Weed Technology

www.cambridge.org/wet

Measurement of foliar spray retention on creeping bentgrass

Pingyuan Zhang[1] and Bruce E. Branham[2]

[1]Former Graduate Student, Department of Crop Sciences, University of Illinois, Urbana, IL, USA and [2]Professor, Department of Crop Sciences, University of Illinois, Urbana, IL, USA

Research Article

Cite this article: Zhang P and Branham BE (2019) Measurement of foliar spray retention on creeping bentgrass. Weed Technol. **33**: 827–832. doi: 10.1017/wet.2019.60

Received: 24 January 2019
Revised: 12 April 2019
Accepted: 21 June 2019
First published online: 19 August 2019

Associate Editor:
Scott McElroy, Auburn University

Nomenclature:
Creeping bentgrass; *Agrostis stolonifera* L. AGSST 'L93'

Keywords:
Adjuvant; dew; foliar retention efficiency; nozzle type; spray volume; tartrazine

Author for correspondence:
Bruce E. Branham, Department of Crop Sciences, University of Illinois, 1201 S. Dorner Drive, Urbana, IL 61801.
(Email:bbranham@illinois.edu)

Abstract

Experiments were conducted to evaluate the impact of spray volume, nozzle type, adjuvants, the presence of dew, and their interactions on foliar retention of creeping bentgrass. Tartrazine, a common food dye, was used as a tracer in this study. Increasing spray volume from 95 L ha^{-1} to 1,500 L ha^{-1} decreased foliar retention efficiency from 98% to approximately 85%. Compared with flat-fan nozzles, air-induction nozzles delivered similar retention efficiency at all spray volumes evaluated. However, flat-fan nozzles provided higher uniformity and more thorough coverage. Adding nonionic surfactants, organosilicone adjuvants, or methylated seed oils at typical concentrations yielded retention efficiency of approximately 90% to 93% regardless of spray volumes. In contrast, with water alone, increasing spray volume reduced retention efficiency from 95.9% to 87.3%. Simulated dew applied at 1,950 L ha^{-1} increased retention efficiency by approximately 3% when spray application volume was 190 L ha^{-1}, while no difference was observed at 750 L ha^{-1}. The presence of dew reduced the impact of adjuvants on retention efficiency. Large quantities of dew, 3,800 L ha^{-1}, did reduce retention efficiency.

Introduction

Foliar spray applications are widely used in agriculture, especially on golf courses, where intensive management practices are conducted to maintain turf quality and performance. Improving the performance of spray applications while reducing costs, labor, and potential environmental impacts are goals for all turf managers and researchers. An effective spray should deposit the active ingredient uniformly to the target site and persist for enough time to exert control (Furmidge 1962). Turf managers can adjust the properties of spray mixtures and spray methods to optimize the response to the application under different situations (Gossen et al. 2008). Spray volume, nozzle type, travel speed, and adjuvant can be varied to increase application efficacy.

The effects of adjuvants, carrier volume, and droplet size on herbicide performance have been extensively studied for many crops, including turf (Kennelly and Wolf 2009; McDonald et al. 2006; McCullough and Hart 2009; Zawierucha and Penner 2001). However, a thorough search of literature did not find any studies that quantified foliar retention or retention efficiency on turfgrasses. The evaluation of foliar retention and retention efficiency are important, because they determine the coverage and the total amount of active ingredient available for foliar uptake. Foliar retention is simply the amount of the spray application retained on the leaf surface. Foliar retention efficiency is the ratio of the volume retained on the leaf surface divided by the volume applied (Byer et al. 2006). For pesticides and nutrients that are absorbed by the foliage, enhancing foliar retention efficiency should lead to better efficacy from the applied chemicals.

A number of studies have reported the influence of spray volume, nozzle type, adjuvants, and their interaction on foliar retention in other crops or weeds, such as wheat (*Triticum aestivum* L.) (Butler Ellis et al. 2004), corn (*Zea mays* L.) (Feng et al. 2003), giant foxtail (*Setaria faberi* Herrm.) (Hart et al. 1992; Young and Hart 1998), green foxtail [*Setaria viridis* (L.) P. Beauv.] (Peng et al. 2005), large crabgrass [*Digitaria sanguinalis* (L.) Scop.] (Zawierucha and Penner 2000), and chick pea (*Cicer arietinum* L.) (Armstrong-Cho et al. 2008). Increasing spray volume increased foliar retention (Peng et al. 2005) but decreased retention efficiency (Byer et al. 2006). Increasing the size of the spray droplets decreased foliar retention (Feng et al. 2003) and foliar retention efficiency (Byer et al. 2006). Adding adjuvants typically increased foliar retention (Hart et al. 1992).

