drift reduction nozzles to a standard flat fan nozzle with respect to the efficacy of postemergence herbicides applied to common cocklebur (*Xanthium strumarium*) and broadleaf signalgrass (*Brachiaria platyphylla*). Spray solutions of glufosinate, glyphosate, and paraquat were applied through all combinations of three nozzles (two venturi) and two application volumes. The venturi nozzles consisted of a Delavan Raindrop Ultra (RU) and a Spraying Systems AI Teejet (AI). A Spraying Systems XR Teejet (XR) flat fan nozzle was included as a standard. Nozzle type had the greatest effect on common cocklebur with the RU nozzle providing the least control ($\leq 93\%$). The AI and XR nozzles provided similar levels of common cocklebur control (92 to 96%). Herbicide choice had a greater effect on broadleaf signalgrass control than nozzle type. Glyphosate provided less ($\leq 88\%$) broadleaf signalgrass control than either glufosinate or paraquat (89 to 98%). Venturi nozzles varied in the level of weed control they provided. The AI nozzle can be as effective as a flat fan nozzle with a variety of postemergence herbicides.

Nomenclature: Broadleaf signalgrass, *Brachiaria platyphylla* (Griseb.) Nash BRAPP; common cocklebur, *Xanthium strumarium* (L.) XANST; glufosinate, 2-amino-4-(hydroxymethylphosphinyl)butanoic acid; glyphosate, isopropylamine salt of – (phosphonomethyl)glycine; paraquat, 1,1'-dimethyl-4,4'-bipyridinium ion.

Additional Index Words: Application volume, drift, venturi nozzle,.

Abbreviations: AI, Spraying Systems AI Teejet; ANOVA, analysis of variance; LSD, least significant difference; NIS, nonionic surfactant; POST, postemergence; RU,

Delavan Raindrop Ultra; VMD, volume median diameter; V205, volume of spray in droplets less than 205 μm in diameter; WAT, weeks after treatment; XR, Spraying Systems XR Teejet.

INTRODUCTION

Growers have readily accepted herbicide-resistant crops and have increased the hectareage treated with non-selective herbicides such as glufosinate and glyphosate. Concerns over drift of these sprays and subsequent damage to non-target vegetation has led growers and applicators to implement drift reduction practices (Mueller and Womac 1997). Venturi-type drift reduction nozzles can minimize the drift potential of herbicide sprays by producing large droplets over a wide range of spray pressure (Etheridge et al. 1999).

Venturi nozzles consist of a flow-metering pre-orifice, an air-fluid venturi and mixing chamber, and a flat fan orifice to define the pattern. These nozzles effectively produce larger droplets than conventional flat fan nozzles at a given pressure (Etheridge et al. 1999). Droplet size is the major determinant of drift potential of herbicide sprays (Whisenant et al. 1993, Yates et al. 1976). Nordby and Skuterud (1975) increased the spray pressure from 250 to 1000 kPa which reduced droplet size mass median diameter from 306 to 196 μm and increased total drift of spray from 1.4 to 2.9%. Under typical use conditions, venturi nozzles produce droplets of 400 to 500 μm but can produce 600 to 700 μm droplets, depending on the manufacturer (Etheridge et al. 1999).

Droplet size also impacts the performance of herbicide sprays. Lake (1977)

increased droplet size from 100 to 200 μm and decreased droplet retention on young leaves of wild oat (*Avena fatua*) plants from 30 to 60 %, depending on the leaf angle. Increasing droplet size above 200 μm had a smaller effect on droplet retention. The effect of droplet size on herbicide efficacy is dependent on a number of factors, but the specific herbicide and plant species is critical. Paraquat efficacy on wild oat (Lake 1977) and sunflower (*Helianthus annuus*) (McKinlay et al. 1974) decreased as droplet size increased above 100 μm , but no response to droplet size was noted when radish (*Raphanus raphanistrum*) was the target plant species (Lake 1977). Applying glyphosate at a constant concentration in large versus small droplets reduced glyphosate absorption and translocation in Canada thistle (*Cirsium arvense*) (Boerboom and Wyse 1988). However, Buhler and Burnside (1987) noted that glyphosate efficacy on volunteer wheat (*Triticum aestivum*) and large crabgrass (*Digitaria sanguinalis*) increased as droplet size increased. It is important to note that for a given volume of liquid, increasing droplet size by 100% can reduce droplet number 800%. While no definite pattern exists, locally active herbicides such as paraquat may be more adversely affected by increasing droplet size than systemic herbicides such as glyphosate.

Growers and applicators have reduced application volumes in an effort to increase time and equipment efficiency. At a constant spray droplet size, glyphosate (Ambach and Ashford 1982, Buhler and Burnside 1983, Cranmer and Linscott 1990) and paraquat (McKinlay et al. 1974) efficacy increase as application volume is reduced. However, clopyralid activity decreases as application volume is reduced (Whisenant et al. 1993). Of particular interest with respect to the new venturi nozzles is the interaction of

application volume with droplet size. Whisenant et al. (1993) noted that clopyralid applied in a spray solution of 625 μm droplets performed better at increased application volumes. With smaller droplets, there was no advantage to increasing application volume.

Due to environmental and economic concerns, growers and applicators are interested in minimizing spray drift and reducing application volume, yet sacrifices in herbicide efficacy are undesirable. The objectives of this research were to: (1) compare the effects of two venturi nozzles (AI and RU) and a standard flat fan nozzle (XR) on the efficacy of common systemic and contact POST herbicides, and (2) evaluate the interaction of nozzle type and application volume on herbicide efficacy. Research concerning the performance of venturi nozzles in a field environment has not previously been reported. Also, the efficacy of these widely used herbicides applied through venturi nozzles has not been documented.

MATERIALS AND METHODS

Field research was conducted in Knoxville Tennessee at the Holston Research Unit comparing the efficacy of two venturi-type nozzles to a standard flat fan nozzle using two application volumes and three herbicides. Four experiments were conducted in 1999. Two experiments were initiated on June 7 and June 10 in an area of monoculture broadleaf signalgrass. Two separate experiments were initiated on May 27 and June 3 in an area of monoculture common cocklebur. Plot areas had been managed separately for either monoculture broadleaf signalgrass or common cocklebur. Bromoxynil at 0.43 kg

ai/ha was applied to the broadleaf signalgrass area to remove broadleaf weeds.

Clethodim at 0.14 kg ai/ha plus crop oil concentrate at 1% v/v was applied to the common cocklebur area to remove grass weeds. Bromoxynil and clethodim applications were made approximately 10 days prior to initiation of each experiment. Plots were 3.1 m x 6.1 m and were arranged in a randomized block design with four replications.

Blocks were separated by 6-m alleys for operational considerations, such as to allow room for the tractor to achieve the target application speed prior to entering each plot.

The venturi nozzles included a Delavan Raindrop Ultra (RU)² and a Spraying Systems AI Teejet (AI)³. The flat fan nozzle was a Spraying Systems XR Teejet (XR)³. Nozzles were spaced 51 cm apart along a 254-cm, tractor-mounted boom which was operated at 13.4 km/h. Spray tips were used for each nozzle which produced fan sprays of 110° spray angle and nominal discharge rates of 0.57 and 1.14 L/min, which produced field application volumes of 50 and 100 L/ha, respectively, at 276 kPa. An electric solenoid valve was mounted on the sprayer to control the flow of spray solution to the boom.

Commercial formulations of glufosinate⁴, glyphosate⁵, and paraquat⁶ were added to water carrier to maintain constant application rates of 0.43, 0.84, and 0.71 kg ai/ha,

² Raindrop Ultra®. Delavan Spray Technologies, Monroe, NC 28110.

³ AI Teejet® and XR Teejet®. Spraying Systems Co., Wheaton, IL 60188.

⁴ Liberty® herbicide. AgrEvo USA Company, Wilmington, DE 19808.

⁵ Roundup Ultra® herbicide. Monsanto Company, St. Louis, MO 63167.

⁶ Gramoxone Extra® herbicide. Zeneca Ag Products, Wilmington, DE 19850-2500.

respectively, at both application volumes. These represent normal use rates for these herbicides (Anonymous 1998a). To accomplish this, separate mixes of each herbicide were prepared in 11-L stainless steel containers and delivered to the nozzles by compressed CO₂. A nonionic surfactant⁷ (NIS) at 0.25% v/v was included with the paraquat solutions. Treatments included 2 untreated controls plus all combinations of the 3 nozzles, 2 application volumes, and 3 herbicides with 4 replications (for a total of 96 experimental units per experiment). Treatments were applied when broadleaf signalgrass and common cocklebur were approximately 9 and 12 cm tall, respectively. Broadleaf signalgrass and common cocklebur densities were approximately 300 and 75 plants/m², respectively.

Visual control was evaluated 1, 2, and 3 weeks after treatment (WAT) on a scale of 0 to 100, with 0 being no control and 100 being complete control. The two untreated plots in each rep and the untreated area between adjacent plots were utilized as a visual reference. Biomass was measured 2 WAT by harvesting all above ground plant material in a 1 m² area in the center of each plot and recording fresh weights in the field. Biomass data for each plot was computed as a percent fresh weight reduction relative to the average of the two untreated plots in the corresponding block. Data were subjected to ANOVA and means of significant effects separated with an LSD at the 5% level. The treatment factors and combinations described above were previously analyzed under controlled laboratory conditions for nozzle droplet characteristics such as volume median

⁷ X-77® nonionic surfactant, which is a mixture of alkylaryl polyoxyethylene, glycols, free fatty acids, and isopropanol. Loveland Industries Inc., Greeley, CO 80632.

diameter (VMD) and percent of spray volume contained in droplets smaller than 205 μm (V205) (Etheridge et al. 1999).

