GEORGIA DOT RESEARCH PROJECT 13-08
FINAL REPORT

ENHANCING EXTENSION RECOMMENDATIONS TO MAXIMIZE EFFICACY OF SPRAY PROGRAMS FOR THE GEORGIA DOT

Georgia Department of Transportation

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Enhancing Extension Recommendations to Maximize Efficacy of Spray Programs for the Georgia DOT

Final Report

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16. Abstract: Research was conducted to evaluate equipment, adjuvants, and water quality used by the Georgia DOT on herbicide efficacy for roadside management. From 19 DOT stations, 68% had alkaline (7.1 to 7.9) water, 32% had hard water (>120 ppm), and 10% had a concentration of more than 5 ppm of suspended solids. Johnsongrass control was reduced from 50 to 75% when glyphosate was sprayed in water containing various levels of calcium, magnesium, and iron, compared to soft water. Weed control from Accord (glyphosate) and Garlon (triclopyr) was reduced by about half when applied with hard water, but control from Milestone (aminopyralid) in one experiment was similar to treatments made in soft water. The efficacy of the standard DOT drift retardant adjuvant, Ground Zero, did not reduce the efficacy of glyphosate in bioassay experiments. The DOT trucks equipped with Boombuster nozzles and Northstar sprayers delivered the targeted calibration volumes. However, applications showed substantial differences in uniformity from visual, volumetric, and whole plant bioassays. From incremental distances from the truck, the total spray volume varied from about 80 to 120% of the targeted application rate. Trucks equipped with Boombuster and Northstar sprayers controlled broomsedge and vaseygrass 89% or greater for plants placed from 0 to 20 feet from the truck. However, control ranged 56 to 69% for plants spaced at 25 and 30 feet from trucks, suggesting the DOT sprayers provide insufficient coverage beyond 20 feet. It is recommend that the DOT sample water several times throughout the year at stations with reported issues in this research. If fresh water sources cannot be used for applications, it is recommended that ammonium sulfate, EDTA, or other amendments be used with water sources containing alkaline pH or hardness levels greater than 100 PPM. Selecting herbicides that have less potential for antagonism is recommend for controlling broadleaf weeds over 2,4-D, glyphosate, or triclopyr when water quality is compromised. It is recommended that the DOT request inspections from the manufacturers of the sprayer equipment to improve consistencies of applications or use alternative sprayers for roadside management.

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EXECUTIVE SUMMARY

Research was conducted to evaluate equipment, adjuvants, and water quality used by the Georgia DOT on the efficacy of herbicides applied for roadside management. From 19 DOT stations, 68% had alkaline (7.1 to 7.9) water, 32% had hard water (>120 ppm), and 10% had a concentration of more than 5 ppm of suspended solids. The efficacy of herbicides was evaluated in field and greenhouse experiments using water with hardness levels similar to samples from the DOT stations. Johnsongrass control was reduced from 50 to 75% when glyphosate was sprayed in hard water containing various levels of calcium and magnesium, compared to soft water. However, iron sulfate concentrations ≤10 PPM did not affect glyphosate efficacy for Johnsongrass control. The control of tall fescue and buckhorn plantain from glyphosate sprayed in hard water was reduced by half of treatments applied in soft water. Catsear dandelion control from Garlon (triclopyr) was also reduced by about half when applied with hard water, but control from Milestone (aminopyralid) was similar to treatments made in soft water in one experiment. The efficacy of the standard DOT drift retardant adjuvant, Ground Zero, did not reduce the efficacy of glyphosate in bioassays. The DOT trucks equipped with Boombuster nozzles and Northstar sprayers delivered the targeted calibration volumes. However, applications showed substantial differences in uniformity from visual, volumetric, and whole plant bioassays. From incremental distances from the truck, the total spray volume varied from about 80 to 120% of the targeted application rate. The control of plants spaced every five feet from the spray truck differed considerably following diquat applications. Trucks equipped with Boombuster and Northstar sprayers controlled broomsedge and vaseygrass 89% or greater for plants placed from 0 to 20 feet from the truck. However, control

ranged 56 to 69% for plants spaced at 25 and 30 feet from trucks, suggesting the DOT sprayers provide insufficient coverage beyond 20 feet. Differences in drying patterns within treated areas and inconsistencies in droplet sizes were also noted.

From this work it can be surmised that there is significant variability in water quality from the sources used for DOT spray trucks that will affect herbicide efficacy. We recommend that the DOT sample water several times throughout the year at stations with reported issues in this research. If fresh water sources cannot be used for applications, it is recommended that ammonium sulfate, EDTA, or other adjuvants be used with water sources with alkaline pH or hardness levels greater than 100 PPM. Selecting herbicides that have less potential for antagonism is recommend for controlling broadleaf weeds over 2,4-D, glyphosate, or Garlon (triclopyr) when water quality is compromised. The spray trucks that were tested were accurately calibrated to deliver the appropriate volume of water targeted for applications. However, the spray trucks did not provide uniform applications. These trucks exhibited spray pattern streaking, failures to spray more than 20 feet in distance, and had linear reductions in control with increased distances away from nozzles. It is recommended that the DOT request inspections from the manufacturers of this equipment to improve the consistencies of applications or use alternative sprayers for roadside management.

ACKNOWLEDGEMENTS

Special thanks Seth Williams, Dr. Jialin Yu, Bill Nutt, and Henry Jordan for technical support with this research. We would also like to thank Ray Dorsey from the Georgia DOT for the opportunity to work on this project and for all of his assistance with helping plan and conduct this research.

INTRODUCTION

Georgia has over 18,000 miles of primary and secondary roads with approximately 720,000 acres of roadside vegetation managed by the DOT. The presence of weeds on roadsides reduces aesthetics, safety, and visibility for drivers on highways, interstates, and other roads throughout the state. Roadsides are mowed infrequently, which may thin grass canopies and reduce competition with weeds. Herbicides are applied for controlling weeds, but are also used to reduce mowing requirements of desirable grasses. Maximizing the performance of herbicides and growth regulators is critical for successful management of roadsides in Georgia.

Many factors influence herbicide efficacy for weed control on Georgia roadsides. For example, sprayer equipment that is improperly calibrated could fail to deliver the targeted application rate. Sprayers with proper calibration that lack application uniformity may allow escaped weeds to become invasive or competitive with roadside grasses. The failure to apply herbicides accurately could also warrant mechanical suppression or increase the costs associated with control. The DOT is also concerned over drift of herbicide applications to non-targeted areas. Drift retarding agents are important components of spray programs for the DOT to minimize potential off target injury. The effects of these materials and current equipment warrant review for improving the DOT maintenance programs.

Water quality is also a major influential factor on herbicide efficacy. The effects of pH, hardness, and sediments in water can affect absorption and physiological activity of herbicides. Antagonism caused by poor water quality could require repeat herbicides applications for acceptable weed control. For example, 2,4-D, dicamba, and other synthetic auxins are weak acids used for broadleaf weed control. These herbicides can bind with calcium, magnesium, and iron in water, and antagonism has been reported for controlling common lambsquarters (*Chenopodium album*), redroot pigweed (*Amaranthus retroflexus*), and other weeds (Roskamp et al. 2013; Woznica et al. 2003). Glyphosate is widely used for nonselective control of weeds in dormant bermudagrass and other areas, but the presence of divalent ions (Ca, Mg, or Fe) in spray solutions may bind to the active ingredient and counteract herbicidal effects of applications (Shilling et al. 1990). Water pH also affects the solubility of many herbicides, including sulfonylureas, which are widely used in roadside management (Matocah et al. 2006).

The interaction of low water pH and diluent ions may further exacerbate herbicide antagonism (Shilling and Haller 1989). Reductions in efficacy of herbicides applied in poor water quality could increase the costs for additional inputs required for effective control of invasive weeds on Georgia roadsides. The analysis of water sources from various DOT stations is necessary to determine the potential of poor water quality affecting efficacy of spray programs throughout the state. Furthermore, determining the performance of herbicides used by the DOT in water with compromised quality may allow agronomists to select appropriate herbicides that have limited risk for antagonism.

Agronomists working for the Georgia DOT could be using equipment and sources of water with variability in factors that affect the long-term success of roadside maintenance. Inconsistent weed control and growth regulation of desirable vegetation could result from poor water quality or if application equipment is ineffective. These concerns warrant further review for DOT agronomists to enhance the efficacy of spray programs in Georgia.

OBJECTIVE

The objectives of this research were to evaluate and review application equipment, water quality, and operations currently incorporated by the Georgia DOT to help maximize efficacy in vegetation management programs.

PROCEDURES

Water quality survey. A survey was conducted in spring 2013 to evaluate the water sources used in spray trucks throughout the state. One liter of water was collected from twenty locations. Samples were sent to the University of Georgia Soil and Water laboratory for testing. Measurements that were performed on these samples included pH, hardness, suspended solids, and turbidity. These parameters are influential on herbicide stability and degradation in spray tanks. Water hardness is measured in parts per million (PPM) of the calcium, magnesium, and iron present in the water samples. The pH was measured on a scale from 1 to 14, where 7 equals neutral, 1 is extremely acidic, and 14 is extremely alkaline. Suspended solids were measured as PPM of the water sample. Turbidity, or clearness of the water, was measured in nephelometric turbidity units (NTU) that measures the intensity of light scattered at 90 degrees as light passes through the sample.

Evaluation of water hardness on Johnsongrass response to glyphosate. Experiments were conducted in a greenhouse at the University of Georgia Griffin Campus to evaluate the influence of diluent ions on the efficacy of glyphosate for Johnsongrass control. The water hardness levels were chosen to mimic levels found in the water surveys from the DOT stations. Greenhouse temperatures were set for 90/80° F (day/night). Johnsongrass was seeded in pots with a 1.5-inch diameter and 8 inch depths. Soil was a sand:peat moss (85:15) mix. Pots received irrigation daily to promote Johnsongrass establishment and growth. Treatments were applied once plants reached a 12” height. Treatments consisted of a factorial combination with three rates of glyphosate (0, 0.19, or 0.75 lb acid equivalent per acre), six concentrations of calcium chloride (0, 10, 20, 40, 80, or 160 ppm), and magnesium chloride (0, 10, 20, 40, 80, or 160 ppm). All possible combinations of glyphosate, calcium chloride, and magnesium chloride were applied.