The properties of the plant surface are a critical factor that influences the behavior of spray droplets (Ruiter et al. 1990). Spray retention on golf fairways may be different than on other crops because of the density of foliage in a highly managed turf. Additionally, dew is often present during spray applications on golf courses (Delvalle et al. 2011; Williams et al. 1998). Dew has been shown to reduce foliar retention on vine grapes (*Vitis vinifera* L.) by 75% (Saab et al. 2017).

The use of tracers in agricultural sprays to assess spray retention and leaf coverage was recently reviewed by Nairn and Forster (2019). The most widely used tracers are fluorescent compounds, visible dyes, or metal salts. The principal disadvantages of fluorescent compounds are the cost of analysis and potential photodegradation of the dye. Using metal salts as tracers requires more expensive laboratory analyses and a higher likelihood of plant uptake (Murray et al. 2000). Tartrazine, a yellow food dye, has been successfully used to measure foliar retention in crops such as tomatoes (*Solanum lycopersicum* L.), apples (*Malus pumila* Mill), and cucumbers (*Cucumis sativus* L.) (Cross et al. 2001; Dorr et al. 2016; Murray et al. 2000; Nairn and Forster 2019; Sanchez-Hermosilla et al. 2008). Tartrazine can be readily recovered from leaf surfaces and is easily quantified using a spectrophotometer. Dyes have multiple uses in spray deposition research, with dyes such as brilliant blue used to visualize spray deposits (van Zyl et al. 2010), while other products such as tartrazine can be used to determine foliar spray retention (Nairn and Forster 2019).

The objective of this research was to quantify the foliar retention efficiency of spray solutions on creeping bentgrass foliage as influenced by spray volumes, nozzle types, adjuvants, the presence of dew, and their interactions.

Materials and Methods

Plant Material

Turf cores were harvested with a 10.6-cm-diameter golf course cup cutter and transported to the laboratory 1 d before each experiment. The cores were collected from a creeping bentgrass turf ('L93'), maintained at a mowing height of 1.3 cm, that was established in August of 2010 at the University of Illinois Landscape Horticulture Research Center, Urbana, IL. Approximately 2.5 cm of soil was preserved, so the height of each core was 3.8 cm. The cores were covered with moistened paper towels to prevent wilting. Plastic bands were wrapped around each core from the leaf surface to the bottom of the core to maintain the leaf surface area and to prevent spray deposition on the side of the foliage (Figure 1).

Tartrazine Recovery Validation

Several experiments were conducted to validate that tartrazine (Sigma-Aldrich, St. Louis, MO) could be quantitatively recovered from turfgrass foliage. In the first experiment, aboveground green tissue and thatch were removed from each core with scissors and placed into a 100-mm petri dishes (Fisherbrand, Waltham, MA). One milliliter of tartrazine solution (20 mmol L^{-1} in distilled water) was uniformly placed on the plant material by pipette. The petri dishes were stored in the dark at 20 C for 4, 12, 24, or 48 h. Each time interval was replicated three times. Tissue samples were extracted four times with 75 ml of distilled water. The rinsates were combined, filtered through a Whatman No. 1 (Buckinghamshire, UK) qualitative filter, and a 7-ml subsample was filtered through a 0.2-μm, 25-mm-diameter syringe filter (CHROMAFIL® Xtra PES-20/25, Macherey-Nagel, Bethlehem, PA). Filtered samples were stored in 7-ml glass bottles in the dark for later measurements. A second experiment was conducted to confirm that tartrazine recovery was quantitative, that is, that any tartrazine not recovered from the leaf tissue had moved into the thatch layer. Turf cores were treated with spray volumes of 190, 750, and 1,500 L ha^{-1} containing tartrazine at 20 mmol L^{-1}. Each spray volume was replicated three times. After all green leaf tissue was collected, the top 0.5 cm of thatch was collected separately. The leaf tissue and thatch were extracted and measured as above.

Figure 1. A plastic band was used to prevent leaf area from expanding beyond the original core size and to prevent spray deposition on the leading edge of the core so the core would receive spray as it would in situ.

Experimental Design

All experiments were conducted at the Plant Science Laboratory Greenhouse in Urbana, IL. In each experiment, a completely randomized design with four replications was used. Each experiment was repeated within 10 d to minimize differences in leaf area of plant material.