RESULTS AND DISCUSSION

Common Cocklebur. Common cocklebur control was > 90% with all treatment combinations except for glyphosate 1 WAT (Table 5). Glyphosate performance improved to $\geq 95\%$ control 2 WAT. Nozzle type affected common cocklebur control at all three evaluation dates (Table 6). At 1 WAT, the AI and XR nozzles provided better control than the RU nozzle (94 & 94% vs 90%) when averaged over all other factors (Table 5). Herbicide choice was also an important factor 1 WAT with glufosinate, paraquat, and glyphosate providing mean control levels of 98, 96, and 84%, respectively. At 2 WAT, the AI and XR nozzles continued to provide better mean levels of control than the RU nozzle (96 & 96% vs 93%). If the interactive effects of nozzle, application volume, and herbicide are considered at 2 WAT (Table 6), each herbicide generally provided the greatest control with the XR nozzle at 100 L/ha and the least control with the RU nozzle at 50 L/ha, except for glyphosate. Glyphosate performed poorest with the RU nozzle at 100 L/ha (91%). Increasing the application volume from 50 to 100 L/ha with the RU nozzle increased the efficacy of glufosinate from 92% to 96% and decreased the efficacy of glyphosate from 95% to 91%. However, with the XR nozzle, increasing application volume increased glyphosate efficacy from 93% to 97%. The RU nozzle produces droplets which are approximately 400% larger than those produced by the XR nozzle (Etheridge et al. 1999) and large droplets result in less leaf area contact per unit

volume than small droplets (Spillman 1984). With large droplets, herbicide concentration per droplet may be more important for adequate weed control than the number of droplets applied. Buehler and Burnside (1987) noted that with large droplets, weed control was reduced as application volume increased.

At 3 WAT, all herbicides performed similarly with the AI and XR nozzles (Table 7), whereas glyphosate performed better (94%) than glufosinate and paraquat (89 & 88%, respectively) with the RU nozzle. Glyphosate efficacy was similar for all combinations of nozzle and application volume (Table 6). Glufosinate and paraquat provided the poorest control with the RU nozzle at application volumes of 50 and 100 L/ha, respectively. The poor performance of paraquat with the RU nozzle, which produces large spray droplets, is in agreement with McKinlay et al. (1974). Application volume did not affect herbicide efficacy, except for glufosinate applied through the RU nozzle where efficacy increased from 86% to 93% as application volume increased. A positive response to increasing application volume when utilizing large droplets was noted by Whisenant et al. (1993) with clopyralid. Biomass measurements were taken 2 WAT and generally reflected the trends in visual control evaluations taken at the same time (Table 5). The AI and XR nozzles provided greater mean levels of biomass reduction than the RU nozzle (92 & 93% vs 87%). Glufosinate and glyphosate produced the greatest reduction in biomass with the XR nozzle at 100 L/ha, whereas paraquat produced the greatest reduction in biomass with the AI nozzle at 100 L/ha (Table 6).

Nozzle affected common cocklebur control at each evaluation date. These differences are likely due to variation in spray droplet size produced by each nozzle

(Etheridge et al. 1999). Specifically, the RU nozzle produced larger (650 μm) droplets than the AI and XR nozzles (475 & 175 μm , respectively). Reduced herbicide efficacy with large droplets could be caused by several factors. Spillman (1984) noted that large droplets falling at terminal velocity have higher kinetic energy than small droplets and that the likelihood of a spray droplet to bounce from a surface increases as the kinetic energy of the droplet increases. Moreover, the kinetic energy of a falling droplet varies to the seventh power of the droplet's diameter (Spillman 1984). However, other factors such as the surface characteristics of the target and surface tension of the applied droplets affect droplet retention. Generally, smooth surfaces and high surface tension reduce droplet retention. Therefore, a 650 μm droplet produced by an RU nozzle is much more likely to bounce on impact than a 175 μm droplet produced by an XR nozzle, assuming all other factors are equal.

Broadleaf Signalgrass. Herbicide choice affected broadleaf signalgrass control at all three evaluation dates (Table 8). Paraquat, glufosinate, and glyphosate provided 98, 92, and 66% control, respectively, 1 WAT when averaged over all other factors. Control provided by glyphosate improved to 88% 2 WAT, but was less than glufosinate and paraquat which each provided 98% control. When averaged over application volume (Table 9), glufosinate and paraquat provided similar control when applied through the AI and XR nozzles. Paraquat was more effective than glufosinate (98 vs 96%) when applied through the RU nozzle. Glyphosate provided the least control regardless of nozzle type. Mean levels of nozzle performance (Table 8) were similar for the AI and XR nozzles (95%) and were greater than that provided by the RU nozzle (93%) (Table 12). At 3

WAT, paraquat provided the greatest mean level of control (97%) followed by glufosinate (95%) and glyphosate (88%) (Table 8). Glyphosate was less effective than glufosinate and paraquat regardless of nozzle type when averaged over application volume (Table 9). Control with glufosinate and paraquat was similar with each nozzle except the RU, where paraquat was more effective than glufosinate. Mean nozzle performance was greater with the AI and XR nozzles than with the RU nozzle (Table 8). Also, the 100 L/ha application volume provided greater mean control than the 50 L/ha volume (94 vs 92%). Biomass reductions generally reflected the trends in visual control evaluations 2 WAT (Table 8). Glyphosate reduced broadleaf signalgrass biomass less than glufosinate and paraquat (81% vs 89 & 91%, respectively) and mean control levels were greater at 100 L/ha (90%) than at 50 L/ha (84%).

Herbicide affected broadleaf signalgrass control at each evaluation date. Based on visual plant symptomology, the broadleaf signalgrass plants in each experiment were somewhat drought stressed at the time of application. Environmental factors which inhibit vigorous plant growth negatively affect systemic herbicides, such as glyphosate, and may account for the relatively poor performance of glyphosate. Buhler and Burnside (1983) noted that glyphosate at 20 to 80 g ai/ha was less effective on drought stressed annual grass species as compared to actively growing plants. Locally active herbicides such as paraquat and to a lesser degree, glufosinate, are less dependent on translocation for activity and would not be as adversely affected by drought stressed plants.

Statistical Analysis. The treatment factors analyzed and their level of significance with respect to common cocklebur and broadleaf signalgrass efficacy are listed (Tables 10 and

11). Also, correlation analysis of nozzle parameters with common cocklebur and broadleaf signalgrass 2 WAT are shown (Table 12). Droplet size was negatively correlated with glufosinate and paraquat performance, indicating that herbicide efficacy decreased as droplet size increased. This is illustrated by reduced mean herbicide performance with the RU nozzle on common cocklebur (Table 5) and broadleaf signalgrass (Table 8). Due to its localized action, paraquat would be expected to exhibit the greatest response to droplet size (McKinlay et al. 1974), since adequate coverage is necessary for acceptable control. Paraquat demonstrated a stronger response to droplet size than glufosinate when common cocklebur was the target. However, there was no correlation between paraquat efficacy and droplet size when broadleaf signalgrass was the target. Broadleaf signalgrass control with paraquat 2 WAT was excellent (> 95%) regardless of nozzle type and so overall control levels may have masked any relationship between efficacy and droplet size. These data would indicate that for the herbicides and rates used herein, the quality of herbicide spray (droplet size) may affect weed control.

Control of common cocklebur and broadleaf signalgrass was > 90% for each herbicide except glyphosate 1 WAT. The necessity of glyphosate to translocate slows its activity relative to paraquat and glufosinate (Anonymous 1994), but by 2 WAT control had improved to > 90%. However, nozzle choice and the resulting droplet size did affect weed control. The tendency of the RU nozzle to produce large droplets reduces the drift potential of the herbicides evaluated, but this benefit may be negated by reduced efficacy. Using the herbicides evaluated herein, the AI and XR nozzles produce spray patterns with mean volume median diameter droplets of 450 and 175 μm (Etheridge et al. 1999),

respectively, yet no consistent differences in weed control were observed. Venturi nozzles can reduce herbicide drift potential relative to standard flat fan nozzles. Based on the data presented herein, venturi nozzles which produce droplets of approximately 450 μm may provide weed control similar to that provided by flat fan nozzles.

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PART IV

ACCURACY OF HERBICIDE PLACEMENT WITH VENTURI DRIFT

REDUCTION NOZZLES¹

¹ To be submitted for publication in Weed Technology.

ABSTRACT

Field studies were conducted to measure the amount and uniformity of herbicide deposited in the target area by two venturi nozzles and one conventional flat fan nozzle at two application volumes and to identify the nozzle parameters responsible for accurate herbicide placement. When a constant herbicide application rate was maintained, each venturi nozzle deposited more herbicide in the target area than the flat fan nozzle. The uniformity of herbicide distribution was similar for the venturi and flat fan nozzles. Increasing application volume (larger tip sizes) improved the uniformity of herbicide deposition for the venturi and flat fan nozzles. Correlation analysis indicated that increasing the percentage of spray volume contained in droplets smaller than approximately 200 μm decreased herbicide deposition in the target area.

Nomenclature: metolachlor, 2-chloro-N-(2-ethyl-6-methylphenyl)-N-2-methoxy-1-methylethyl)acetamide.

Additional Index Words: Deposition, drift.

Abbreviations: AI, Spraying Systems AI Teejet; ANOVA, analysis of variance; CV, coefficient of variation; DEP, percent herbicide deposition; LSD, least significant difference; RU, Delavan Raindrop Ultra; VMD, volume median diameter; V205, volume of spray in droplets less than 205 μm in diameter; XR, Spraying Systems XR Teejet.