In a separate experiment, Johnsongrass plants were established as previously described. Treatments were the factorial combination of glyphosate at 0, 0.19, or 0.75 lb ae/acre and iron sulfate at 0, 1.25, 2.5, 5, 10, or 20 PPM. The glyphosate product applied was Roundup Pro (3 lb ae/gal, Monsanto, St. Louis, MO). The calcium, magnesium, and iron products were laboratory grade material purchased from Sigma Aldrich. Applications were made with a CO_2-pressured sprayer calibrated at 40 gallons per acre with a single 9504E flat-fan nozzle.

The experimental design was a randomized complete block with four replications. Johnsongrass control was visually evaluated on a percent scale where 0 equaled no injury and 100 equaled complete necrosis. Data were subjected to the analysis of variance with SAS (v. 9.3, SAS Institute, Cary, NC). Multiple regression analysis was conducted using SigmaPlot (Systat Software, Inc., San Jose, CA) for the first experiment. Data were plotted on graphs using the multiple parabolic regression equation, $z = a + b*x + c*y + d*x\^2 + e*y\^2$, where a, b, c, d, and e are constants determined from the data, x is calcium chloride concentration (ppm), y is magnesium chloride concentration (ppm), and z is Johnsongrass visual injury (%). For the iron sulfate evaluation, means were separate with Fisher's LSD test at $\alpha = 0.05$

Evaluation of herbicides used by the DOT in hard water. Two field experiments were conducted in Griffin, GA to evaluate the influence of hard water sources on the efficacy of herbicides commonly applied in the DOT spray program for weed control. Treatments were the factorial combination of four herbicides applied in three levels of water hardness soft (less than 80 PPM), hard (80 to 100 PPM), very hard (greater than 160 PPM). Herbicides applied were Milestone (aminopyralid 2 lb/gal) at 3.5 oz/acre, Banvel (dicamba 4L) at 1 lb ae/acre, Garlon 3A (triclopyr 3 lb ae/gal) at 1 pt/acre, and Accord XRT (glyphosate 4 lb ae/gal) at 1 pt/acre. Water hardness levels were created with tap water by adding calcium chloride and magnesium chloride at 40 PPM each for hard water treatments and at 80 PPM each for very hard water treatments. Treatments were applied on November 3, 2014 to a simulated roadside at University of Georgia Research and Education Gardens in Griffin, GA for both experiments. The local soil was a sandy clay loam with about 2.5% organic matter and 6.0 pH. From visual evaluations on the day of treatments, the plot cover of tall fescue, buckhorn plantain, and catsear dandelion measured 20% (±1.7 SE), 26% (±1.0), and 6% (±0.6), respectively. Treatments were applied with a CO_2-pressured backpack sprayer equipped with three 8002 flat-fan nozzles spaced 20” apart.

The experimental design was a randomized complete block with four replications of 5 x 10-foot plots. Weed control and cover were visually rated on a percent scale. Data were subjected to analysis of variance and means were separated with Fisher’s LSD test at $\alpha = 0.05$.

Evaluation of Ground Zero drift retardant on glyphosate efficacy. Experiments were conducted in a greenhouse at the University of Georgia Griffin Campus to evaluate the influence of the DOT standard drift retardant, Ground Zero, on the efficacy of glyphosate. Johnsongrass was used to quantify control levels for the bioassay. Greenhouse temperatures were set for 90/80° F (day/night). Johnsongrass was seeded in pots with a 1.5-inch diameter and 8 inch depths. Soil was a sand:peat moss (85:15) mix. Pots received irrigation daily to promote Johnsongrass establishment and growth. Treatments were applied once plants reached a 12” height. Treatments were the factorial combination of four rates of glyphosate (0.025, 0.05, 0.095, or 0.19 lb acid equivalent per acre) and three rates of Ground Zero (0, 4, or 8 fl oz per acre). A nontreated check was included. The glyphosate product applied was Roundup Pro (3 lb ae/gal, Monsanto, St. Louis, MO) and Ground Zero (Helena Chemical Co., Collierville, TN). Treatments were applied in a spray chamber calibrated at 20 gallons per acre of spray volume with a single 8002E flat-fan nozzle.

The experimental design was a randomized complete block with four replications. Johnsongrass control was visually evaluated at 2 and 4 weeks after treatment (WAT) on a percent scale where 0 equaled no injury and 100 equaled complete necrosis. Shoot biomass was harvested at 4 WAT, oven-dried at 60° C for 72 hours, and then weight. Data were subjected to analysis of variance with the General Linear Model Procedure in SAS (SAS, 9.2, SAS Institute Inc., Cary, NC 27513). Application rate required to injure Johnsongrass 50% (I_{50}) or reduce shoot mass 50% (GR_{50}) from nontreated were determined from the following equation:

$$y = a*(1-\exp(-b*x))$$

where y is injury or shoot mass reduction, a is the asymptote, b is the slope, and x is the herbicide rate (kg ae ha^{-1}). The 95% confidence limits for I_{50} and GR_{50} values were determined in SigmaPlot (Version 12.5, Systat Software, Inc., San Jose, CA).

Spray truck evaluations. Experiments were conducted to evaluate accuracy and consistency of trucks equipped with Boombuster nozzles and Northstar sprayers for delivering the targeted spray volume through volumetric, visual, and plant bioassays. This work was conducted at the DOT station in Atlanta, GA. In the first experiment, the truck was run at the standard speed (10 miles per hour) for spraying herbicides on roadsides. Water was sprayed on pavement or over beige paper that stretched 35 feet in length away from the truck with a 3-foot width. The paper was marked every five feet for visual assessment of the application uniformity. The drying patterns were visually for the treatments that were sprayed on pavement without paper.

In the second experiment, the calibration and application uniformity were measured by spraying tracking dye from the truck and measuring dye collected with a spectrophotometer. Trays containing 10 glass scintillation vials (20 mL each) were spaced at 0, 5, 10, 15, 20, 25, or 30 feet from the truck. The treatments were repeated four times with different vials (40 vials total per spacing). Subsequently, the dye was removed from vials by rinsing 5 mL of 1:1 methanol:water in each vial and then sampling an aliquot in a spectrophotometer. The dye collected was compared to a standard curve created from water sprayed directly from the truck. Data was converted to gallons per acre from the known standard concentration of dye collected from truck that was previously calibrated at 20 gallon per acre volume. This calibration was conducted by measuring the total amount of water sprayed from the truck after running a five second calibration run at 10 miles per hour.

In the third experiment, the uniformity of applications was quantified using plant bioassays. Broomsedge and vaseygrass were seeded individually in pots measuring 1.5 x 8” with sand:peat moss (85:15) soil. Plants were established in a greenhouse at the University of Georgia Griffin Campus set for 90/80° F. Irrigation was applied to prevent moisture deficiencies and fertilizer was applied to promote growth. Plants used for the experiments were approximately 12” in height and actively growing on the day of treatments.

Plants of each species were placed on trays spaced at 0, 5, 10, 15, 20, 25, or 30 feet from the truck. These distances were chosen because 30 feet is the boom length that is guaranteed from the manufacturers at the settings used by the DOT. Diquat (Reward 2L, Syngenta Crop Protection, Greensboro, NC) was applied at 1 pint per acre by making passes in one of two trucks. The first truck evaluated was equipped with the Northstar sprayers and the second was a truck equipped with boom-buster nozzles. One and two subsamples of each species were used per replication for the boombuster and Northstar trucks, respectively. Four passes were made per truck to different plants. Plants were allowed to dry on site, and then transported back to the aforementioned greenhouse at the UGA Griffin Campus. Nontreated checks were included in the analysis for each species.

Control was rated at 3, 7, and 14 days after treatment on a percent scale where 0 equaled no injury and 100 equaled complete desiccation. Shoot biomass was harvested at 14 days after treatment, oven-dried, and weighed. Results were converted to percent reductions of the nontreated by replication. The designs for the experiments were randomized complete blocks. Data were subjected to analysis of variance. The significance of main effects was determined at the 0.05 probability level. Regression analysis was performed plant bioassay data after plotting treatment means on graphs to determine the analysis that best characterized the relationship of plant responses with the distances from the truck.

In the fourth experiment, calibration runs were made with the spray trucks applying water at the standard application speed and pressure. The amount of water that was remaining was quantified in the tank and compared to the amount that was in the tank before the application. The volume was converted to gallons per acre applied in a 100-foot calibration run. In another assay, paper cups were placed every five feet from the spray trucks. Water was sprayed at the standard operation speed from the DOT trucks used for broadcast applications. Three passes were made for the two trucks and the volume collected per cup was measured. The results were pooled over replications and converted to gallons per acre at each individual placement.

FINDINGS

Water quality survey. The first measurement for the samples collected at DOT stations throughout the state was water pH. The pH levels influence the rate of herbicide dissociation in a spray tank. Weak acid herbicides, such as 2,4-D or glyphosate, are more stable when water pH is acidic (less than 7.0). These herbicides have less dissociation in acidic water under the presence of high concentrations of H+ ions. An extreme pH can also reduce the solubility of herbicides in the spray tank that may contribute to application uniformity problems. From the 19 DOT stations samples, 16% (three locations) had neutral pH while 68% were alkaline (7.1 to 7.9; Table 1). Three locations had moderate pH levels ranging less than 7.0. Two of these locations had moderately acidic pH (6.6 and 6.9). The sample from Marion County had the highest acidity, and measured 5.3.

Neutral to alkaline water could warrant the use of an acidifier to lower the pH of the sprayer water. Generally, most herbicides used by the DOT could be applied in water sources with a pH of 6.0 to 7.0 within a few hours of mixing. This duration could be extended up to 24 hours of storage if the pH is dropped to a range of 4.0 to 6.0. Alkaline water (>7.0 pH) is favorable for use with sulfonylurea herbicides since these compounds remain neutral under higher pH levels. Conversely, acidic water could reduce the efficacy of sulfonylurea herbicides if the treatments remain in the spray tank for extended periods of time (>6 hours).

The water hardness levels were a measurement of parts per million (ppm) of calcium, magnesium, and iron in the samples (Table 1). Hard water (>120 ppm) is concerning for spraying weak acids, such as glyphosate, that exhibit competitive binding with cations in diluent water. This binding could deactivate herbicides or alter the parent molecule that would compromise efficacy for controlling weeds. From the 19 locations, 32% had hard water. The sample from Sterling had 205 ppm, which was the highest level of water hardness detected in these samples. The other samples with hard water ranged between 120 to 155 PPM. The majority of the samples collected were characterized as moderately hard (60 to 84 ppm) or soft (4 to 60 PPM). Moreover, 37% of the samples had water harness levels of 50 PPM.