All experiments were conducted using a Generation III Research Track Sprayer (DeVries Manufacturing, Hollandale, MN). The spray height for flat-fan nozzles was 41 cm, while the spray height was 46 cm for air-induction nozzles (TeeJet Technologies, Glendale, IL). The pressure of the sprayer was set at 276 kPa for all experiments.

Tartrazine was added to each spray solution. The tartrazine concentration was 50 mmol L^{-1} at spray volumes of 95 and 190 L ha^{-1}. At the 380 or 550 L ha^{-1} spray volumes, tartrazine concentration was 20 mmol L^{-1}, while at spray volumes of 750, 850, 1,125, or 1,500 L ha^{-1}, tartrazine concentration was 10 mmol L^{-1}.

Influence of Spray Volume, Nozzle Type, Adjuvants, and Dew on Foliar Retention Efficiency

A series of experiments were conducted to determine the effects of various factors on foliar retention efficiency. In the first experiment, six spray volumes were evaluated using flat-fan nozzles (TeeJet Technologies) (Table 1). These experiments were conducted on July 26 and 29, 2017.

To compare flat-fan versus air-induction nozzles, spray volumes of 190, 380, 750, or 1,125 L ha^{-1}were used (Table 1). These experiments were conducted on September 12 to 14 and 20 to 23, 2017.

To determine the effects of spray adjuvants, three adjuvant classes, nonionic surfactant (NIS; Induce®, Helena Chemical Company, Memphis, TN), organosilicone (OSA; Kinetic®, Helena Chemical Company), and methylated seed oil (MSO; BASF, Research Triangle Park, NC) were added to distilled water at concentrations of 0.25% v/v, 0.125% v/v, or 0.75% v/v, respectively. Distilled water was included as a control. Three spray

Table 1. Nozzle type and traveling speed required to reach desired spray volumes.

Spray volume	Nozzle type	Nozzle number[b]	Size of droplet[a]	Traveling speed
L ha^{-1}				m s^{-1}
95	Flat fan	Evs8001	F	0.73
190	Flat fan	Evs8002	F	0.82
380	Flat fan	Evs8004	M	0.93
750	Flat fan	Evs8008	M	0.89
1,125	Flat fan	Evs8010	C	0.66
1500	Flat fan	Evs8010	C	0.50
190	Air induction	AIxr11003	VC	0.96
380	Air induction	AI9504E	XC	0.70
750	Air induction	AI9508E	UC	0.76
1,125	Air induction	AI9508E	UC	0.50

[a]F, fine droplet with a volume median diameter (VMD) between 136 and 177 microns; M, medium droplet with VMD between 177 and 218 microns; C, coarse droplet with VMD between 218 and 349 microns; VC, very coarse droplet with VMD of 349 to 428 microns; XC, extremely coarse droplet with VMD between 428 and 622 microns; UC, ultra-coarse droplet with VMD larger than 622 microns.
[b]TeeJet® Technologies, Glendale, IL.

volumes, 190, 750, or 1,125 L ha^{-1}, were used, and the experiments were conducted on August 21 to 23 and September 1 to 3, 2017.

To determine the impact of dew on foliar retention efficiency, naturally occurring dew at the University of Illinois Landscape Horticulture Research Center, Urbana, IL, was measured on five random dates during August and September 2017, between 7:00 AM and 9:00 AM with five replications per measurement. Based upon those results, the Generation III sprayer was used to apply simulated dew at 1,950 L ha^{-1} to turf cores using a flat-fan nozzle (EVS8001, TeeJet Technologies). A no-dew control was included. Adjuvant treatments of NIS or MSO were added to distilled water at a concentration of 0.25% v/v or 0.75% v/v at spray volumes of 190 or 750 L ha^{-1}. These experiments were conducted on April 20 to 23 and 24 to 26, 2018.

To further determine the effect of dew, three levels of dew, 950, 1,900, or 3,800 L ha^{-1}, were applied using the Generation III sprayer. Following dew application, the turf cores were immediately treated with spray volumes of 190, 550, or 850 L ha^{-1} with NIS at 0.25% v/v. These experiments were conducted on May 4 to 6 and 7 to 9, 2018.

Application Methods and Analysis

Filter paper with a diameter of 185 mm (Whatman No. 1) was placed before and after each set of four bentgrass cores and treated with one pass of the sprayer. The quantity of tartrazine on the filter papers was used to estimate the applied spray volume. For spray volumes lower than 750 L ha^{-1}, one filter paper was placed at each end while two layers of filter paper were needed to fully absorb spray droplets produced at spray volumes above 750 L ha^{-1}.