INTRODUCTION

Pesticides must reach the target at some threshold amount to be optimally effective. Herbicide use rates have been reduced over the past 10 years from 1 to 2 kg

ai/ha to as little as 0.01 to 0.02 kg ai/ha. Also, economic savings have prompted growers and applicators to cover more area with less equipment usually by increasing application speed, reducing application spray volume, or both. Accurate herbicide application procedures are necessary to maintain acceptable weed control.

Drift of only a small portion of the applied herbicide solution can cause damage to susceptible vegetation. Byass and Lake (1977) noted that drift of paraquat and picloram could cause unacceptable injury at as little as 0.1 and 0.01%, respectively, of the applied rate. Nordby and Skuterud (1975) noted that under unfavorable conditions such as high wind and improper sprayer adjustment, drift could amount to 37% of the total spray volume. Minimizing drift of widely used non-selective herbicides is especially critical.

Nozzle manufacturers routinely test nozzles for uniformity of spray volume distribution across the effective pattern width of the nozzle or nozzles and generally report the results in terms of a coefficient of variation (CV). These measurements are typically made under controlled conditions with a stationary nozzle arrangement and are representative of the optimal uniformity of spray volume distribution that can be expected with a given nozzle. Little work has been reported concerning the uniformity of herbicide application under field conditions. Environmental and application factors can increase herbicide drift and therefore could reduce herbicide distribution uniformity.

Accurate herbicide application is necessary to minimize drift and maintain acceptable weed control. Venturi nozzles can reduce the drift potential of herbicide sprays. However, little data has been published concerning the uniformity of herbicide solution application with venturi nozzles, especially in a field environment. The

objectives of this study were to (1) characterize the spray pattern characteristics of venturi nozzles, (2) determine the amount and uniformity of metolachlor that is deposited in the target area under field conditions, and (3) identify application parameters which increase the accuracy of herbicide application.

MATERIALS AND METHODS

Droplet Characterization. Two venturi-type drift reduction nozzles were analyzed and compared to a standard flat fan nozzle. The venturi nozzles included a Delavan Raindrop Ultra (RU)² and a Spraying Systems AI Teejet (AI)³. The flat fan nozzle was a Spraying Systems XR Teejet (XR)³. For each nozzle type, two tip sizes were evaluated and tips produced fan sprays of 110° spray angle with nominal discharge rates of 0.57 and 1.14 L/min at 276 kPa. The tip sizes producing 0.57 and 1.14 L/min application volumes are hereafter referred to as 110015 and 11003, respectively.

A commercial formulation of metolachlor⁴ was added to water carrier to maintain a theoretically constant application rate of 1.8 kg ai/ha by preparing separate mixtures in 11-L stainless steel containers. The solution utilized for the 110015 tips was prepared by adding 440 ml metolachlor and 30 ml NIS to the container and bringing to a total volume of 11 L with water. The solution for the 11003 tips was prepared similarly, except 225 ml of metolachlor was added. Metolachlor was selected because it is widely used in

² Raindrop Ultra®. Delavan Spray Technologies, Monroe, NC 28110.

³ AI Teejet® and XR Teejet®. Spraying Systems Co., Wheaton, IL 60188.

⁴ Dual II Magnum® herbicide. Novartis Crop Protection Inc., Greensboro, NC 27419.

agronomic and turf weed control systems, and its chemical analysis is not problematic. A NIS at 0.25% v/v was added to the metolachlor solutions to simulate typical herbicide solution characteristics, such as surface tension, and resulting spray droplet characteristics. Spray solution was delivered to the nozzle by compressed air at a spray pressure of 276 kPa. A Malvern 2605 Lc droplet/particle size analyzer⁵ fitted with a 1000-mm lens was utilized to quantify the spray droplet spectrum according to the procedures previously described by Etheridge et al. (1999).

Each run of an experimental unit produces a tremendous amount of information, consisting of the percentage of spray volume in each of 32 ranges of droplet size from 5 to 1880 μm . The volume median diameter (VMD), which is the point where one-half of the spray volume is in smaller droplets, and the percentage of spray volume in droplets less than 205 μm (V205) are presented. Instrument lens selection and corresponding divisions of droplet sizes resulted in the instrument producing a division in the droplet spectrum at 205 μm , which is near the well-accepted 200 μm level used for describing a “driftable” droplet. While there is no clear definition of a “driftable” droplet, Nordby and Skuterud (1975) reported an increase in total drift of spray solution from 1.4% to 2.9% as mass median diameter droplet size was reduced from 306 to 196 μm . Thus the V205 data may provide a reasonable measure of the amount of small or driftable droplets present. Due to the precision of the test system and repeatability of results over time, the study was conducted in a completely randomized design with three replicates and data subjected to an analysis of variance (ANOVA). Means of significant effects were

⁵ Malvern Instruments, Malvern England.

compared using LSD mean separation technique at the 5% level.

Herbicide Deposition. Field experiments were conducted in Knoxville Tennessee at the Holston Research Unit to compare the amount of metolachlor deposited in a target area with venturi nozzles (AI and RU) and a standard flat nozzle (XR) relative to the amount applied. Two experiments were conducted, one on May 27 and another on June 10.

Alpha cellulose sheets were used as spray targets to allow for laboratory measurement of metolachlor deposition in each plot. Alpha cellulose is the material used by the National Spray Drift Task Force. Plots were 3.1 m by 6.1 m and were arranged in a randomized block design with four replications. Blocks were separated by 6-m alleys for operational considerations, such as to allow room for the tractor to achieve the target application speed prior to entering the plot.

Nozzles were spaced 51 cm apart along a 254-cm, tractor-mounted boom operated at 13.4 km/h. For each nozzle type, 110015 and 11003 tips were used and produced field application volumes of 50 and 100 L/ha, respectively, at 276 kPa. An electric solenoid valve was mounted on the sprayer to control the flow of spray solution to the boom. As described previously for the droplet characterization, two separate spray solutions were prepared to maintain a theoretically constant metolachlor rate of 1.8 kg ai/ha. Three untreated controls were sprayed with water only to provide a measure of possible contamination during the application and sampling procedures. Treatments consisted of all combinations of 3 nozzles and 2 application volumes plus the 3 controls with 4 replications (3 targets per plot and 2 experiments = 216 experimental units). Spray solution was delivered to the boom with compressed CO₂.

Three alpha cellulose sheets (20 by 20 cm) were placed in each plot, one in the center and one 3.1 m from either end. The boom was mounted such that all nozzles were beyond the wheel base of the tractor. This allowed the tractor to be driven between plots with only the boom passing over the plot area and targets. The sheets were placed in the centerline of the plot (center of boom during application) on top of plastic planting pots measuring 8 cm in diameter and 10 cm in height such that the sheet was horizontal with the ground. The target sheet placement was consistent for all treatments. These sheets were positioned immediately prior to and removed immediately following application, folded, and placed in 250-ml low density polyethylene⁵ (LDPE) bottles. The LDPE bottles containing the sample sheets were immediately placed in an ice-filled cooler until they were placed in a freezer for storage. A portable weather station was used to record wind speed and direction every 60 s during herbicide application (Table 13).

Sample sheets (contained inside LDPE bottles) were thawed at room temperature for 8 h, 100 ml of methanol was added to each bottle, and the bottles were agitated for 8 h on a reciprocating-action shaker (Eberbach, Ann Arbor, MI) operated at 180 rpm. An aliquot of methanol-herbicide solution was taken from each bottle and placed in a 2-ml auto-sample vial for later use in GC analysis. Fortification studies determined that metolachlor extraction efficiency from the alpha cellulose sheets was 99% for both application volumes (data not shown). Metolachlor concentration was determined using gas chromatography utilizing an NPD detector (data not shown). Analysis of untreated control plots indicated no cross-contamination of samples (data not shown).

⁵ Nalgene®. Nalge International, Rochester, NY.

Metolachlor concentrations measured from each alpha cellulose sheet were converted to a rate in kg ai/ha and a percentage of herbicide deposition (DEP) was then computed relative to the 1.8 kg ai/ha target rate. The variability of herbicide deposition resulting from each combination of nozzle and application volume was compared by calculating a CV according to procedures detailed by Sokal and Rohlf (1981). The data were subjected to ANOVA and means of significant effects separated with an LSD at the 5% level. A correlation analysis was performed to quantify any relationship between herbicide deposition and nozzle pattern parameters.

RESULTS AND DISCUSSION

Droplet Characterization. The interaction of nozzle and tip size was significant with respect to VMD and V205 (Table 14). The venturi nozzles collectively produced larger droplets (579 μm vs 181 μm) and fewer small droplets (9% vs 59.6%) than the flat fan nozzle. The AI and RU nozzles produced mean VMD values of 478 and 679 μm , respectively, and mean V205 values of 12.4 and 5.6%, respectively. Droplet size with the AI nozzle was not affected by tip size. Increasing tip size produced smaller droplets with the RU nozzle and larger droplets with the XR nozzle. Increasing tip size generally results in larger droplets being formed. The opposite trend exhibited by the RU nozzle may be due to excessive turbulence in the venturi chamber.

Herbicide Deposition. Data from the two experiments were pooled and when averaged over application volume, the AI, RU, and XR nozzles produced percent herbicide deposition values (DEP) of 108, 105, and 93%, respectively (Table 15), indicating that

the venturi nozzles deposited more herbicide in the target area than the flat fan nozzle. It is important to note that the XR nozzle provided the least herbicide deposition (93%) (Table 15) and also produced the smallest droplets (Table 14). The most (114%) and least (84%) herbicide deposition occurred with the RU + 11003 and XR +110015 nozzle + tip size combinations, respectively (individual datum not shown). Correlation analysis to determine the strength and direction of any relationships between herbicide deposition and nozzle parameters was limited by the relatively small number of data points. However, V205 was negatively correlated with herbicide deposition ($R = -0.21$). This is in agreement with earlier work documenting increased drift as droplet size decreased (Nordby and Skuterud 1975).