Hard water and high pH have synergistic effects on herbicide antagonism. Water with a high pH has greater potential for most weak acid herbicides to dissociate. This may enhance the binding of cations (Ca, Mg, or Fe) to the herbicide molecule under hard water conditions. Agronomists working at the Abbeville, Sterling, and Tifton stations should consider using ammonium sulfate or other acidifying materials to lower the pH. Ammonium sulfate binds cations present in high concentration in hard water that reduces competitive binding with weak acid herbicides. Ammonium sulfate also can enhance the absorption of herbicides, such as glyphosate, by acidifying the plant cuticle for improving foliar penetration.

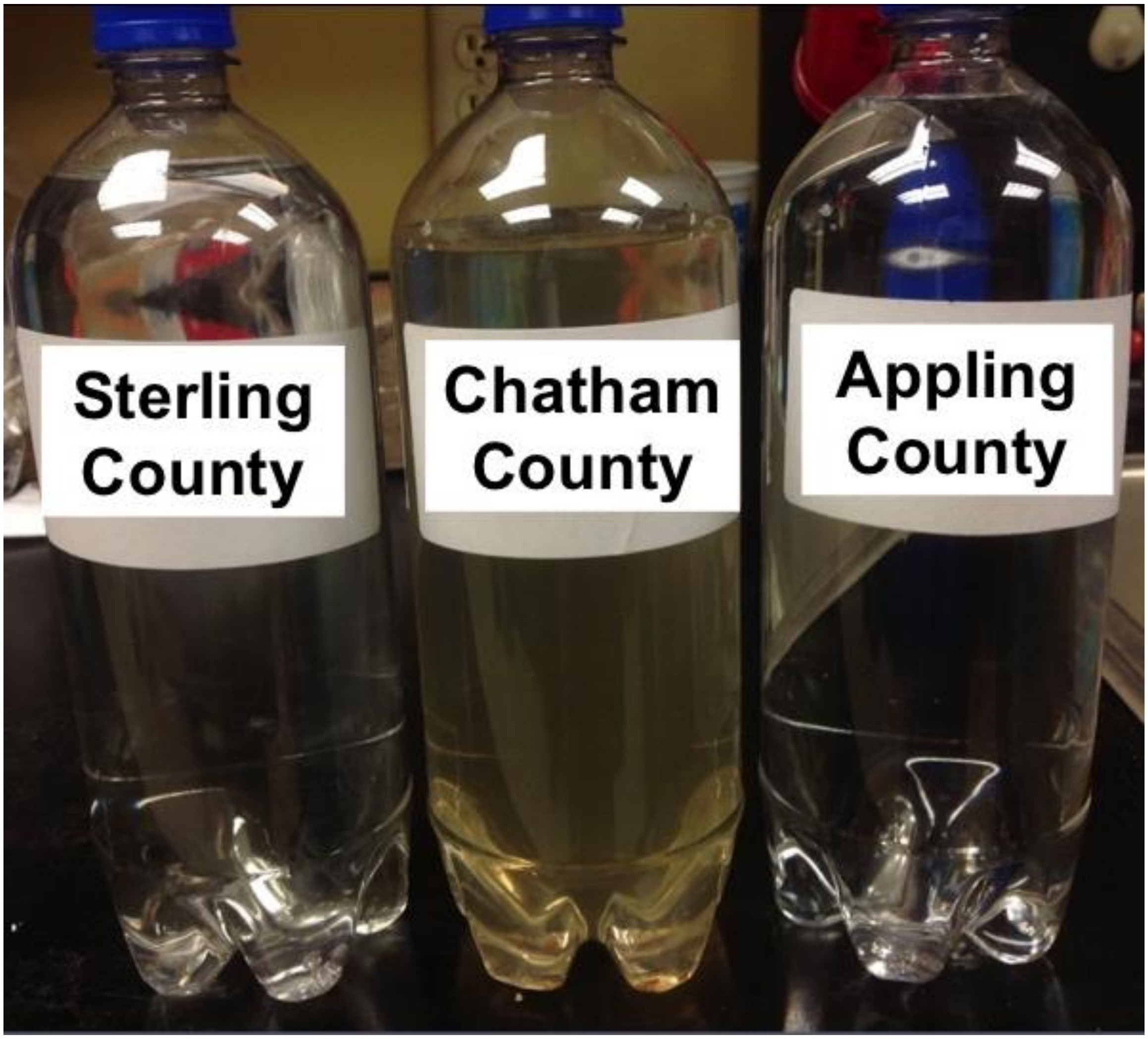
Suspended solids in water samples are concerning when spraying certain herbicides, such as preemergence herbicides with Koc values. These properties would enable the herbicide to bind with suspended solids in the diluent mix that causes antagonism for weed control. From the survey, 90% of the samples had a concentration of less than 5 ppm of suspended solids. Samples from Pooler and Spalding County had suspended solid concentrations of 11 and 17 ppm, respectively. These were the highest levels identified in the survey suggesting the majority of DOT stations did not have significant levels of suspended solids that contribute to problems with herbicide applications.

Turbidity is a measurement of visual clarity of water (scattering and absorption of light by particles in water) versus a calibrated standard. Nephelometric turbidity units (NTU) are caused by suspended particles, dissolved organic matter, and planktonic organisms in the water column. The minimum turbidity level for drinking water by the U.S. EPA is 1.0 NTU. Anything above this level is indicative of contaminants present in the sample that can be hazardous for consumption, recreation, and the safety to aquatic life. Potential sources of pollutants that contribute to turbidity include industrial and municipal discharges, forestry, agriculture, construction, and mining activities. The levels of turbidity ranged 0 to 1 NTU in 68% of the samples with 42% having no detectable levels (Table 1, Picture 1, Picture 2). Three locations had turbidity levels ranging 2 to 3 NTU. However, the samples from Marion and Pooler County measured 36 and 38 NTU, respectively. The material present in the water samples was not measured and it is unknown if the water contained hazardous contaminants. Nonetheless, these turbidity levels are concerning for spraying herbicides used in the DOT program.

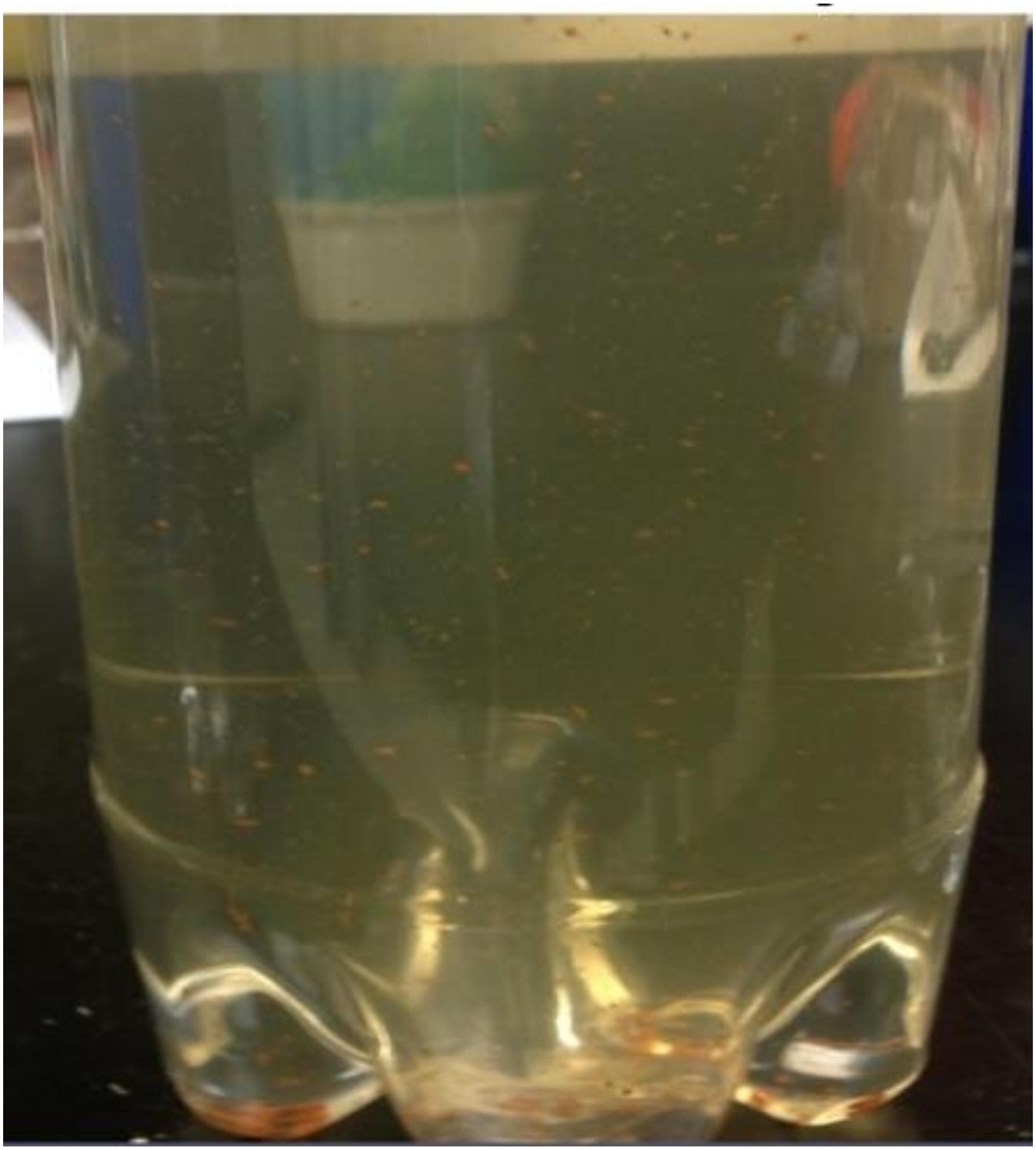
Table 1. Analysis of water samples collected in spring 2013 from sources used for herbicide treatments by the Georgia DOT.