Following spray application, the cores were air-dried for 1 h in a fume hood before leaf removal. For dew studies, two dryers, placed 1.2 m above the turf cores, were used for 30 min to hasten the drying process. After drying, all green tissue was carefully removed, extracted, and filtered following the procedure outlined in the validation section.

Sample absorbance was measured using a spectrophotometer (SPECTRONIC 20D, Thermo Fisher, Waltham, MA) at 425 nm, where the absorbance of tartrazine is maximized (Pergher 2000). Standard curves were determined for each experiment. Applied volume, retention efficiency, and foliar retention volume were calculated using the following formulas:

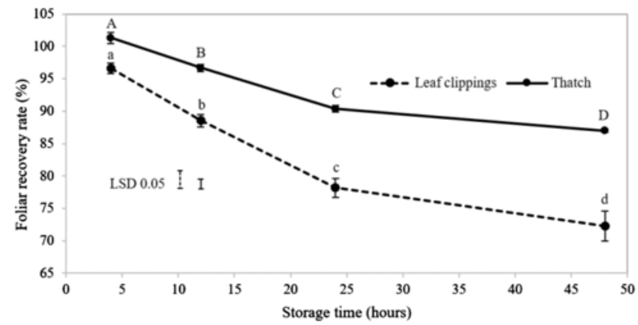

Figure 2. The recovery rate of tartrazine on leaf clippings and thatch from creeping bentgrass as influenced by different storage times. Capital or lowercase letters indicate significant differences in foliar recovery rate in thatch or foliage, respectively.

$$\text{Applied volume } (AV) = 0.32 C_f V_f) \times S / C_{\text{tracer}} V_{\text{tracer}}$$
$$\text{Retention efficiency } (RE) = (C_t V_t - 0.112)/0.32 C_f V_f$$
$$\text{Retention volume } (RV) = AV \times RR = (C_t V_t - 0.112) \times S / C_{\text{tracer}} V_{\text{tracer}}$$
$$\text{Coefficient of variance } (CV) = \sigma/\text{Marginal mean}$$

where

0.32 = the ratio of the area of the turf core (86.2 cm^2) to the area of each filter paper (268.8 cm^2)

C_f = the concentration of tracer extracted from filter papers (mg ml^{-1})

V_f = the volume of spray solution determined from the filter paper (ml)

S = targeted spray volume (L ha^{-1})

C_{tracer} = the concentration of tracer in spray mixture (mg ml^{-1})

V_{tracer} = the volume of spray mixture deposited within each experimental unit area (86.2 cm^2) based on targeted spray volume (ml)

C_t = the concentration of the rinsate extracted from turf clippings (mg ml^{-1})

V_t = the volume of rinsate reclaimed from turf clipping extractions (ml)

0.112 = absorbance due to clipping rinsate (i.e., background)

ANOVA was performed using JMP Pro v. 11.2 (SAS Institute, Cary, NC). Several experiments (nozzle types by spray volumes; adjuvant types by spray volumes; dew levels by spray volumes) were analyzed as a two-factor factorial. A three-factor design was used in analyzing the interaction between the presence of dew, adjuvants, and spray volumes. In all studies, means were compared by the Fisher's LSD test at the 0.05 probability level.

Results and Discussion

Tartrazine Recovery Validation

Tartrazine recovery from filter paper averaged 99.5 ± 0.9% ($n = 9$). From clippings and thatch, the recovery rates of tartrazine decreased linearly with time (Figure 2), suggesting that tartrazine should be extracted within 4 h after treatment to ensure quantitative recovery (96.6 ± 1.6%). These data indicate that degradation may be the main limitation of using tartrazine as a tracer in creeping bentgrass. Nairn and Forster (2019) tested the stability of several dye tracers by placing the dye on the leaves of the brown barrel tree (*Eucalyptus fastigata* H. Deane & Maiden) in direct sunlight for up to 7 h and concluded that tartrazine was photostable.

https://doi.org/10.1017/wet.2019.60 Published online by Cambridge University Press

Table 2. The recovery rate of tartrazine deposited on creeping bentgrass foliage and thatch under different spray volumes.

Spray volume	Plant canopy[a]		
	Foliage	Thatch	Total (foliage + thatch)
L ha^{-1}	Recovery rate[b]		
	%		
190	91.1	9.8 a	101.0
750	84.8	13.5 ab	98.3
1500	89.4	16.5 b	106.7
LSD (0.05)	NS	3.8	NS

[a]Aboveground green tissues and top 0.5 cm of thatch were carefully collected and analyzed separately.
[b]Recovery rates were averaged across two runs of study due to insignificant interactions. Different letters indicate significant differences as determined by Fisher's protected LSD test at P = 0.05.