The variability of herbicide deposition within the target area was calculated (Table 16). The uniformity of metolachlor deposition from venturi nozzles and the XR nozzle were similar. However, reducing the application volume increased the variability of metolachlor distribution with each nozzle type. The trends in metolachlor deposition within the field are consistent with the variability of the nozzle spray volume distribution, which was previously measured with water only under controlled conditions (Etheridge et al. 1999). The nozzle spray volume distribution was not affected by environmental conditions such as wind and therefore represents the inherent variability in spray volume distribution of a particular nozzle. The consistency of the field and laboratory values indicates that the uniformity of herbicide distribution is primarily determined by the nozzle itself.

These data indicate that venturi nozzles produce spray droplets which increased

herbicide placement within the target area relative to flat fan nozzles. The uniformity of herbicide distribution in the target area was similar with venturi and flat fan nozzles and improved as application volume increased. However, it is important to note that postemergence weed control studies (data not shown) with these nozzle and application volume combinations resulted in reduced efficacy with the RU nozzle and similar levels of weed control with the AI and XR nozzles. Venturi nozzles producing droplets of approximately 450 μm appear to have the most potential to maximize the accuracy of herbicide placement and maintain acceptable weed control.

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LITERATURE CITED

Al-Khatib, K., G.I. Mink, G. Reisenauer, R. Parker, H. Westberg, and B. Lamb. 1993. Development of a biologically-based system for detection and tracking of airborne herbicides. *Weed Technol.* 7:404-410.

Ambach, R.M. and R. Ashford. 1982. Effects of variations in drop makeup on the phytotoxicity of glyphosate. *Weed Sci.* 30:221-224.

Amrhein, N., B. Deus, P. Gehrke, and H.C. Steinrucken. 1980. The site of the inhibition of the shikimate pathway by glyphosate. *Plant Physiol.* 66:830-834.

Anonymous. 1994. Weed Science Society of America. *Herbicide Handbook*. 7th ed. Weed Sci. Soc. Am., Champaign, IL. pp. 147-152, 226-228.

Anonymous. 1995. *Lurmark Spray Tips, Handbook 4*. Lurmark LTD, Long Stanton, Cambridge. Distributed by Precision Fitting and Valve Co. Inc., Farmington, MN 55024.

Anonymous. 1997. Test procedure for measuring deposits and airborne spray from ground swath sprayers. *ASAE Standards*. pp. 251-253.

Anonymous. 1998a. *Crop Protection Chemicals Reference*. Chemical and Pharmaceutical Press, New York. pp. 76-78, 1381-1391, 2291-2296.

Anonymous. 1998b. Delavan AgSpray Nozzles, Accessories, Pumps, and Spray Kits. Delavan Spray Technologies, Monroe, NC 28110.

Anonymous. 1998c. Greenleaf TurboDrop Nozzle Tabulations. Greenleaf Technologies, Covington, LA 70434.

Anonymous. 1998d. TeeJet Agricultural Spray Products, Catalog 47. Spraying Systems Co., Wheaton, IL 60189.

Anonymous. 1999. Ag Consultant. Meister Publishing Co., Willoughby, OH 44094. Vol. 55(5):13

Boerboom, C.M. and D.L. Wyse. 1988. Influence of glyphosate concentration on glyphosate absorption and translocation in Canada thistle (*Cirsium arvense*). Weed Sci. 36:291-295.

Brewster, B.D. and A.P. Appleby. 1990. Effect of rate, carrier volume, and surfactant on imazamethabenz efficacy. Weed Technol. 4:291-293.

Buhler, D.D. and O.C. Burnside. 1983. Effect of spray components on glyphosate toxicity to annual grasses. Weed Sci. 31:124-130.

Buhler, D.D. and O.C. Burnside. 1987. Effects of application variables on glyphosate phytotoxicity. *Weed Technol.* 1:14-17.

Byass, J. B. and J. R. Lake. 1977. Spray drift from a tractor-powered sprayer. *Pestic. Sci.* 8:117-126.

Combella, J.H., N.M. Western, and R.G. Richardson. 1996. A comparison of the drift potential of a novel twin fluid nozzle with conventional low volume flat fan nozzles when using a range of adjuvants. *Crop Prot.* 15: 147-152.

Cranmer, J.R. and D.L. Linscott. 1990. Droplet makeup and the effect on phytotoxicity of glyphosate in velvetleaf (*Abutilon theophrasti*). *Weed Sci.* 38:406-410.

De Block, M., J. Bottermann, M. Vandeweyle, J. Dockx, C. Thoen, V. Gosselle, N.R. Movva, C. Thompson, M. Van Montague, and J. Leemans. 1987. Engineering herbicide resistance in plants by expression of a detoxifying enzyme. *EMBO J.* 6:2513-2518.

Etheridge, R.E., A.R. Womac, and T.C. Mueller. 1999. Characterization of the spray droplet spectra and patterns of four venturi-type drift reduction nozzles. *Weed Technol.* 13:(4)XX.

Kapusta, G. 1981. HOE 661: A new herbicide for control of vegetation in no-till fields. Proc. North Cent. Weed Control Conf. 36:92.

Kapusta, G. and M. Bates. 1982. Evaluation of 'burndown' herbicides for the control of tall grasses and weeds. Res. Rep. North Cent. Weed Control Conf. 39:284.

Knoche, M. 1994. Effect of droplet size and carrier volume on performance of foliage-applied herbicides. Crop Prot. 13:163-178.

Lake, J. R. 1977. The effect of drop size and velocity on the performance of agricultural sprays. Pestic. Sci. 8:515-520.

Lanie, A.J., J.L. Griffin, P.R. Vidrine, and D.B. Reynolds. 1994. Weed control with non-selective herbicides in soybean (*Glycine max*) stale seedbed culture. Weed Technol. 8:159-164.

Lea, P.J., K.W. Joy, J.L. Ramos, M.G. Guerrero. 1984. The action of the 2-amino-4-(methylphosphinyl)-butanoic acid (phosphinothricin) and its 2-oxo-derivative on the metabolism of cyanobacteria and higher plants. Phytochemistry 23 1-6.

Marshall, G., R.C. Kirkwood, and D.J. Martin. 1987. Studies on the mode of action of asulam, aminotriazole, and glyphosate in *Equisetum arvense* L. (field horsetail). I: The

uptake and translocation of [^{14}C]asulam, [^{14}C]aminotriazole, and [^{14}C]glyphosate. *Pestic.Sci.* 18:55-64.

Martin, R.A. and L.V. Edgington. 1981. Comparative systemic translocation of several xenobiotics and sucrose. *Pestic. Biochem. Physiol.* 16:87-96.

McKinlay, K.S., S.A. Brandt, P. Morse, and R. Ashford. 1972. Droplet size and phytotoxicity of herbicides. *Weed Sci.* 20:450-452.

McKinlay, K.S., R. Ashford, and R.J. Ford. 1974. Effects of drop size, spray volume, and dosage on paraquat toxicity. *Weed Sci.* 22:31-34.

McMullen, P.M. 1995. Effect of spray volume, spray pressure, and adjuvant volume on efficacy of sethoxydim and fenoxapro-p-ethyl. *Crop Prot.* 14:549-554.

Mueller, T.C. and A.R. Womac. 1997. Effect of formulation and nozzle type on droplet size with isopropylamine and trimesium salts of glyphosate. *Weed Technol.* 11:639-643.

Nordby, A and R. Skuterud. 1975. The effects of boom height, working pressure and wind speed on spray drift. *Weed Res.* 14:385-395.

Sokal, R.R. and F.J. Rohlf. 1981. Descriptive techniques. p. 38-61 in Biometry. 2nd Edition. W.H. Freeman and Company, New York, 776 pp.

Spillman, J. J. 1984. Spray impaction, retention and adhesion: An introduction to basic characteristics. Pestic. Sci. 15:97-106.

Steel, R.G. and J.H. Torrie. 1980. Multiple comparisons. p. 179-198 in Principles and Procedures of Statistics: A Biometrical Approach. 2nd Edition. McGraw-Hill Co., New York, 481 pp.

Thompson, C.J., R.N. Movva, R.Tizard, R. Cramer, J.E. Davies, M. Lauwereys, and J. Bottermann. 1987. Characterization of the herbicide-resistant gene *bar* from *Streptomyces hygroscopicus*. EMBO J. 6:2519-2523.

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 Manage. 46:257-261.

Wild, A. and C. Wendler. 1990. Effect of glufosinate (phosphinothricin) on amino acid content, photorespiration, and photosynthesis. Pestic. Sci. 30:422-424.

Womac, A.R., J.C. Goodwin, and W.E. Hart. 1997. Tip Selection for Precision Application of Herbicides: A Look-Up Table of Drop Sizes to Assist in the Selection of Nozzles. Bulletin 695, The University of Tennessee Agricultural Experiment Station, Knoxville, TN.

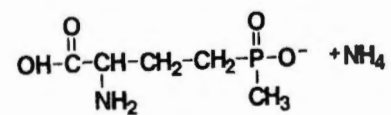
Womac, A.R., R.A. Maynard, and I.W. Kirk. 1999. Measurement variations in reference sprays for nozzle classification. Transactions of the Amer. Soc. Agr. Eng. 42:609-616.

Yates, E.W., N.B. Akesson, and D. Bayer. 1976. Effects of spray adjuvants on drift hazards. Transactions of the ASAE. pp. 41-46.