Location	pH	Hardness (PPM)	TSS (PPM)	Turbidity (NTU)
Abbeville	7.5	143	<3.4	0
Atlanta	7.7	39	<5.04	1
Baldwin Co.	7.2	38	<3.59	1
Baxley	7.7	139	<3.46	0
Carnesville	6.6	59	<4.54	1
Chatsworth	7.4	129	<4.16	0
Fitzgerald	7.9	84	<3.4	3
Gainesville	7.1	25	<4.31	0
Jefferson	7.5	17	<4.54	0
Jefferson Co.	7.0	55	<3.75	0
Lafayette	7.5	121	<3.57	0
Marion Co.	5.3	4	<3.99	36
Pooler	7.2	64	11	38
Rome	7.9	73	<5.17	1
Spalding Co.	7.0	34	17	2
Sterling	7.9	205	<3.44	2
Tifton	7.8	154	<3.48	0
Upson Co.	7.0	15	<3.84	8
Washington Co.	6.9	51	<3.70	1

Picture 1. Water samples collected from three locations for analysis. Note the differences in clarity between samples that are pictured.



Picture 2. Sediments found in a sample from the water surveys.



Water hardness evaluation on efficacy of DOT herbicides. Since water hardness was the most common problem found in the survey from DOT stations, experiments were conducted to evaluate various concentrations of cations associated with herbicide antagonism in field and greenhouse experiments. These evaluations were conducted by simulating water hardness through spiking in calcium, iron, or magnesium. Regression analysis revealed that Johnsongrass control was highly dependent on the glyphosate rate and concentrations of calcium and magnesium present in diluent. Glyphosate at 0.25 lb ae/acre failed to provide effective control of Johnsongrass and control was ≤ 32% at 2 and 4 week after treatment (WAT), regardless of the concentrations of calcium and magnesium (Figure 1 and 2, Table 2). Johnsongrass control decreased substantially with increasing calcium and magnesium concentrations from the high glyphosate rate (Picture 3).

Johnsongrass control was significantly improved as glyphosate rate increased, but antagonism was detected from calcium and magnesium. The combination of calcium and magnesium synergistically reduced Johnsongrass control from glyphosate at 2 WAT, as compared to calcium or magnesium alone. At 2 WAT, glyphosate at 0.5 lb ae/acre provided 65% control of Johnsongrass when spray solutions contained calcium and magnesium at 100 ppm. The control was 97 and 75% when spray solutions contained calcium or magnesium alone at 100 ppm (moderately hard water). Magnesium alone caused greater antagonistic effect on glyphosate efficacy compared to calcium. At 2 WAT, glyphosate at 0.5 lb ae/acre provided excellent Johnsongrass control (>90%) regardless of the concentrations of calcium, whereas control was poor (<70%) when glyphosate solutions were mixed with magnesium alone at ≥120 ppm (hard water levels).

At 4 WAT, glyphosate at 0.5 lb ae/acre provided good control (≥80%) of Johnsongrass when the spray mix contained calcium alone at ≤120 ppm. However, control was poor when treatments contained magnesium alone at ≥100 ppm.

Iron sulfate was antagonistic at 4 weeks after treatment from glyphosate at 0.19 lb ae/acre at all concentrations evaluated, ranging 1.5 to 20 ppm (Table 3). Johnsongrass control was reduced from 60% at 0 ppm iron sulfate to less than 35% with iron added. The effects of iron were less antagonistic on the high glyphosate of 0.75 lb ae/acre. However, the highest concentration (20 ppm) of iron sulfate reduced Johnsongrass control from 100% to 75% after 4 weeks.

These results are consistent with other research in that calcium, iron, and magnesium have antagonistic effects through binding to the glyphosate molecule (Buhler and Burnside 1983; Stahlman and Phillips 1979; Mueller et al. 2006). The use of water-conditioning additives, such as ammonium sulfate, ammonium nitrate, and potassium phosphate, has proven effective at ameliorating cation-caused antagonism (Soltani et al. 2011; Wills et al. 1998; Thelen et al. 1995; Mueller et al. 2006). Results suggested that the addition of these water conditioners to glyphosate solutions might not be necessary if the spray carrier contained calcium and magnesium at a threshold concentration that causes inconsequential levels of antagonism. However, the combined effects of calcium and magnesium together at individual concentrations of ≥60 ppm could result in unacceptable levels of weed control from glyphosate.

Figure 1. Johnsongrass injury at 2 weeks after treatment from glyphosate application at 0.5 lb ae/acre with various concentrations of calcium and magnesium in a greenhouse experiment.

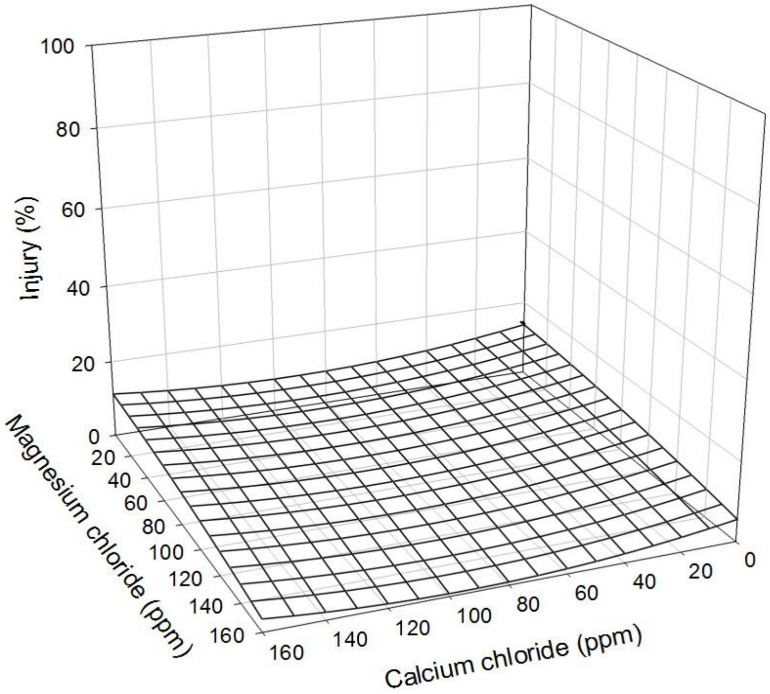


Figure 2. Johnsongrass injury at 4 weeks after treatment from glyphosate application at 0.25 lb ae/acre with various concentrations of calcium and magnesium in a greenhouse experiment.

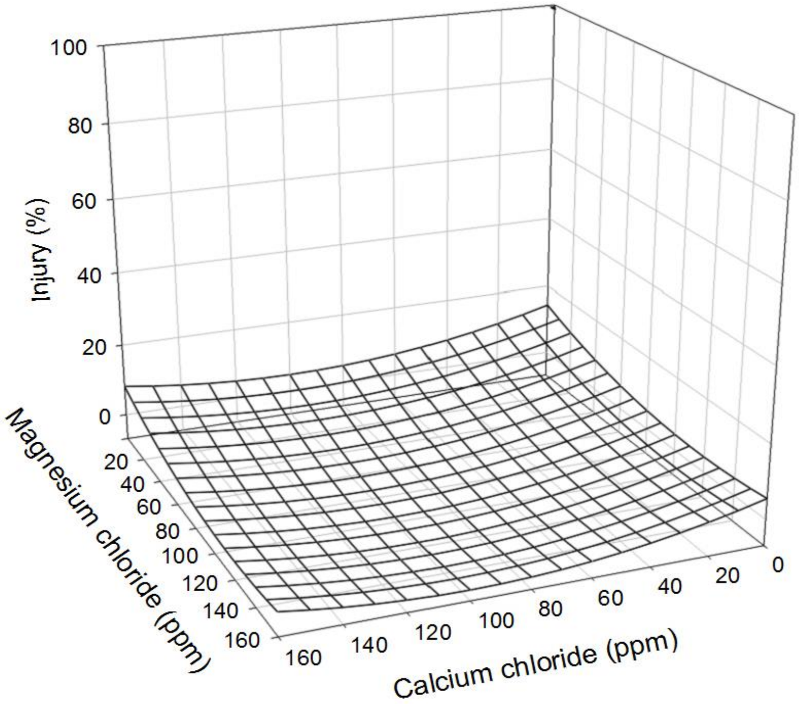


Figure 3. Johnsongrass injury at 2 weeks after treatment from glyphosate application at 0.5 lb ae/acre with various concentrations of calcium and magnesium in a greenhouse experiment.

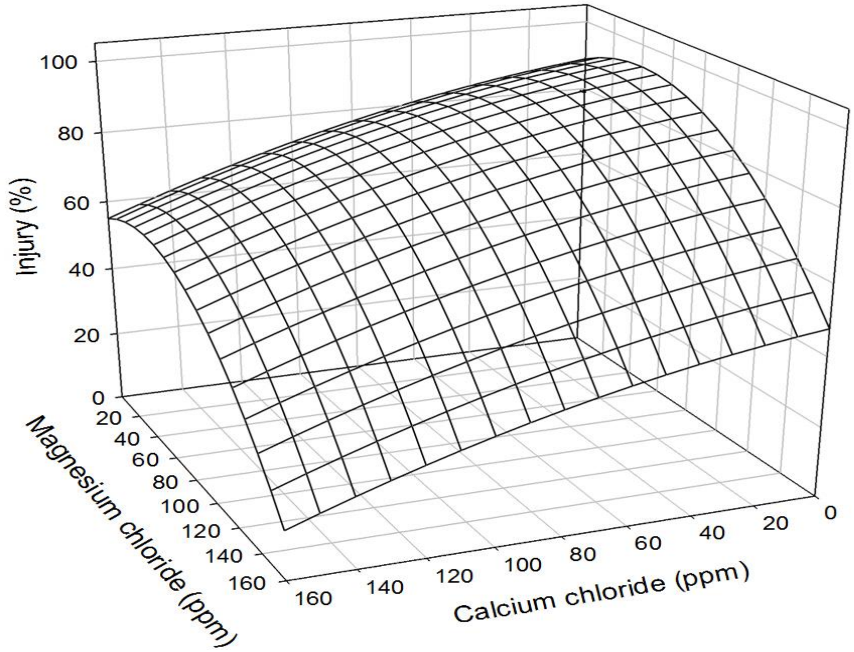


Figure 4. Johnsongrass injury at 4 weeks after treatment from glyphosate application at 0.5 lb ae/acre with various concentrations of calcium and magnesium in a greenhouse experiment.