Table 3. The recovery efficiency of tartrazine deposited on creeping bentgrass foliage under different spray volumes.

Spray volume	Recovery efficiency[a]
L ha^{-1}	%
95	98.3 a
190	95.2 a
380	90.8 b
750	85.3 c
1,125	88.3 bc
1500	85.3 c
LSD (0.05)	3.5

[a]Recovery efficiency was averaged across two runs of study due to nonsignificant *F*-test. Different letters indicate significant differences as determined by Fisher's protected LSD test at P = 0.05.

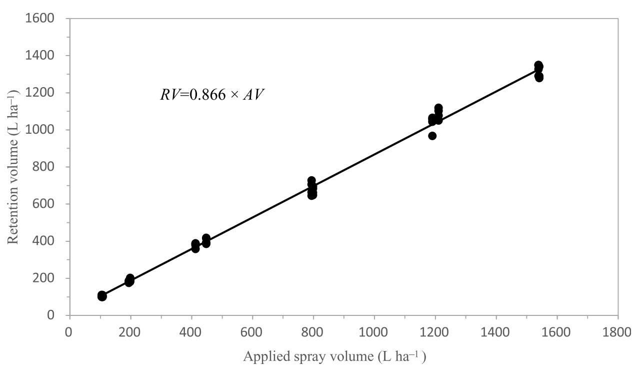

Figure 3. Linear regression between applied volume (L ha^{-1}) and foliar retention volume (L ha^{-1}) on creeping bentgrass. Retention volume (*RV*) = 0.866 × applied volume (*AV*).

Nairn and Forster also tested recovery of tartrazine from brown barrel leaf samples stored in bags for up to 8 d and again saw no degradation.

Based upon our results, the rate of tartrazine degradation should be determined before beginning experiments in other cropping systems.

The recovery of tartrazine in the foliage plus thatch layer, when averaged over all three spray volumes, was 102.0 ± 5.3%. The recovery in the thatch layer was higher at 1,500 L ha^{-1} spray volume than at lower spray volumes (Table 2), indicating that the lower foliar recovery rates are caused by movement of tartrazine into the turf profile rather than degradation or loss of tracer during analysis.

Influence of Spray Volume, Nozzle Type, Adjuvants, and Dew on Foliar Retention Efficiency

Six spray volumes typically used on golf courses were evaluated. Foliar retention volume was linearly correlated with applied spray volume ($R^2 = 0.99$) (Figure 3). The linear increase in foliar retention with increasing spray volume indicates that bentgrass leaves could hold additional spray volume without runoff or drainage. Peng et al. (2005) showed a similar linear response on green foxtail at spray volumes up to 2,000 L ha^{-1}.

Foliar retention efficiency decreased as spray volume increased from 95 L ha^{-1} to 750 L ha^{-1}. At spray volumes above 750 L ha^{-1}, the retention efficiency plateaued around 85%. The highest recovery, 98.3%, was achieved at the lowest spray volume, 95 L ha^{-1} (Table 3). These results indicate that creeping bentgrass turf has the ability to retain the majority of foliar-applied chemicals at the spray volumes typically used. If the target site of application is the thatch layer or surface soil, irrigation immediately following application will be more effective than increasing spray volumes. A lower spray volume will deposit more active ingredients on the foliage, but herbicide efficacy is more complex than simply ensuring the herbicide is on the leaf. Lower spray volumes could reduce golf course labor costs, because less time would be required to complete a spraying program, as each spray tank would cover more acreage.

Other researchers have analyzed foliar retention on a variety of crops (Byer et al. 2006; Peng et al. 2005). Peng et al. (2005) showed a steady increase in foliar retention as spray volume increased; however, Byer et al. (2006) found that spray retention efficiency decreased as spray volume increased. These results highlight the difference between spray retention and retention efficiency. As spray volume increases, the volume of solution deposited on the leaf surfaces should naturally increase; however, the retention efficiency, or active ingredient deposition, can decrease, because a higher spray volume will have a lower concentration of active ingredient. In our study, spray volumes between 750 and 1,500 L ha^{-1} resulted in near-constant retention efficiency. Several variables, such as droplet velocity and the size of spray droplets (Miller and Butler Ellis 2000), may affect foliar retention and retention efficiency. In particular, higher spray droplet velocity enhances foliar runoff and spray droplet bounce and shatter (Dorr et al. 2016). In this study, the traveling speed of the nozzle was reduced from 0.89 m s^{-1} at 750 L ha^{-1} to 0.50 m s^{-1} at 1,500 L ha^{-1} to achieve the higher spray volume. The reduced velocity may decrease the likelihood of droplets running or bouncing off the foliage. The high leaf density and overlapping foliage also helped retain more of the foliar spray.