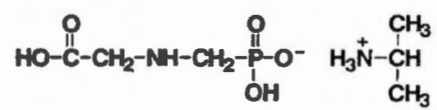
APPENDICES

APPENDIX A FIGURES

Glufosinate ammonium salt



Glyphosate isopropylamine salt



Paraquat dichloride salt

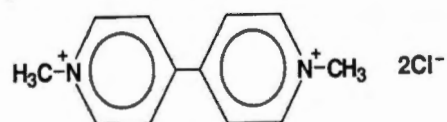


Figure 1. Herbicide chemical structures.

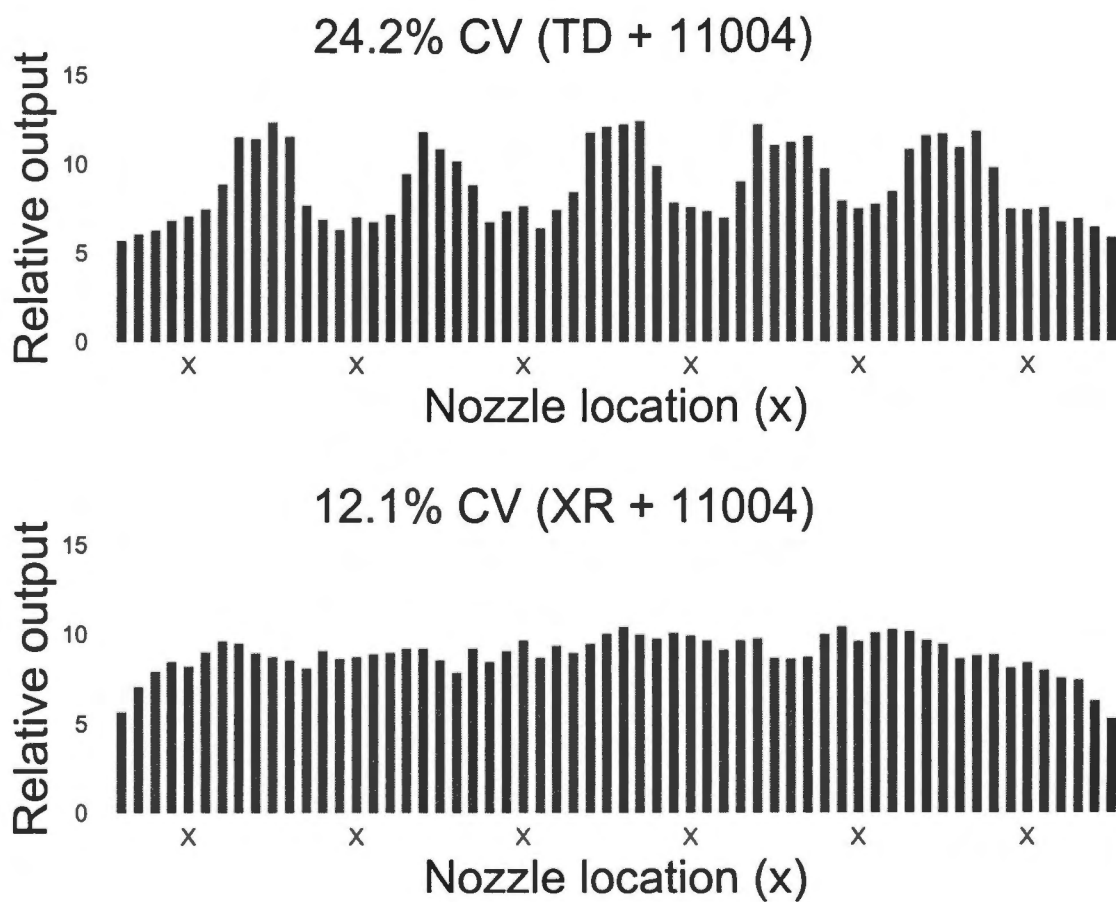


Figure 2. Relative distribution of output across the spray pattern represented by coefficient of variation (CV) values of 24.2 and 12.1%. These values were recorded for the TD + 11004 and XR + 11004 nozzle type + tip size combinations, respectively.

APPENDIX B
TABLES

Table 1. Mean volume median diameter (VMD) and percent of spray volume in droplets less than 205 μm (V205) pooled over nozzle, herbicide, tip size, and pressure.

Variable pooled across		VMD	V205
		(μm)	(%)
Nozzle ^a	AI	472	18.3
	LM	439	18.6
	RU	654	10.5
	TD	467	17.9
	XR	173	64.8
	HSD ^b	3.3	0.3
Herbicide	Glufosinate	399	30.4
	Glyphosate	458	25.1
	Paraquat	467	22.7
	HSD ^b	2.2	0.2
Tip size	110015	448	29.6
	11003	421	26.4
	11004	454	22.1
	HSD ^b	2.2	0.2
Pressure (kPa)	100	650	14.5
	276	432	24.6
	450	361	30.4
	625	322	34.7
	HSD ^b	2.5	0.3

^a Delavan Raindrop Ultra (RU), Greenleaf TurboDrop (TD), Lurmark Ultra Lo-Drift (LM), Spraying Systems AI Teejet (AI), and Spraying Systems XR Teejet (XR).

^b Tukey's Honest Significant Difference (HSD) mean separation technique at the 5% significance level.

Table 2. Interactive effects of nozzle type and herbicide, averaged over tip size and pressure, on volume median diameter (VMD) and percent of spray volume in droplets less than 205 μm (V205).

Nozzle ^a	Herbicide					
	Glufosinate	Glyphosate	Paraquat	Glufosinate	Glyphosate	Paraquat
	VMD (μm)			V205 (%)		
AI	416	491	509	24.0	17.3	13.7
LM	416	452	449	21.3	17.8	16.7
RU	586	690	687	15.3	9.3	7.0
TD	415	481	506	23.0	17.2	13.5
XR	161	175	182	68.1	63.7	62.5
HSD ^b	-----24-----			-----1.5-----		

^a Delavan Raindrop Ultra (RU), Greenleaf TurboDrop (TD), Lurmark Ultra Lo-Drift (LM), Spraying Systems AI Teejet (AI), and Spraying Systems XR Teejet (XR).

^b Tukey's Honest Significant Difference (HSD) mean separation technique at the 5% significance level.

Table 3. Interactive effects of nozzle type and tip size, averaged over herbicide and pressure, on volume median diameter (VMD) and percent of spray volume in droplets less than 205 μm (V205).

Nozzle ^a	Tip size					
	110015	11003	11004	110015	11003	11004
	VMD (μm)			V205 (%)		
AI	461	475	481	20.9	17.5	16.6
LM	384	401	531	24.4	19.9	11.5
RU	790	608	565	7.6	11.8	12.3
TD	467	444	491	16.1	20.8	16.9
XR	138	176	204	79.0	62.2	53.2
HSD ^b	-----24-----			-----1.5-----		

^a Delavan Raindrop Ultra (RU), Greenleaf TurboDrop (TD), Lurmark Ultra Lo-Drift (LM), Spraying Systems AI Teejet (AI), and Spraying Systems XR Teejet (XR).

^b Tukey's Honest Significant Difference (HSD) mean separation technique at the 5% significance level.

Table 4. Effects of nozzle type and tip size on coefficient of variation (CV) in spray pattern.

Nozzle ^a	Tip Size	CV
		(%)
AI	110015	22.6
AI	11003	13.6
AI	11004	17.1
LM	110015	13.3
LM	11003	15.0
LM	11004	16.5
RU	110015	27.2
RU	11003	14.3
RU	11004	14.2
TD	110015	19.0
TD	11003	16.7
TD	11004	24.2
XR	110015	12.3
XR	11003	13.3
XR	11004	12.1
HSD ^b		1.6

^a Delavan Raindrop Ultra (RU), Greenleaf TurboDrop (TD), Lurmark Ultra Lo-Drift (LM), Spraying Systems AI Teejet (AI), and Spraying Systems XR Teejet (XR).

^b Tukey's Honest Significant Difference (HSD) mean separation technique at the 5% significance level.

Table 5. Pooled effects of nozzle, application volume, and herbicide on percent control and biomass reduction of common cocklebur (*Xanthium strumarium*).

Variable pooled across		Control			Biomass
		1 WAT	2 WAT	3 WAT	2 WAT
		(%)			(%)
Nozzle ^a	AI	94	96	95	92
	RU	90	93	90	87
	XR	94	96	95	93
	LSD ^b	1.2	1.2	1.4	2.8
Application volume (L/ha)	50	92	95	93	90
	100	93	96	94	92
	LSD ^b	ns	ns	1.2	ns
Herbicide	glufosinate	98	96	93	91
	glyphosate	84	95	96	91
	paraquat	96	95	93	92
	LSD ^b	1.2	ns	1.5	ns

^a Delavan Raindrop Ultra (RU), Spraying Systems AI Teejet (AI), and Spraying Systems XR Teejet (XR).

^b Least Significant Difference (LSD) mean separation technique at the 5% significance level.

Table 6. Interactive effects of nozzle, application volume, and herbicide on percent control and biomass reduction of common cocklebur (*Xanthium strumarium*).