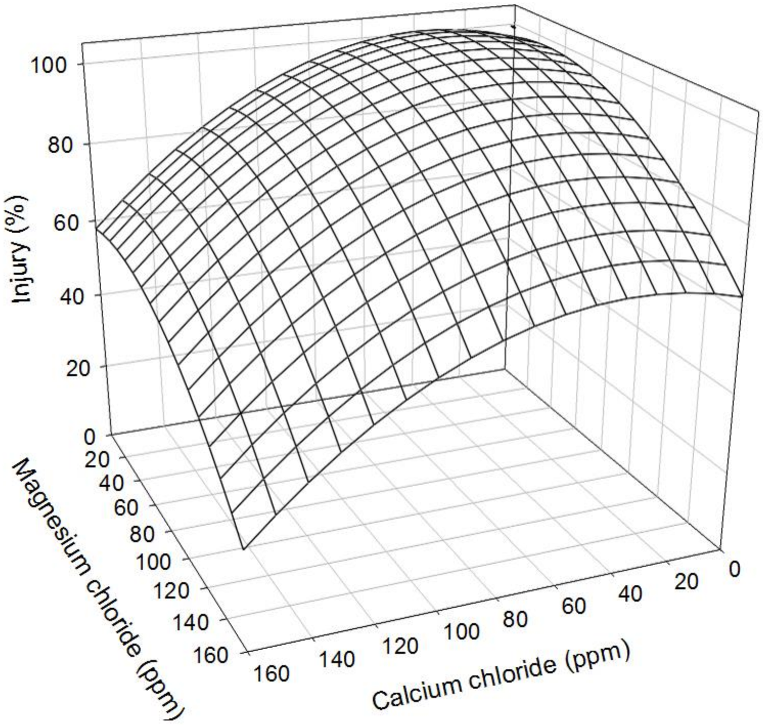


Table 2. Regression parameters for data presented in figures.

Glyphosate rate[a] (g ae ha^{-1})	Time	a	b	c	d	e	R^2	SE
0.28	2 WAT	13.7111	-0.1059	-0.0235	0.0006	-0.0002	0.2382	5.8523
	4 WAT	14.4638	-0.196	-0.1784	0.001	0.0008	0.1297	12.1583
0.56	2 WAT	88.9483	-0.095	0.2465	-0.0007	-0.0032	0.4674	21.8461
	4 WAT	96.5835	0.2106	0.1077	-0.0028	-0.002	0.5061	19.6242

[a] The regression equation for the Paraboloid Nonlinear Regression is $z = a + b*x + c*y + d*x^2 + e*y^2$. Abbreviations: WAT, weeks after treatment; SE, standard error of the estimate.

Picture 3. Johnsongrass control at four weeks after treatment with glyphosate in soft water (left) compared to hard water (right).

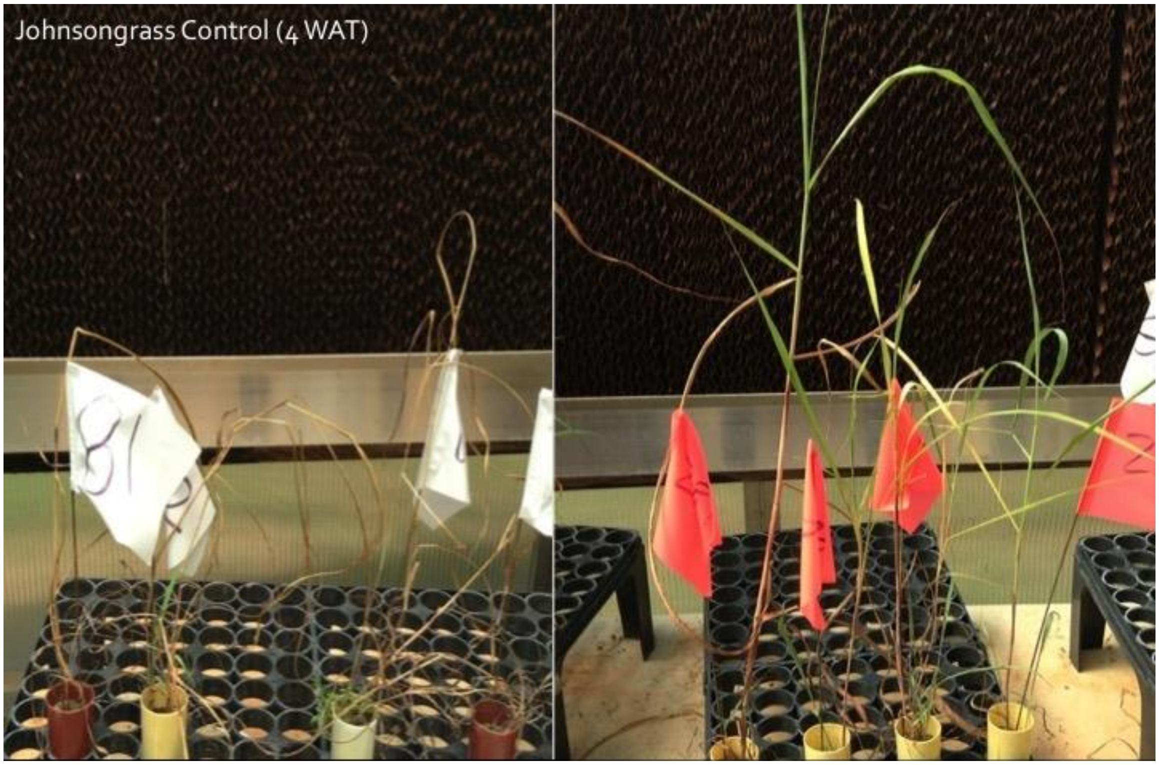


Table 3. Effect of iron sulfate concentration on glyphosate efficacy for controlling Johnsongrass in a greenhouse experiment.

Glyphosate[a]	Iron Sulfate	2 WAT	4 WAT
lb ae/acre	PPM	——————— %	———————
0.19	0	14	60
	1.25	9	29
	2.5	8	24
	5	8	32
	10	18	30
	20	14	26
0.75	0	100	100
	1.25	100	88
	2.5	100	100
	5	93	94
	10	90	90
	20	60	75
	$LSD_{0.05}$	18	23

[a] The glyphosate product applied was Roundup Pro (3 lb ae of glyphosate/gal).

Evaluation of DOT herbicides applied in hard water. In field experiments, the influence of water hardness levels was evaluated with herbicides used by the DOT for roadside weed control. Tall fescue and buckhorn plantain were controlled ~60% from glyphosate applied in soft and moderately hard water (80 to 100 ppm, Table 4). However, control of both weeds was reduced by half of these levels when glyphosate was applied in hard water (>160 ppm) at 8 weeks after treatment. The efficacy of Banvel (dicamba) for buckhorn plantain control after 8 weeks was reduced by more than half when applied in hard water compared with soft water. However, buckhorn plantain was controlled less than 20% after 8 weeks in soft water and was similar to control from treatments in moderately hard water (data not shown). Nevertheless, these results illustrate that the efficacy of dicamba can be reduced when applied with hard water under roadside conditions.

In another field experiment, Garlon (triclopyr) controlled catsear dandelion 75 to 83% when applied in soft or moderately hard water after four months (Table 5). Garlon treatments in hard water only controlled catsear dandelion by 36%. Milestone (aminopyralid) treatments on the other hand, completely controlled catsear dandelion in all levels of water hardness tested (Picture 4). Although reductions in control were not detected with Milestone, previous research has shown aminopyralid to be susceptible to antagonism when applied in hard water. Milestone may have less potential for antagonism than Garlon, but these results could also vary by weed species, growth stage, and application rates. It is recommended that the DOT agronomists consider adding ammonium sulfate when hard water is used for applying the standard DOT herbicides if fresh water sources are unavailable.

Table 4. Tall fescue and buckhorn plantain control at eight weeks after treatmetns with Accord XRT (glyphosate 4 lb ae/gal) at 1 pt/acre with three levels of water hardness in a field experiment, 2013-2014.

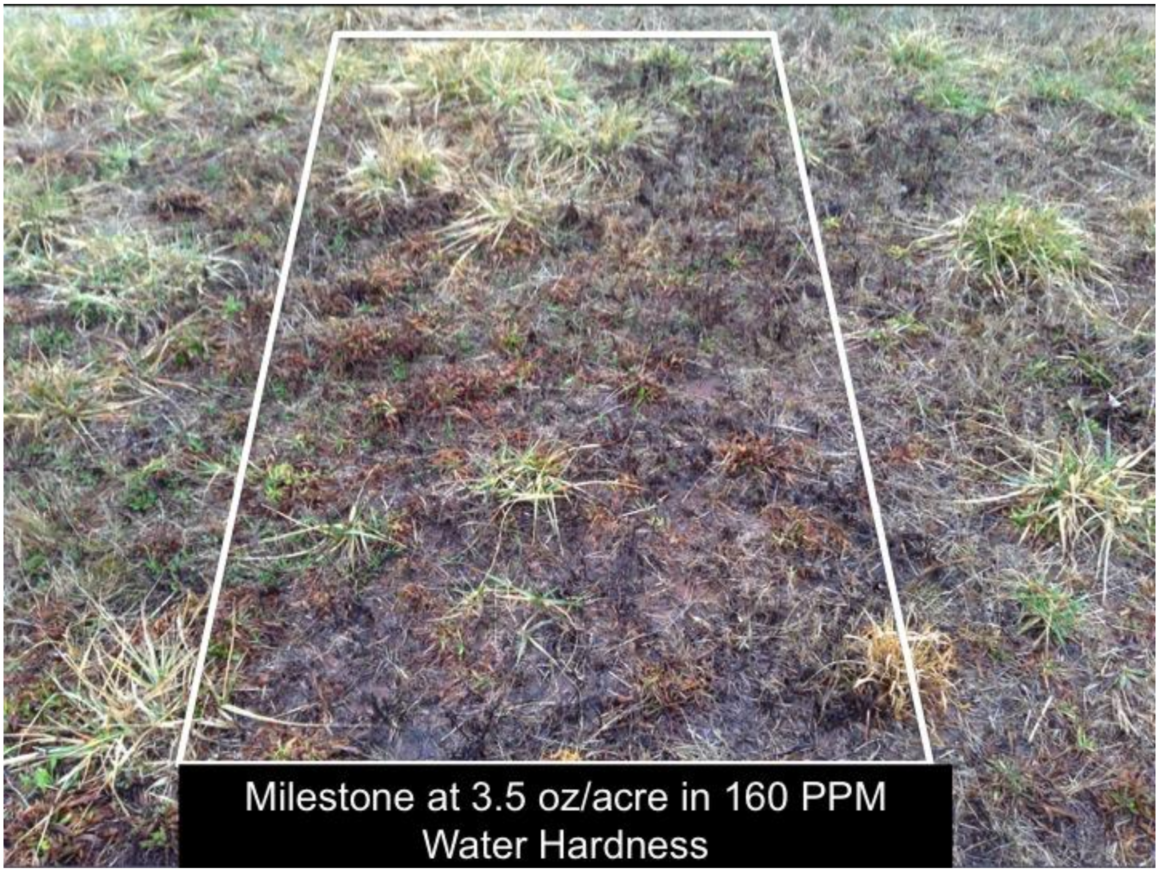
Hardness	Tall Fescue Control	Buckhorn Plantain
	——— % ———	
Soft (<60 ppm)	63	65
Moderate (80 to 100 ppm)	58	74
Hard (>160 ppm)	38	39
$LSD_{0.05}$	18	22

Table 5. Catsear dandelion with Garlon 3A (triclopyr) and Milestone (aminopyralid) at four months after treatments with three levels of water hardness in a field experiments, 2013-2014.