When comparing flat-fan nozzles to air-induction nozzles at four different spray volumes, we found no difference in foliar retention efficiency between flat-fan and air-induction nozzles (P = 0.9699). Additionally, no interactions were observed between nozzle type and spray volume (P = 0.8188). These findings run counter to the idea that larger spray droplets lead to less foliar retention (Feng et al. 2003), as using an air-induction nozzle doubles the droplet size compared with a flat-fan nozzle at similar spray volumes and orifice sizes. The high density of turf, with a leaf area index (LAI) of 2.2 in April 2018, 2.4 in June 2017, and 3.1 in September 2017 (average of five measurements), may explain why runoff does not occur with coarser droplets. The dense bentgrass canopy can retain the majority of the spray droplets and reduce foliar runoff. Spray volume did have a significant impact on foliar

Table 4. Recovery efficiency of tartrazine deposited on creeping bentgrass as influenced by spray volumes and adjuvants.

	Adjuvant[a]			
Spray volume	NA	NIS	OSA	MSO
L ha^{-1}	Recovery efficiency[b] — %			
190	95.9 a	93.7 abc	93.5 abc	93.6 abc
750	88.0 e	91.7 cd	91.9 bcd	92.0 bcd
1,125	87.3 e	91.7 cd	89.8 de	94.9 ab
LSD (0.05)	3.1			

[a]NIS, nonionic surfactant (Induce®, Helena Chemical Company, Memphis, TN, USA); OSA, organosilicone adjuvant (Kinetic®, Helena Chemical Company); MSO, methylated seed oil (BASF, Research Triangle Park, NC, USA) were mixed with distilled water at a concentration of 0.25% v/v, 0.125% v/v, or 0.75% v/v, respectively. NA, no addition of adjuvant.
[b]Recovery efficiency was averaged across two runs of the study due to nonsignificant *F*-test. Different letters indicate significant differences as determined by Fisher's protected LSD test at P = 0.05.

Table 5. Recovery efficiency of tartrazine across three adjuvant levels on creeping bentgrass as influenced by different spray volumes and different levels of dew.

Source	Recovery efficiency[a]
Spray volume	%
L ha^{-1}	
190	84.6 a
550	82.6 b
850	76.7 c
LSD (0.05)	1.9
Dew levels[b]	
L ha^{-1}	
950	85.9 a
1,900	84.2 a
3,800	73.6 b
LSD (0.05)	1.9

[a]Recovery efficiency was averaged across two experiments and three adjuvant levels due to insignificant interactions. Different letters indicate significant differences as determined by Fisher's protected LSD test at P = 0.05.
[b]Different levels of dew were artificially produced by multiple sprays using the Generation III sprayer with a flat-fan nozzle (EVS8001, TeeJet Technologies, Glendale, IL).

retention efficiency and followed the same trend as the previous spray volume study (Table 3). Air-induction nozzles produced a significantly higher coefficient of variation (6.6) than flat-fan nozzles (3.3), implying less uniformity of application.

Effects of Adjuvants

When adjuvants were added to the spray solution, the main effects of spray volume and adjuvant were significant, as was the spray volume by adjuvant interaction (Table 4). Adding NIS, OSA, or MSO resulted in recovery efficiency that remained unchanged between 90% and 94% at all three spray volumes. As seen previously, spraying water alone resulted in decreased retention efficiency as spray volume increased. Adjuvants affected retention efficiency differently at each spray volume. At 190 L ha^{-1}, retention was similar with or without adjuvants. At 750 L ha^{-1}, adding NIS, OSA, and MSO increased retention efficiency by roughly 4% compared with water only; however, there were no differences between adjuvants. At 1,125 L ha^{-1}, differences among adjuvants were observed. The addition of NIS increased retention efficiency compared with water alone, while OSA provided retention efficiency similar to water alone. At 1,125 L ha^{-1}, MSO increased retention efficiency compared with all other treatments (Table 4).