Nozzle ^a	Application volume (L/ha)	Herbicide	Control			Biomass
			1 WAT	2 WAT	3 WAT	2 WAT
				(%)		(%)
AI	50	glufosinate	99	97	95	90
AI	50	glyphosate	86	96	96	94
AI	50	paraquat	97	96	94	91
AI	100	glufosinate	98	96	94	91
AI	100	glyphosate	86	95	97	91
AI	100	paraquat	98	98	96	96
RU	50	glufosinate	95	92	86	84
RU	50	glyphosate	83	95	95	90
RU	50	paraquat	93	92	89	89
RU	100	glufosinate	97	96	93	89
RU	100	glyphosate	80	91	94	83
RU	100	paraquat	93	92	86	87
XR	50	glufosinate	98	96	94	93
XR	50	glyphosate	84	93	95	87
XR	50	paraquat	98	97	95	93
XR	100	glufosinate	99	97	96	96
XR	100	glyphosate	86	97	97	96
XR	100	paraquat	99	98	96	95
LSD ^b			ns	2.8	3.5	6.8

^a Delavan Raindrop Ultra (RU), Spraying Systems AI Teejet (AI), and Spraying Systems XR Teejet (XR).

^b Least Significant Difference (LSD) mean separation technique at the 5% significance level.

Table 7. Interactive effects of nozzle and herbicide, averaged over application volume, on percent control and biomass reduction of common cocklebur (*Xanthium strumarium*).

Nozzle ^a	Herbicide	Control			Biomass
		1 WAT	2 WAT	3 WAT	2 WAT
			(%)		(%)
AI	glufosinate	98	96	94	90
AI	glyphosate	86	96	96	93
AI	paraquat	98	97	95	93
RU	glufosinate	96	94	89	87
RU	glyphosate	81	93	94	87
RU	paraquat	93	92	88	88
XR	glufosinate	98	97	95	94
XR	glyphosate	85	95	96	92
XR	paraquat	98	98	96	94
LSD ^b		ns	ns	2.5	ns

^a Delavan Raindrop Ultra (RU), Spraying Systems AI Teejet (AI), and Spraying Systems XR Teejet (XR).

^b Least Significant Difference (LSD) mean separation technique at the 5% significance level.

Table 8. Pooled effects of nozzle, application volume, and herbicide on percent control and biomass reduction of broadleaf signalgrass (*Brachiaria platyphylla*).

Variable pooled across		Control			Biomass
		1 WAT	2 WAT	3 WAT	2 WAT
		(%)			(%)
Nozzle ^a	AI	86	95	95	87
	RU	84	93	91	86
	XR	86	95	94	88
	LSD ^b	ns	1.1	1.4	ns
Application volume (L/ha)	50	85	94	92	84
	100	86	95	94	90
	LSD ^b	ns	0.9	1.2	2.7
Herbicide	glufosinate	92	98	95	89
	glyphosate	66	88	88	81
	paraquat	98	98	97	91
	LSD ^b	3.9	1.1	1.4	3.3

^a Delavan Raindrop Ultra (RU), Spraying Systems AI Teejet (AI), and Spraying Systems XR Teejet (XR).

^b Least Significant Difference (LSD) mean separation technique at the 5% significance level.

Table 9. Interactive effects of nozzle and herbicide, averaged over application volume, on percent control and biomass reduction of broadleaf signalgrass (*Brachiaria platyphylla*).

Nozzle ^a	Herbicide	Control			Biomass
		1 WAT	2 WAT	3 WAT	2 WAT
		(%)			(%)
AI	glufosinate	93	98	97	90
AI	glyphosate	66	90	90	81
AI	paraquat	98	98	98	90
RU	glufosinate	91	96	91	86
RU	glyphosate	65	87	87	81
RU	paraquat	97	98	96	89
XR	glufosinate	93	99	96	90
XR	glyphosate	67	89	89	81
XR	paraquat	98	98	98	93
LSD ^b		ns	1.8	2.4	ns

^a Delavan Raindrop Ultra (RU), Spraying Systems AI Teejet (AI), and Spraying Systems XR Teejet (XR).

^b Least Significant Difference (LSD) mean separation technique at the 5% significance level.

Table 10. Analysis of variance for treatment factor effects on percent control and biomass reduction of common cocklebur (*Xanthium strumarium*).

Factor(s)	Control			Biomass
	1 WAT	2 WAT	3 WAT	2 WAT
	(Probability > F)			
Nozzle	0.0001	0.0001	0.0001	0.0001
Application volume	0.5311	0.0575	0.0233	0.0938
Herbicide	0.0001	0.0573	0.0002	0.5021
Nozzle * Application volume	0.3694	0.0584	0.4343	0.0455
Nozzle * Herbicide	0.1497	0.0612	0.0180	0.4166
Application volume * Herbicide	0.9385	0.3894	0.2000	0.3921
Nozzle * Application volume * Herbicide	0.2119	0.0012	0.0240	0.0058

Table 11. Analysis of variance for treatment factor effects on percent control and biomass reduction of broadleaf signalgrass (*Brachiaria platyphylla*).

Factor(s)	Control			Biomass
	1 WAT	2 WAT	3 WAT	2 WAT
	(Probability > F)			
Nozzle	0.7044	0.0002	0.0001	0.3151
Application volume	0.6050	0.0012	0.0003	0.0001
Herbicide	0.0001	0.0001	0.0001	0.0001
Nozzle * Application volume	0.9235	0.9419	0.7655	0.5290
Nozzle * Herbicide	0.7803	0.0011	0.0073	0.8087
Application volume * Herbicide	0.9001	0.3933	0.3527	0.0569
Nozzle * Application volume * Herbicide	0.8536	0.6825	0.8831	0.7326

Table 12. Correlation analysis of nozzle parameters with herbicide performance on common cocklebur (*Xanthium strumarium*) and broadleaf signalgrass (*Brachiaria platyphylla*) at 2 weeks after treatment.

Weed	Herbicide	Nozzle Parameter	
		VMD	V205
		(R) ^a	
Cocklebur	glufosinate	-0.41	ns
Cocklebur	glyphosate	ns	ns
Cocklebur	paraquat	-0.58	0.41
Signalgrass	glufosinate	-0.76	0.64
Signalgrass	glyphosate	ns	ns
Signalgrass	paraquat	ns	ns

^a Pearson's Correlation Coefficient. Significance based on $\alpha = 0.05$.

Table 13. Wind speed and direction during treatment application in two metolachlor deposition studies.

Date	Treatment factors		Wind speed ^a		Wind direction ^b
	Nozzle ^c	Application volume	Average	Maximum/minimum	
		(L/ha)	(km/h)		(degrees)
May 27, 1999	AI	50	8.5	13.2 / 3.2	70
	AI	100	7.2	10.5 / 4.0	52
	RU	50	8.2	10.8 / 0.8	64
	RU	100	7.4	9.2 / 5.3	46
	XR	50	5.5	12.6 / 0	75
	XR	100	7.9	13.0 / 6.1	49
June 3, 1999	AI	50	8.1	16.9 / 3.7	73
	AI	100	8.9	11.9 / 6.8	41
	RU	50	8.2	11.9 / 2.6	57
	RU	100	7.2	11.3 / 2.4	42
	XR	50	8.5	13.0 / 2.4	78
	XR	100	5.3	10.6 / 1.4	47

^a Wind speed recorded each minute and averaged over the duration of treatment application, which was approximately five minutes.

^b Wind direction recorded each minute and averaged over the duration of treatment application, which was approximately five minutes. Direction is relative to the path of spray application in the plots (0 degrees).

^c Delavan Raindrop Ultra (RU), Spraying Systems AI Teejet (AI), and Spraying Systems XR Teejet (XR).

Table 14. Interactive effects of nozzle and tip size on volume median diameter (VMD) and percent of spray volume in droplets less than 205 μm (V205) with metolachlor at a spray pressure of 276 kPa.

Nozzle ^a	Tip size	VMD	V205
		(μm)	(%)
AI	110015	481	12.7
AI	11003	476	12.1
RU	110015	767	5.0
RU	11003	592	6.2
XR	110015	156	69.4
XR	11003	206	49.7
LSD ^b		9.5	1.0

^a Delavan Raindrop Ultra (RU), Spraying Systems AI Teejet (AI), and Spraying Systems XR Teejet (XR).

^b Least Significant Difference (LSD) mean separation technique at the 5% significance level.

Table 15. Pooled effects of nozzle and tip size on metolachlor deposition (DEP) at a spray pressure of 276 kPa.

Variable pooled across		DEP
		(%)
Nozzle ^a	AI	108
	RU	105
	XR	93
	LSD ^b	9.5
Tip size	110015	110
	11003	94
	LSD ^b	ns

^a Delavan Raindrop Ultra (RU), Spraying Systems AI Teejet (AI), and Spraying Systems XR Teejet (XR).

^b Least Significant Difference (LSD) mean separation technique at the 5% significance level.

Table 16. Pooled effects of nozzle and tip size on variability of metolachlor deposition (CV).

Variable pooled across		CV
		(%)
Nozzle ^a	AI	15.2
	RU	14.9
	XR	11.2
	LSD ^b	ns
Tip size	110015	17.7
	11003	9.8
	LSD ^b	7.4

^a Delavan Raindrop Ultra (RU), Spraying Systems AI Teejet (AI), and Spraying Systems XR Teejet (XR).

^b Least Significant Difference (LSD) mean separation technique at the 5% significance level.

APPENDIX C
DISCRETE DATUM FOR MALVERN LASER ANALYSIS OF SPRAY
DROPLET SPECTRA

Interactive effects of nozzle, herbicide, tip size, and pressure on volume median diameter (VMD) and percent of spray volume in droplets less than 205 μm (V205).