Hardness	Garlon[a]	Milestone
	——— % ———	
Soft (<60 ppm)	75	100
Moderate (80 to 100 ppm)	83	100
Hard (>160 ppm)	36	100
$LSD_{0.05}$	18	NS

[a] Herbicides applied were Milestone (aminopyralid 2 lb/gal) at 3.5 oz/acre and Garlon 3A (triclopyr 3 lb ae/gal) at 1 pt/acre.

Picture 4. Broadleaf weed control with Milestone applied in hard water in field experiments.



Evaluation of Ground Zero on Herbicide Efficacy for Johnsongrass control.

At 2 WAT, the rate of glyphosate that caused 50% injury (I_{50} values) measured 170, 154, and 228 g ha^{-1} when glyphosate was tank-mixed with Ground Zero at 0, 4, and 8 oz/100 gal, respectively (Table 6, Fig. 5). At 4 WAT, I_{50} values were substantially reduced and measured 58, 81, and 115 g ha^{-1} when glyphosate tank-mixed with Ground Zero at 0, 4, and 8 oz/100 gal, respectively. SR_{50} values from glyphosate measured 278, 170, and 288 g ha^{-1} when glyphosate was tank-mixed with Ground Zero at 0, 4, and 8oz/100 gal, respectively (Table 6, Fig. 6). There was no statistical difference among these values according to the 95% confidence limits. These findings suggested that Ground Zero does not antagonize glyphosate efficacy. Further research is needed to determine if weed control is reduced from other herbicides when applied with Ground Zero.

Table 6. Regression parameters for Figures 5 and 6.

Time	Ground Zero	Injury					
	(oz/100 gal)	a	b	R^2	SE	I_{50}	95% CL for I_{50}
						-----------g ae ha^{-1}----------	
2 WAT	0	95.72	0.0044	0.41	28.09	170	<105 – 279
	4	101.44	0.0045	0.67	17.87	154	110 –197
	8	102.88	0.0029	0.46	24.61	228	126 – 320
4 WAT	0	91.97	0.0138	0.17	18.04	58	<105 – 115
	4	102.87	0.0082	0.56	17.88	81	<105 – 122
	8	104.15	0.0057	0.66	17.71	115	<105 – 168
		Shoot mass reduction					
		a	b	R^2	SE	SR_{50}	95% CL for SR_{50}
						------------g ae ha^{-1}---------	
4 WAT	0	61.42	0.0059	0.14	33.45	278	106 – >840
	4	64.99	0.0087	0.18	23.11	170	<105 – 354
	8	94.68	0.0026	0.50	26.04	288	119 – 456

[a] I_{50} and SR_{50} were determined according to the equation of $y = a*(1-\exp(-b*x))$.
Abbreviation: WAT = weeks after treatment; SE= standard error of the estimate.

Figure 5. Johnsongrass injury following glyphosate treatments with ground zero a in greenhouse experiment, Griffin, GA. Vertical bars represent standard errors (n = 4). Abbreviation: WAT = weeks after treatment.

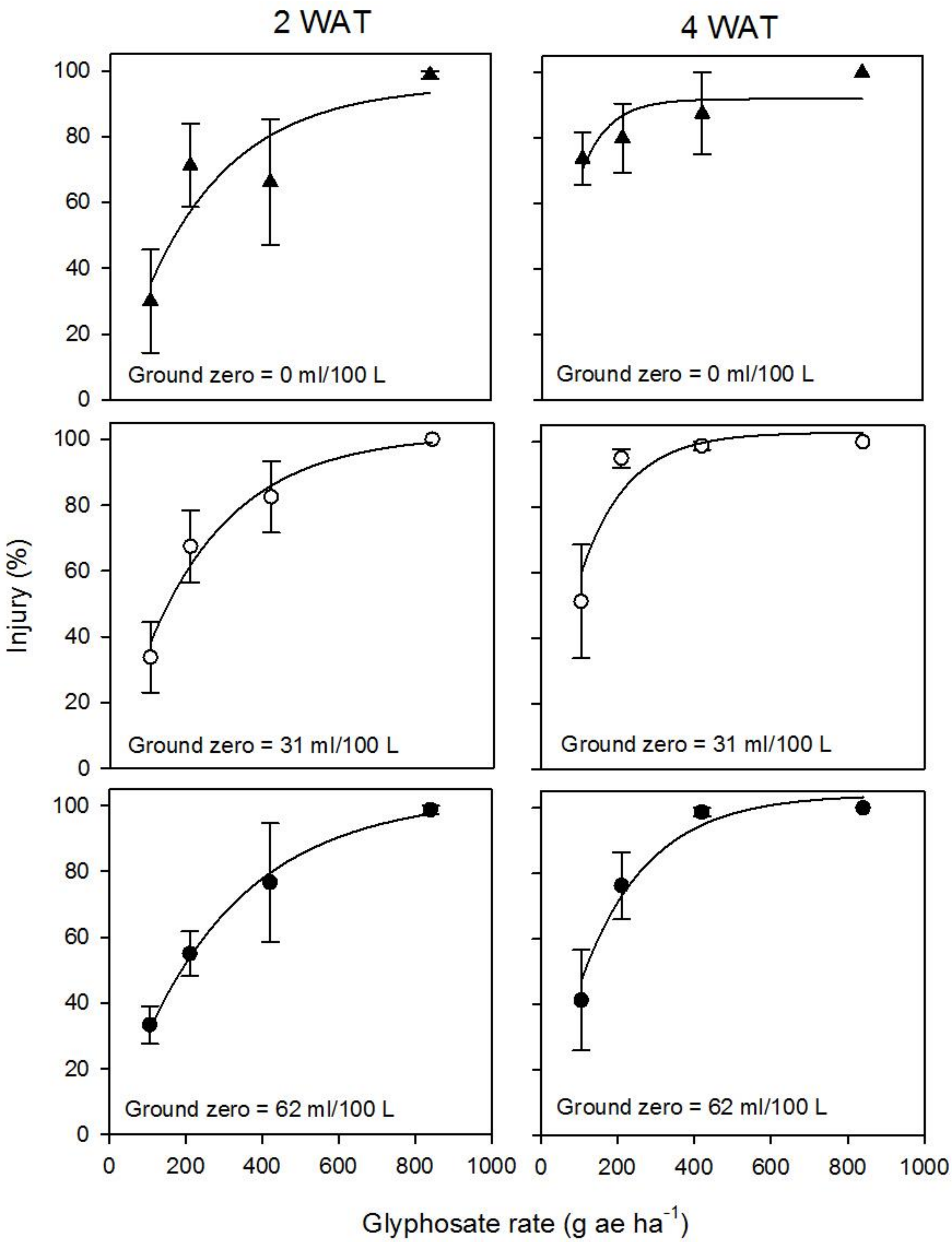
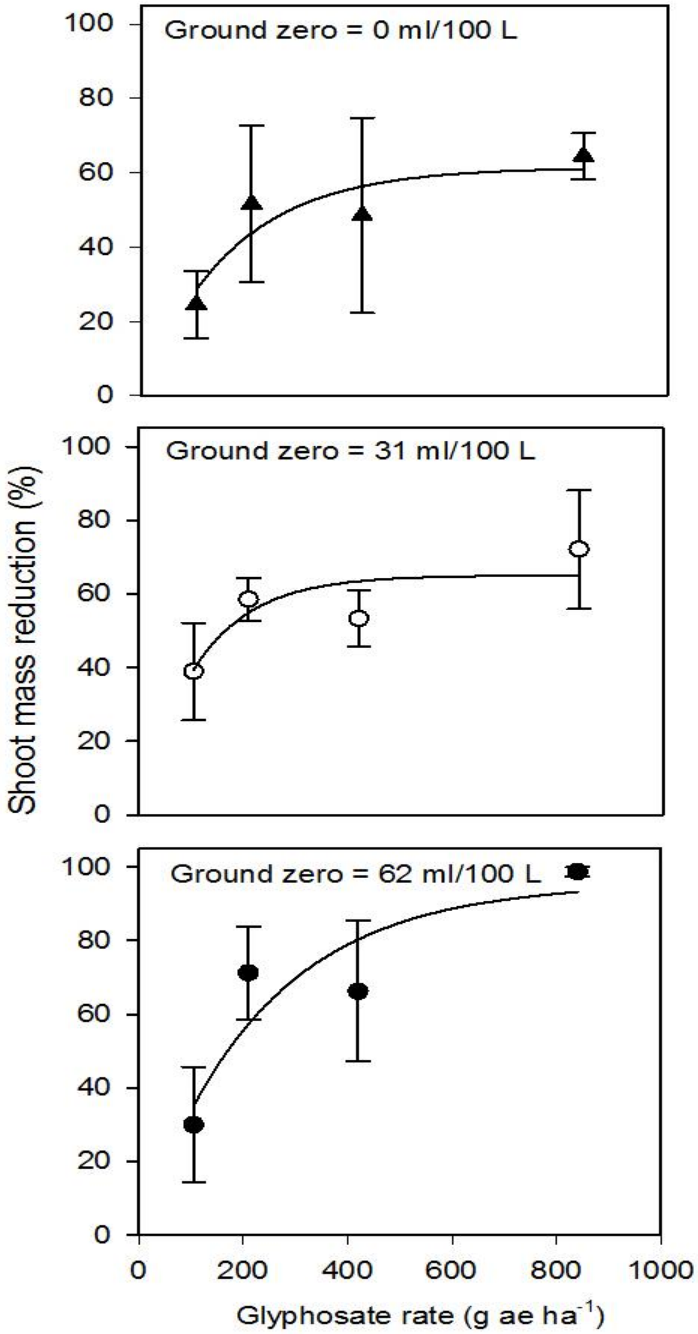


Figure 6. Johnsongrass shoot mass reduction following glyphosate treatments with Ground Zero in a greenhouse experiment, Griffin, GA. Vertical bars represent standard errors (n = 4). Abbreviation: WAT = weeks after treatment.