Prado et al. (2016) showed the concentration of adjuvant can influence foliar retention. This research group observed a nonlinear response of foliar retention on *Eucalyptus* leaves using eight concentrations of six adjuvants. As the adjuvant concentration increased from 0% to 2% v/v, spray retention (μg cm^{-2}) increased to a peak and then dropped to a plateau. It is difficult to predict the change in foliar retention as the concentration of a given adjuvant is increased. Previous studies (Feng et al. 2003; Furmidge 1962; Hall et al. 1993; Holloway et al. 2000; Ramsdale and Messersmith 2001) have reported the impact of MSO, NIS, OSA, and other adjuvants on foliar retention as case specific. The rate of adjuvant, the formulation of the pesticide, and the characteristics of plant surfaces all can influence foliar retention. Pesticide formulations are complex and contain multiple compounds, such as adjuvants, to achieve stable and reliable pest control. However, adding an adjuvant is still a routine strategy when mixing chemicals for spray application. The effects of adjuvants and adjuvant concentration on herbicide performance has been an active area of research for many years and was reviewed by Knoche (1994). These results suggest that the use of adjuvants may increase foliar retention efficiency when used at standard rates and spray volumes on bentgrass fairways.

An additional factor that may impact foliar retention efficiency is dew. The presence of dew and spray volume was significant, as was their interaction; however, adjuvants did not influence foliar retention efficiency. Increasing spray volume decreased foliar retention efficiency regardless of dew. At 190 L ha^{-1}, the presence of dew increased retention efficiency to 87.1% from 83.8% for dry foliage. However, no difference was observed between wet (80.0%) or dry (79.9%) leaves when sprayed at 750 L ha^{-1}. This finding was contrary to what had been observed on grape (Saab et al. 2017) and the common perception that dew negatively influences foliar retention.

A second study was conducted to determine the influence of dew quantity at three different spray volumes. The main effects of spray volume and dew quantity influenced retention efficiency (Table 5). Retention efficiency decreased as the spray volume increased. No changes in retention efficiency were observed at dew levels of 950 or 1,900 L ha^{-1}, but at 3,800 L ha^{-1}, retention efficiency decreased by approximately 11% compared with the lower dew levels (Table 5). These results indicate that the quantity of dew is important, and when dew quantity is high (e.g., greater than 1,900 L ha^{-1}), increased foliar runoff from creeping bentgrass maintained under fairway conditions is likely.

The dew studies conducted in April and May 2018 with an LAI of 2.2 yielded lower foliar retention compared with experiments run when LAI values were ~3.1 (Table 5). The morphological differences of species and mowing heights used in turf may give different patterns of spray deposition, making the extrapolation of these results beyond creeping bentgrass at fairway height questionable.

Implications for Herbicide Use

Leaf surfaces vary in wax content, wax type, the presence of trichomes, and other characteristics that influence spray retention (Holloway 1993). Pesticide formulations contain utility adjuvants to ensure solution compatibility, and label instructions often suggest adding activator adjuvants or fertilizer solutions to enhance herbicidal activity. This research examined the role of several

https://doi.org/10.1017/wet.2019.60 Published online by Cambridge University Press

factors on foliar retention efficiency in creeping bentgrass and demonstrated that spray volume, adjuvant addition, and quantities of dew can interact to affect retention efficiency. Additional research should study these factors with commercial formulations of herbicides on the plant targets of choice.

Acknowledgments. This research received no specific grant from any funding agency or the commercial or not-for-profit sectors.

Conflicts of interest. No conflicts of interest have been declared.

References

Armstrong-Cho C, Wolf T, Chongo G, Gan Y, Hogg T, Lafond G, Johnson E, Banniza S (2008) The effect of carrier volume on ascochyta blight (*Ascochyta rabiei*) control in chickpea. Crop Prot 27:1020–1030

Butler Ellis MC, Webb DA, Western NM (2004) The effect of different spray liquids on the foliar retention of agricultural sprays by wheat plants in a canopy. Pest Manag Sci 60:786–794

Byer KN, Peng G, Wolf TM, Caldwell BC (2006) Spray retention and its effect on weed control by mycoherbicides. Biol Control 37:307–313

Cross JV, Walklate PJ, Murray RA, Richardson GM (2001) Spray deposits and losses in different sized apple trees from an axial fan orchard sprayer: 1. Effects of spray liquid flow rate. Crop Prot 20:13–30

Delvalle TC, Landschoot PJ, Kaminski JE (2011) Effects of dew removal and mowing frequency on fungicide performance for dollar spot control. Plant Dis 95:1427–1432

Dorr GJ, Forster WA, Mayo LC, McCue SW, Kempthorne DM, Hanan J, Turner IW, Belward JA, Young J, Zabkiewicz JA (2016) Spray retention on whole plants: modelling, simulations, and experiments. Crop Prot 88:118–130

Feng PCC, Chiu T, Sammons RD, Ryerse JS (2003) Droplet size affects glyphosate retention, absorption, and translocation in corn. Weed Sci 51:443–448