Nozzle ^a	Herbicide	Tip size	Pressure	VMD	V205
			(kPa)	(μm)	(%)
AI	Glufosinate	110015	100	712	7.4
AI	Glufosinate	110015	276	340	28.1
AI	Glufosinate	110015	450	281	34.3
AI	Glufosinate	110015	625	264	36.7
AI	Glufosinate	11003	100	657	9.4
AI	Glufosinate	11003	276	376	25.3
AI	Glufosinate	11003	450	333	28.5
AI	Glufosinate	11003	625	313	29.9
AI	Glufosinate	11004	100	624	12.1
AI	Glufosinate	11004	276	398	23.3
AI	Glufosinate	11004	450	365	25.3
AI	Glufosinate	11004	625	335	28.0
AI	Glyphosate	110015	100	803	5.9
AI	Glyphosate	110015	276	432	20.1
AI	Glyphosate	110015	450	347	26.7
AI	Glyphosate	110015	625	305	30.4
AI	Glyphosate	11003	100	723	6.5
AI	Glyphosate	11003	276	470	16.2
AI	Glyphosate	11003	450	402	20.9
AI	Glyphosate	11003	625	378	22.2
AI	Glyphosate	11004	100	714	7.4
AI	Glyphosate	11004	276	493	14.1
AI	Glyphosate	11004	450	431	17.3

AI	Glyphosate	11004	625	393	20.0
AI	Paraquat	110015	100	829	4.3
AI	Paraquat	110015	276	489	13.3
AI	Paraquat	110015	450	389	19.7
AI	Paraquat	110015	625	343	23.9
AI	Paraquat	11003	100	738	4.6
AI	Paraquat	11003	276	498	11.5
AI	Paraquat	11003	450	430	15.4
AI	Paraquat	11003	625	383	19.6
AI	Paraquat	11004	100	712	5.1
AI	Paraquat	11004	276	490	11.9
AI	Paraquat	11004	450	430	15.5
AI	Paraquat	11004	625	383	19.7
LM	Glufosinate	110015	100	601	7.0
LM	Glufosinate	110015	276	353	24.0
LM	Glufosinate	110015	450	267	35.2
LM	Glufosinate	110015	625	231	42.3
LM	Glufosinate	11003	100	515	12.7
LM	Glufosinate	11003	276	384	21.8
LM	Glufosinate	11003	450	318	27.8
LM	Glufosinate	11003	625	301	30.0
LM	Glufosinate	11004	100	688	5.4
LM	Glufosinate	11004	276	505	12.8
LM	Glufosinate	11004	450	430	16.9
LM	Glufosinate	11004	625	400	20.6
LM	Glyphosate	110015	100	677	4.4

LM	Glyphosate	110015	276	375	21.1
LM	Glyphosate	110015	450	288	31.5
LM	Glyphosate	110015	625	253	36.5
LM	Glyphosate	11003	100	557	10.4
LM	Glyphosate	11003	276	416	17.3
LM	Glyphosate	11003	450	352	22.8
LM	Glyphosate	11003	625	315	27.1
LM	Glyphosate	11004	100	739	4.2
LM	Glyphosate	11004	276	547	9.9
LM	Glyphosate	11004	450	476	11.9
LM	Glyphosate	11004	625	427	16.4
LM	Paraquat	110015	100	640	6.0
LM	Paraquat	110015	276	384	18.8
LM	Paraquat	110015	450	295	28.8
LM	Paraquat	110015	625	247	37.6
LM	Paraquat	11003	100	569	7.5
LM	Paraquat	11003	276	422	14.9
LM	Paraquat	11003	450	351	21.1
LM	Paraquat	11003	625	317	25.3
LM	Paraquat	11004	100	724	3.1
LM	Paraquat	11004	276	539	8.2
LM	Paraquat	11004	450	464	12.1
LM	Paraquat	11004	625	434	16.3
RU	Glufosinate	110015	100	1242	1.4
RU	Glufosinate	110015	276	713	8.2
RU	Glufosinate	110015	450	529	14.8

RU	Glufosinate	110015	625	430	20.2
RU	Glufosinate	11003	100	846	3.7
RU	Glufosinate	11003	276	525	14.1
RU	Glufosinate	11003	450	406	23.1
RU	Glufosinate	11003	625	356	27.4
RU	Glufosinate	11004	100	767	3.9
RU	Glufosinate	11004	276	459	17.6
RU	Glufosinate	11004	450	396	23.3
RU	Glufosinate	11004	625	360	26.4
RU	Glyphosate	110015	100	1240	1.6
RU	Glyphosate	110015	276	817	5.4
RU	Glyphosate	110015	450	656	8.8
RU	Glyphosate	110015	625	557	12.1
RU	Glyphosate	11003	100	951	3.4
RU	Glyphosate	11003	276	642	8.1
RU	Glyphosate	11003	450	502	13.6
RU	Glyphosate	11003	625	439	18.3
RU	Glyphosate	11004	100	894	3.2
RU	Glyphosate	11004	276	622	8.1
RU	Glyphosate	11004	450	508	12.6
RU	Glyphosate	11004	625	455	16.4
RU	Paraquat	110015	100	1215	1.4
RU	Paraquat	110015	276	820	3.6
RU	Paraquat	110015	450	672	5.6
RU	Paraquat	110015	625	584	7.9
RU	Paraquat	11003	100	953	2.2

RU	Paraquat	11003	276	661	5.2
RU	Paraquat	11003	450	539	9.3
RU	Paraquat	11003	625	473	12.8
RU	Paraquat	11004	100	878	2.2
RU	Paraquat	11004	276	564	7.0
RU	Paraquat	11004	450	463	11.6
RU	Paraquat	11004	625	418	15.3
TD	Glufosinate	110015	100	607	8.0
TD	Glufosinate	110015	276	432	17.4
TD	Glufosinate	110015	450	360	23.3
TD	Glufosinate	110015	625	317	27.9
TD	Glufosinate	11003	100	611	8.8
TD	Glufosinate	11003	276	363	26.3
TD	Glufosinate	11003	450	285	35.6
TD	Glufosinate	11003	625	267	38.2
TD	Glufosinate	11004	100	639	9.4
TD	Glufosinate	11004	276	436	20.6
TD	Glufosinate	11004	450	348	28.3
TD	Glufosinate	11004	625	321	32.1
TD	Glyphosate	110015	100	706	4.6
TD	Glyphosate	110015	276	462	14.1
TD	Glyphosate	110015	450	391	19.1
TD	Glyphosate	110015	625	337	26.0
TD	Glyphosate	11003	100	701	5.4
TD	Glyphosate	11003	276	416	21.3
TD	Glyphosate	11003	450	373	24.4

TD	Glyphosate	11003	625	336	28.7
TD	Glyphosate	11004	100	725	5.7
TD	Glyphosate	11004	276	496	14.3
TD	Glyphosate	11004	450	436	19.1
TD	Glyphosate	11004	625	393	23.7
TD	Paraquat	110015	100	723	4.2
TD	Paraquat	110015	276	503	10.8
TD	Paraquat	110015	450	412	16.1
TD	Paraquat	110015	625	355	21.4
TD	Paraquat	11003	100	706	4.7
TD	Paraquat	11003	276	496	11.8
TD	Paraquat	11003	450	434	18.0
TD	Paraquat	11003	625	341	26.3
TD	Paraquat	11004	100	710	4.4
TD	Paraquat	11004	276	530	9.6
TD	Paraquat	11004	450	460	15.1
TD	Paraquat	11004	625	398	20.0
XR	Glufosinate	110015	100	158	67.6
XR	Glufosinate	110015	276	130	83.0
XR	Glufosinate	110015	450	127	85.3
XR	Glufosinate	110015	625	121	88.0
XR	Glufosinate	11003	100	192	53.7
XR	Glufosinate	11003	276	170	62.7
XR	Glufosinate	11003	450	161	67.9
XR	Glufosinate	11003	625	148	73.1
XR	Glufosinate	11004	100	205	50.0

XR	Glufosinate	11004	276	179	58.2
XR	Glufosinate	11004	450	172	62.2
XR	Glufosinate	11004	625	165	65.6
XR	Glyphosate	110015	100	162	65.6
XR	Glyphosate	110015	276	132	81.4
XR	Glyphosate	110015	450	124	85.9
XR	Glyphosate	110015	625	124	84.7
XR	Glyphosate	11003	100	203	50.6
XR	Glyphosate	11003	276	179	59.0
XR	Glyphosate	11003	450	162	67.4
XR	Glyphosate	11003	625	151	72.1
XR	Glyphosate	11004	100	283	35.5
XR	Glyphosate	11004	276	216	46.9
XR	Glyphosate	11004	450	191	55.0
XR	Glyphosate	11004	625	176	60.7
XR	Paraquat	110015	100	188	55.7
XR	Paraquat	110015	276	145	76.2
XR	Paraquat	110015	450	131	84.1
XR	Paraquat	110015	625	120	90.3
XR	Paraquat	11003	100	254	38.0
XR	Paraquat	11003	276	188	56.4
XR	Paraquat	11003	450	163	68.1
XR	Paraquat	11003	625	142	77.8
XR	Paraquat	11004	100	291	33.0
XR	Paraquat	11004	276	216	46.5
XR	Paraquat	11004	450	185	57.6

XR	Paraquat	11004	625	164	66.7
HSD ^b				32.6	3.3

^a Delavan Raindrop Ultra (RU), Greenleaf TurboDrop (TD), Lurmark Ultra Lo-Drift (LM), Spraying Systems AI Teejet (AI), and Spraying Systems XR Teejet (XR).

^b Tukey's Honest Significant Difference (HSD) mean separation technique at the 5% significance level.

APPENDIX D
PRELIMINARY EFFICACY DATA

A field study was conducted in Knoxville Tennessee at the Holston Research Unit comparing the efficacy of a venturi-type nozzle to a standard flat fan nozzle using three application volumes and three herbicides. Two experiments were conducted in 1998. One experiment was initiated on July 2 in an area containing broadleaf signalgrass and entireleaf morningglory and another experiment was initiated on July 4 in an area containing broadleaf signalgrass (*Brachiaria platyphylla*) and Palmer amaranth (*Amaranthus palmeri*). Plots were 3.1 m by 6.1 m and were arranged in a randomized block design with four replications. Blocks were separated by 6-m alleys to allow room for the tractor to achieve the target application speed prior to entering the plot.