Evaluation of Truck Application Uniformity. The spray trucks used by the DOT were evaluated for application uniformity and calibration. Several evaluations were used to measure the calibration of trucks equipped with Northstar and Boombuster nozzles including cup collections and measuring losses from the sprayer after timed increments. These evaluations all revealed that the trucks were delivering approximately 25 gallons per acre as the total targeted spray volume. However, inconsistencies were detected in spray volumes delivered at various distances from the truck. In cup collections, it was noted that the spray volume of the Northstar trucks ranged from 83 to 113% of the targeted spray volume at various distances from the truck out to 15 feet. The truck equipped with boombuster nozzles also ranged 88 to 118% of the targeted spray volume at these distances.

In bioassays, broomsedge and vaseygrass plants were spaced every five feet from trucks that sprayed diquat (Picture 5). Significant variability in control was observed at 3, 7 and 14 days after treatment. The control levels of both grasses quadratically decreased with increased distance from spray trucks after 14 days (Figure 7, Table 7). The trucks equipped with Boombuster nozzles had control range from 58 to 89% and 56 to 91% for broomsedge and vaseygrass, respectively. Control levels were fairly consistent ranging 89 to 95% from 0 to 15 feet from the truck for both species. However, control dropped significantly for plants spaced at 25 and 20 feet from the truck for broomsedge and vaseygrass, respectively. The levels of control ranged 58 to 79% for plants spaced beyond these distances.

Significant variability with broomsedge and vaseygrass control was also noted from diquat applied with Northstar trucks (Figure 7, Table 7). Control declined quadratically for both species as the distance from the truck increased. The most notable decline occurred for plants spaced at 25 and 30 feet from the truck, ranging 63 to 69% control. Dry biomass reductions from the nontreated did not correspond with the visual injury evaluations and the trends were erratic (data not shown). This likely occurred because diquat is a contact herbicide and the perennial plants used in these experiments were not completely controlled from applications. Nevertheless, these results support the supposition that trucks equipped with Northstar and Boombuster sprayers are not providing acceptable control beyond 20 feet from the truck.

Further evaluations were made visually by rolling paper away from the sprayer and evaluating the uniformity of spray droplets. This procedure revealed substantial differences in water coverage of the paper from 0 to 20 feet from the spray truck. Minimal to no water was detected at the 25 to 30 foot distance from the truck, which is concerning because the Northstar truck was designed to spray a 30 foot pattern (Pictures 7, 8). One potential limitation to these application evaluations was that the trucks were spraying water without herbicides in the tank. Herbicides with different formulations and adjuvants in the mix can exhibit variability in droplet size when applied with different nozzle types. Nevertheless, the truck did not cover the targeted area and was consistent with anecdotal observations from escaped weeds and results from the bioassay experiments. It was also noted that the sprayers had significant streaking in the drying patterns on the concrete after spraying and the areas furthest away from the truck dried the quickest. These patterns are consistent the measurements taken from plant bioassays and cup measurements from the spray trucks.

In another experiment, tracking dye was added to the spray truck to quantify the inconsistencies in spray pattern delivery within a one-foot measurement every five feet from the truck (Picture 9). After capping vials, the intensity of the blue dye was measured in a laboratory at the UGA Griffin Campus. However, the measurements were determined to be inconclusive due to the significant amount dye that was adsorbed to the glass vials (data not shown).

Picture 5. Evaluation of application uniformity of the DOT spray trucks using plant bioassays.

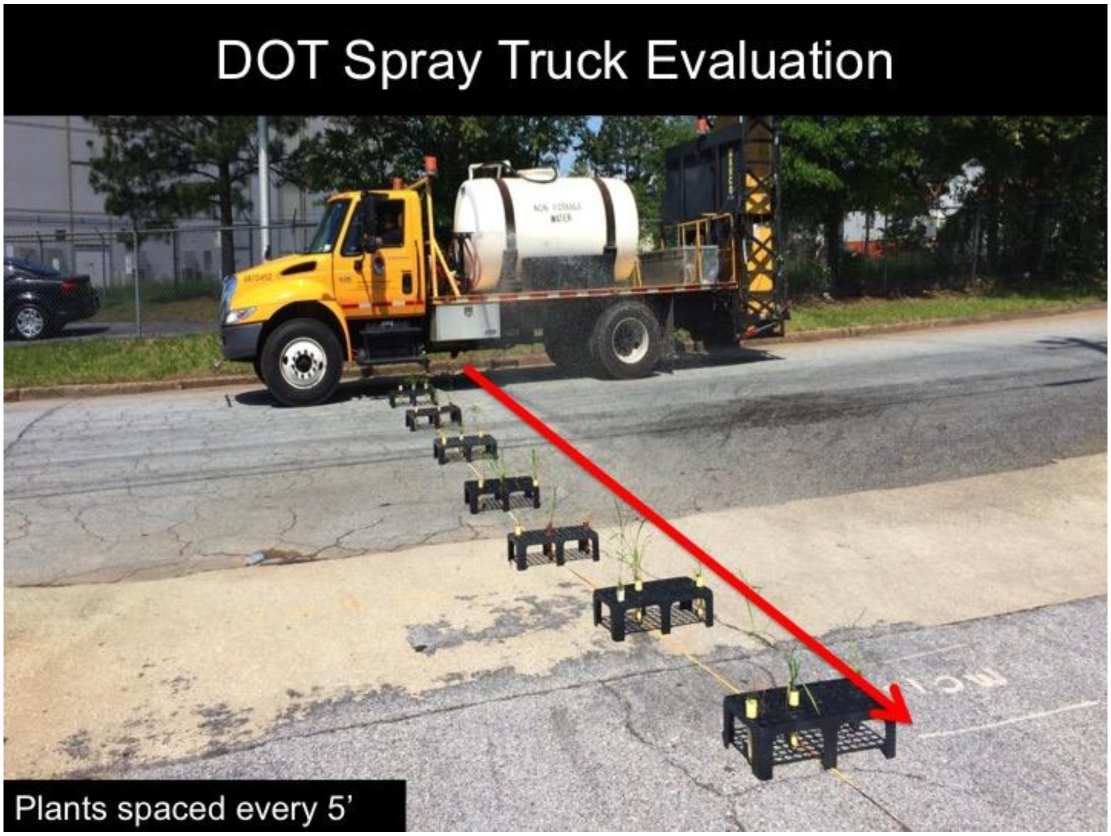


Figure 7. Control of broomsedge and vaseygrass following treatments of diquat from trucks equipped with Northstar and boombuster sprayer equipment. Vertical bars represent the standard error of the means (n = 4).