Furmidge CGL (1962) Physico-chemical studies on agricultural sprays. IV. The retention of spray liquids on leaf surfaces. J Sci Food Agric 13:127–140

Gossen BD, Peng G, Wolf TM (2008) Improving spray retention to enhance the efficacy of foliar-applied disease- and pest-management products in field and row crops. Can J Plant Pathol 30:505–516

Hall FR, Chapple AC, Downer RA, Kirchner LM, Thacker JRM (1993) Pesticide application as affected by spray modifiers. Pestic Sci 38:123–133

Hart SE, Kells JJ, Penner D (1992) Influence of adjuvants on the efficacy, absorption, and spray retention of Primisulfuron. Weed Technol 6:592–598

Holloway PJ (1993). Structure and chemistry of plant cuticles. Pestic Sci 37: 203–232

Holloway PJ, Butler-Ellis MC, Webb DA, Western NM, Tuck CR, Hayes AL, Miller PCH (2000) Effects of some agricultural tank-mix adjuvants on the deposition efficiency of aqueous sprays on foliage. Crop Prot 19:27–37

Kennelly MM, Wolf RE (2009) Effect of nozzle type and water volume on dollar spot control in greens-height creeping bentgrass. Appl Turfgrass Sci 6, 10.1094/ATS-2009-0921-01-RS

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

McCullough PE, Hart SE (2009) Chelated iron and adjuvants influence bispyribac-sodium efficacy for annual bluegrass (*Poa annua*) control in cool-season turfgrasses. Weed Technol 23:519–523

McDonald SJ, Dernoeden PH, Bigelow CA (2006) Dollar spot control in creeping bentgrass as influenced by fungicide spray volume and application timing. Appl Turfgrass Sci 3, 10.1094/ATS-2006-0531-01-RS

Miller PCH, Butler-Ellis MC (2000) Effects of formulation on spray nozzle performance for applications from ground-based boom sprayers. Crop Prot 19:609–615

Murray RA, Cross JV, Ridout MS (2000) The measurement of multiple spray deposits by sequential application of metal chelate tracers. Ann Appl Biol 137:245–252

Nairn JJ, Forster WA (2019) Due diligence required to quantify and visualise agrichemical spray deposits using dye tracers. Crop Prot 115:92–98

Peng G, Wolf TM, Byer KN, Caldwell B (2005) Spray retention on green foxtail (*Setaria viridis*) and its effect on weed control efficacy by *Pyricularia setariae*. Weed Technol 19:86–93

Pergher G (2000) Recovery rate of tracer dyes used for deposit assessment. Trans ASAE 44:787–794

Prado EP, Raetano CG, Pogetto MHF, Do AD, Chechetto RG, Filho PJF, Magalhaes AC, Miasaki CT (2016) Effects of agricultural spray adjuvants in surface tension reduction and spray retention on *Eucalyptus* leaves. Afr J Agric Res 11:3959–3965

Ramsdale BK, Messersmith CG (2001) Nozzle, spray volume, and adjuvant effects on carfentrazone and imazamox efficacy. Weed Technol 15:485–491

Ruiter HD, Uffing AJM, Meinen E, Prins A (1990) Influence of surfactants and plant species on leaf retention of spray solutions. Weed Sci 38: 567–572

Saab OJGA, Griesang F, Alves KA, Higashibara LR, Genta W (2017) Pesticides deposition in vineyards on different conditions of leaf wetness. Engenharia Agricola 37:286–291

Sanchez-Hermosilla J, Medina R, Rodriguez F, Callejon A (2008) Use of food dyes as tracers to measure multiple spray deposits by ultraviolet-visible absorption spectrophotometry. Trans ASABE. 51:1177–1186

van Zyl SA, Brink J, Calitz FJ, Fourie PH (2010) Effects of adjuvants on deposition efficiency of fenhexamid sprays applied to Chardonnay grapevine foliage. Crop Prot 29:843–852

Williams DW, Powell AJ, Dougherty CT, Vincelli P (1998) Separation and quantitation of the sources of dew on creeping bentgrass. Crop Sci 38: 1613–1617

Young BG, Hart SE (1998) Optimizing foliar activity of Isoxaflutole on giant foxtail (*Setaria faberi*) with various adjuvants. Weed Sci 46:397–402

Zawierucha JE, Penner D (2000) Absorption, translocation, metabolism, and spray retention of quinclorac in *Digitaria sanguinalis* and *Eleusine indica*. Weed Sci 48:296–301

Zawierucha JE, Penner D (2001) Adjuvant efficacy with quinclorac in canola (*Brassica napus*) and turfgrass. Weed Technol 15:220–223