The venturi nozzle was a Delavan Raindrop Ultra (RU)¹ and the flat fan nozzle was a Spraying Systems XR Teejet (XR)². Nozzles were spaced 51 cm apart along a 254-cm, tractor-mounted boom which was operated at 13.4 km/h. Spray tips were used for each nozzle which produced fan sprays of 110° spray angle and nominal discharge rates of 0.57, 1.14, and 1.51 L/min, which produced application volumes of 50, 100, and 150 L/ha, respectively, at 276 kPa.

Commercial formulations of glufosinate³, glyphosate⁴, and paraquat⁵ were added to water carrier to maintain constant application rates of 0.43, 0.84, and 0.71 kg ai/ha,

¹ Raindrop Ultra®. Delavan Spray Technologies, Monroe, NC 28110.

² XR Teejet®. Spraying Systems Co., Wheaton, IL 60188.

³ Liberty® herbicide. AgrEvo USA Company, Wilmington, DE 19808.

⁴ Roundup Ultra® herbicide. Monsanto Company, St. Louis, MO 63167.

⁵ Gramoxone Extra® herbicide. Zeneca Ag Products, Wilmington, DE 19850-2500.

respectively, at both application volumes. To accomplish this, separate mixes of each herbicide were prepared in 11-L stainless steel containers and delivered to the nozzles by compressed CO₂. These represent normal use rates for these herbicides (Anonymous 1998a). A nonionic surfactant⁶ (NIS) at 0.25% v/v was included with the paraquat solutions. Treatments included 2 untreated checks plus all combinations of the 2 nozzles, 3 application volumes, and 3 herbicides. Treatments were applied when broadleaf signalgrass, common cocklebur, and Palmer amaranth were approximately 30, 40, and 45 cm tall, respectively.

Visual control was evaluated 1, 2, and 3 weeks after treatment (WAT) on a scale of 0 to 100, with 0 being no control and 100 being complete control. The two untreated plots in each rep and the untreated area between adjacent plots were utilized as a visual reference. Biomass was measured 2 WAT by harvesting all above ground plant material in a 0.093 m² area in the center of each plot and recording fresh weights in the field. Biomass data for each plot was computed as a percent fresh weight reduction relative to the average of the two untreated plots in the corresponding block.

The presence of multiple weed species in each experiment confounded the biomass data and it will not be presented. Also, common cocklebur and Palmer amaranth control ratings will not be presented since neither weed species was evaluated in more than one experiment. The combined broadleaf signalgrass data from the two experiments are shown below:

⁶X-77® nonionic surfactant, which is a mixture of alkylaryl polyoxyethylene, glycols, free fatty acids, and isopropanol. Loveland Industries Inc., Greeley, CO 80632.

1998. Pooled effects of nozzle, application volume, and herbicide on percent control and biomass reduction of broadleaf signalgrass (*Brachiaria platyphylla*).

Variable pooled across		Control		
		1 WAT	2 WAT	3 WAT
		%		
Nozzle ^a	RU	57	63	23
	XR	59	67	34
	LSD ^b	ns	ns	ns
Application volume (L/ha)	50	56	65	28
	100	64	71	34
	150	54	59	23
	LSD ^b	5	6	ns
Herbicide	glufosinate	71	64	2
	glyphosate	16	47	39
	paraquat	87	84	43
	LSD ^b	11	8	6

^a Delavan Raindrop Ultra (RU) and Spraying Systems XR Teejet (XR).

^b Least Significant Difference (LSD) mean separation technique at the 5% significance level.

APPENDIX E
TANK SAMPLE ANALYSIS

A field study was conducted in Knoxville Tennessee at the Holston Research Unit to evaluate the amount and uniformity of herbicide concentration within two application volumes when a constant herbicide mixture was maintained. This study was one component of a larger study to evaluate nozzle type and application volume effects on herbicide deposition in the spray target area (Data previously reported). Metolachlor was selected because it is widely used in agronomic and turf weed control systems, and it's chemical analysis is not problematic. A NIS at 0.25% v/v was added to the metolachlor solutions to simulate typical herbicide solution characteristics, such as surface tension, and resulting spray droplet characteristics. Two experiments were conducted in 1999, one on May 27 and another on June 10.

Spray nozzles were spaced 51 cm apart along a 254-cm, tractor-mounted boom. Spray tips were used which produced fan sprays of 110° spray angle and nominal discharge rates of 0.57 and 1.14 L/min at 276 kPa. At a field application speed of 13.4 km/h, the spray tips produced application volumes of 50 and 100 L/ha, respectively. A commercial formulation of metolachlor¹, containing 915 g/L of the resolved isomer of metolachlor, was added to water carrier to maintain a theoretically constant application rate of 1.8 kg ai/ha by preparing separate mixtures in 11-L stainless steel containers. The solution utilized for the 50 L/ha application volume was prepared by adding 440 ml metolachlor and 30 ml NIS to the container and bringing to a total volume of 11 L with water (36600 ppm metolachlor). The solution for the 100 L/ha application volume was prepared similarly, except 225 ml of metolachlor was added (17716 ppm metolachlor).

¹ Dual II Magnum® herbicide. Novartis Crop Protection Inc., Greensboro, NC 27419.

Spray solution was delivered to the boom with compressed CO₂.

Plots were 3.1 m by 6.1 m and were arranged in a randomized block design with four replications. Blocks were separated by 6-m alleys for operational considerations, such as to allow room for the tractor to achieve the target application speed prior to entering the plot and also to provide room to sample the spray solution output. Prior to entering each plot, spray solution was sampled by placing a 20-ml vial under one of the center two nozzles on the boom and collecting 10 ml. Due to the time necessary to drive through each plot, process the sample sheets, and move to the next plot, spray solution samples were collected approximately every 10 minutes. All treatments involving the 50 L/ha application volume were applied first followed by the 100 L/ha treatments, which allowed each tank mixture to be sampled over time. The vials of spray solution were kept on ice until they were placed in a refrigerator and stored until analysis. Spray solution samples were allowed to warm at room temperature for 4 h. Samples were diluted 1:1000 using methanol. The dilution was performed to produce metolachlor concentrations in the samples which were within the linear dynamic range of the GC instrument. An aliquot of each sample was placed in a 2-ml auto-sample vial. Metolachlor concentration was determined using gas chromatography utilizing an NPD detector. The concentration of herbicide in parts per million (ppm) over time and a coefficient of variation (CV) of the tank samples are listed below:

Amount and uniformity of metolachlor concentration applied within two application volumes at a constant dosage^a.

Experiment	Time ^b (minutes)	Application volume	
		50 L/ha	100 L/ha
		Concentration (1000 ppm)	
1	0:00	-	17.1
1	0:10	24.2	13.4
1	0:20	-	16.0
1	0:30	28.6	14.8
1	0:40	27.2	12.3
1	0:50	31.0	15.0
1	0:60	30.9	14.7
1	0:70	25.3	14.5
1	0:80	27.9	14.7
1	0:90	28.5	12.7
1	1:00	24.8	15.2
1	1:10	26.8	11.6
1	CV ^c	8.5%	11.0%
2	0:00	17.5	13.0
2	0:10	14.7	10.2
2	0:20	23.7	13.7
2	0:30	21.5	13.1
2	0:40	22.2	13.0
2	0:50	21.2	8.5
2	0:60	23.8	12.4
2	0:70	20.5	13.6

2	0:80	25.2	13.1
2	0:90	21.5	14.5
2	1:00	16.9	12.2
2	1:10	26.5	12.7
2	CV ^c	16.4%	13.1%

^a The 50 L/ha solution was prepared by adding 440 ml metolachlor and 30 ml NIS to an 1 l-L container and bringing to volume with water (36600 ppm metolachlor). The 100 L/ha solution was prepared similarly, except 225 ml of metolachlor was added (17716 ppm metolachlor).

^b Time is in minutes elapsed from spray solution preparation (0:00) until the final sample was taken (1:10).

^c Coefficient of variation.

VITA

Robert Etheridge was born on October 27, 1970 in Hampton, South Carolina. He lived briefly in Florida and Texas but was raised in Bowman, South Carolina and graduated from Bowman Academy in 1988. Robert worked on a large dairy farm throughout high school and on the weekends and summers while attending Clemson University. Robert received his B.S. in Agronomy in 1992 and completed his M.S. in Weed Science under the direction of Dr. Ed Murdock in 1994. While at Clemson, Robert was active in several student organizations including the Agronomy Club (president), the Dairy Science Club (vice-president), the Student Senate, and the Fellowship of Christian Athletes. Upon completion of his M.S., Robert was employed by McLawhorn Crop Services as a consultant in eastern North Carolina where he assisted growers in making management decisions in a variety of crops. He actively participated in consultant's organizations at both the state (NCCA) and national (NAICC) level. In January of 1997, Robert was employed full-time by The University of Tennessee and also began a Ph.D. program in Weed Science under the direction of Dr. Tom Mueller. He has presented research data to local, regional, and national audiences and won first place in the SWSS graduate student paper contest. Robert has been active in both oral and written extension education activities, has authored eight abstracts published in the proceedings of professional societies, and was awarded the 1999 Outstanding PhD Student Award by the Tennessee Agricultural Production Association. He is senior author on several refereed journal articles. Robert is happily married to the former Elizabeth Pettett and completed his Ph.D. in December, 1999.

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