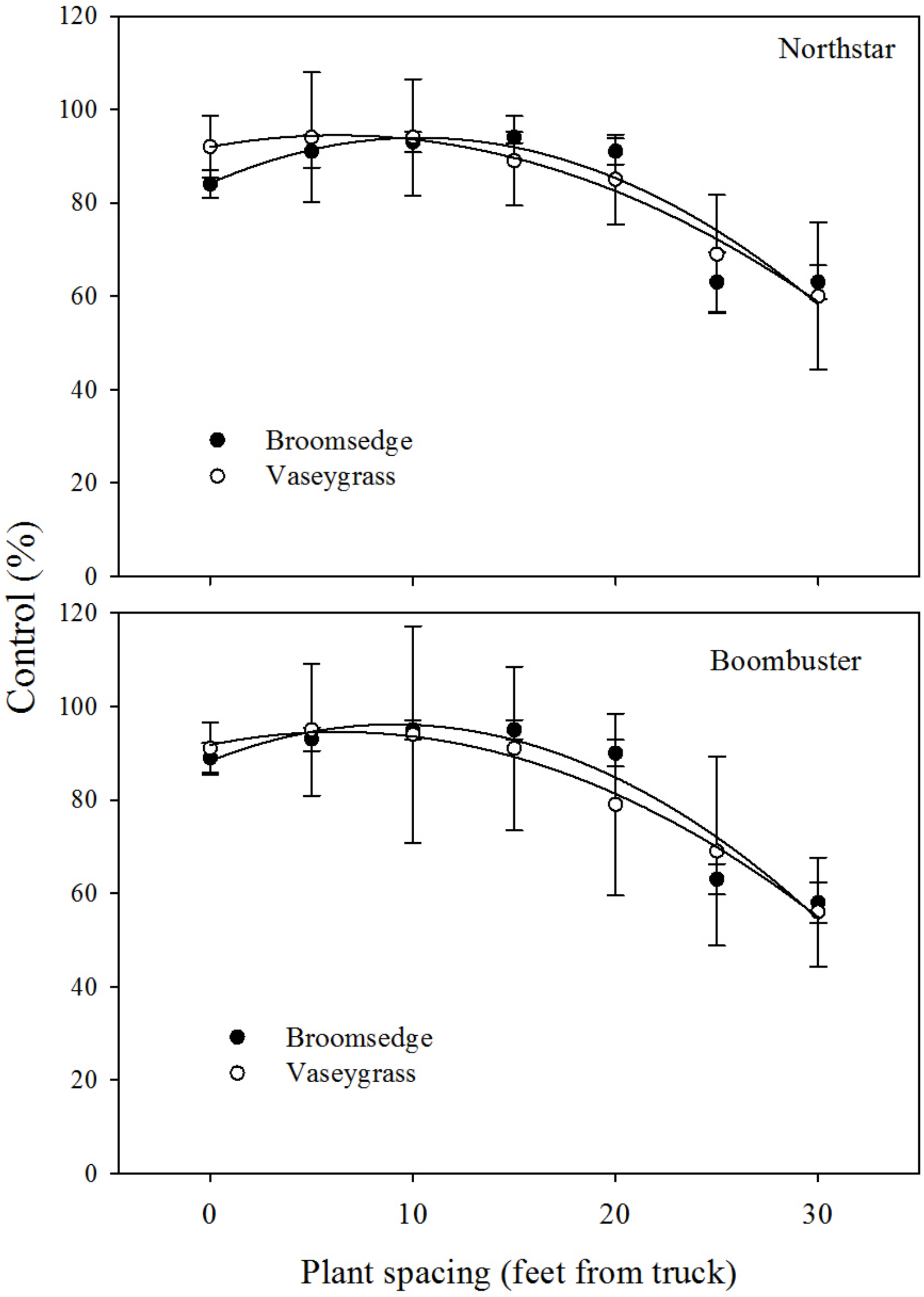
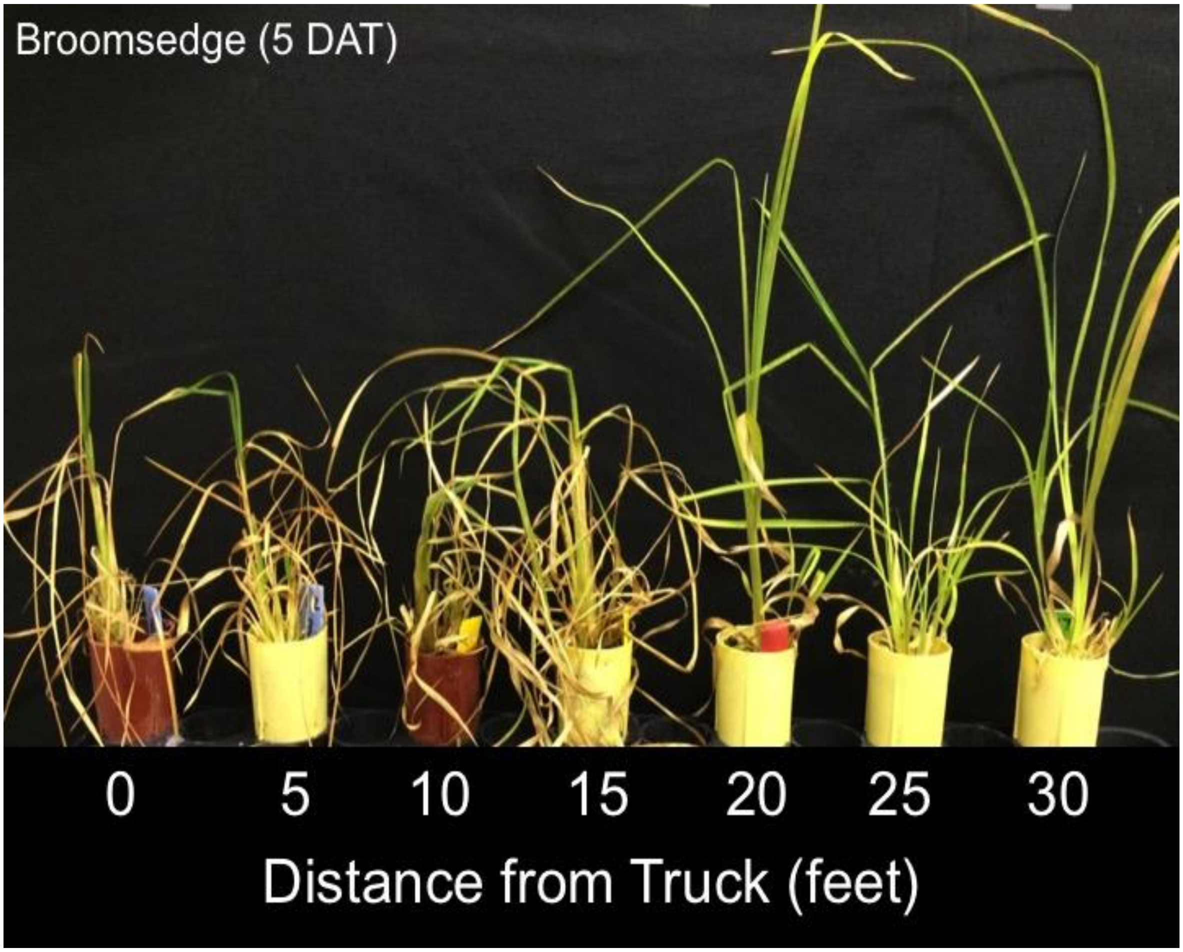


Table 7. Regression parameters for data presented in Figure 7.

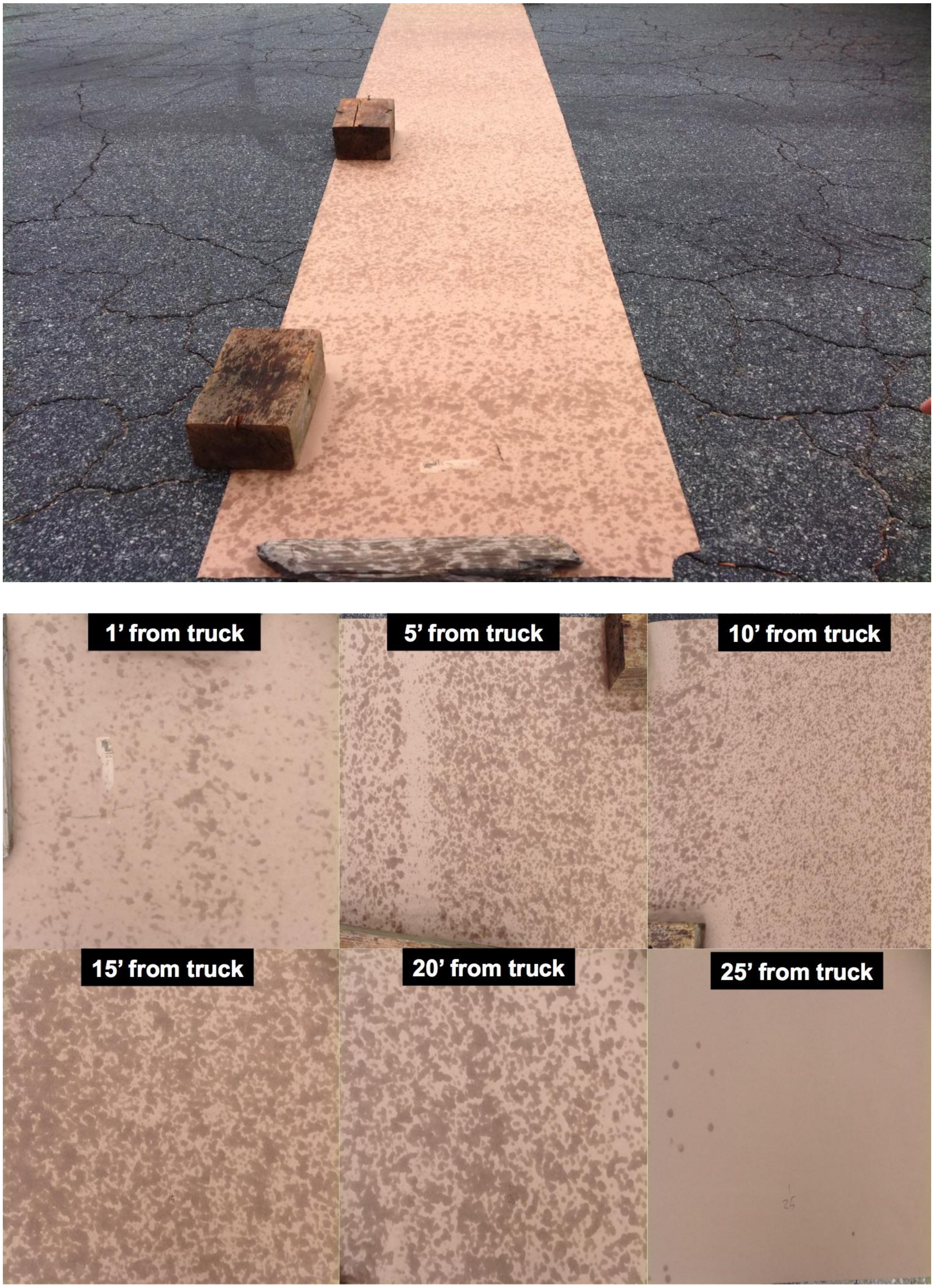
Truck	Species	r^2	Equation
Boombuster	Broomsedge	0.81	$y = 87.92 + 1.78x - 0.097x^2$
	Vaseygrass	0.78	$y = 91.99 + 0.84x - 0.069x^2$
Northstar	Broomsedge	0.68	$y = 83.89 + 1.92x - 0.093x^2$
	Vaseygrass	0.76	$y = 91.93 + 0.82x - 0.064x^2$

Picture 6. Broomsedge plants treated with diquat at five days after treatments. Plants shown were spaced every five feet from the spray truck in the experiment.



Picture 7. Streaking of the spray pattern noted in truck evaluations with drying patterns that indicate volumetric differences in solution applied at various distances in the spray pattern.

Picture 8. Spray droplets at various distances from the truck in calibration evaluations.



Picture 9. Evaluation of spray pattern uniformity using tracking dye and 20-mL glass vials.

CONCLUSIONS

There is significant variability in water quality from sources used for DOT spray trucks that affects herbicide efficacy. The majority of DOT stations had good quality water for herbicide applications. Several locations had water hardness, pH levels, and sediment levels that will reduce herbicide efficacy in spray programs. Results from field experiments demonstrate that most herbicides used in the DOT spray program are susceptible to antagonism by hard water. We recommend that the DOT sample water several times throughout the year at stations with reported issues in this research. If fresh water sources cannot be used for applications, it is recommended that ammonium sulfate or other adjuvants be used with water sources containing alkaline pH or hardness levels greater than 100 PPM. Selecting herbicides that have less potential for antagonism is recommend for controlling broadleaf weeds over 2,4-D, dicamba, glyphosate, or Garlon (triclopyr) when water quality is compromised.

The spray trucks tested were accurately calibrated to deliver the appropriate volume of water targeted for applications. However, the spray trucks did not provide uniform applications. These trucks exhibited spray pattern streaking, failures to spray accurately more than 20 feet in distance, and had reductions in weed control with increased distances away from nozzles. It is recommended that the DOT request inspections from the manufacturers of this equipment to improve the consistencies of applications or use alternative sprayers for roadside management.

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