ABSTRACT

LECOMPTE, MATHIEU CHRISTOPHE. Characterization of Herbicide Fate Through Dislodgeable Foliar Residue and Lateral Movement in Turfgrass Systems. (Under the direction of Dr. Travis Gannon).

Weeds in turfgrass systems are problematic, having reduced wear tolerance, short life cycles, and less consistent growth habits, leading to increased risk of uneven surfaces and erosion where present. Chemical weed control is an integral component of many integrated weed management programs due to time, labor, cost, and efficacy benefits associated with herbicide use. During this time of heightened awareness regarding pesticide use, research surrounding how herbicides persist and move within the environment following application is critical for better understanding how to increase efficacy of applications while minimizing exposure of people, pets, and sensitive ecosystems via off-target movement. This is of particular interest in managed turfgrass systems, often centered around areas of heavy human activity such as parks, athletic fields, or home lawns. Field research was conducted to evaluate herbicide fate through dislodgeable foliar residue and lateral movement in turfgrass systems following application.

Field studies were conducted in Raleigh, NC to assess the effect of application rate, application season, commercially formulated product, and time of sample collection on dislodgeability of dicamba and 2,4-D from non-overseeded hybrid bermudagrass (*Cynodon dactylon* L x *C. transvaalensis* Burtt Davy cv. 'Tifway 419'). Each of the two evaluated commercially formulated herbicides applied at high and low rates corresponding to 2,4-D being applied at 857 and 1,110 g ae ha^{-1} and dicamba applied at 78 and 118 g ae ha^{-1}. Dislodgeable residue samples were collected using modified California roller methods at 0,1,2,4, and 8 days after treatment (DAT). Two experimental runs were conducted in each of 4 seasons. For both products, greater percentages of applied 2,4-D and dicamba were dislodged from high rate of

application compared to low rate of application. Greater dislodgeable foliar residue was recovered during spring samplings than summer, fall, and winter.

Field studies characterizing herbicide lateral movement were conducted in Raleigh, NC and Jackson Springs, NC on dormant hybrid bermudagrass overseeded with a perennial ryegrass blend (*Lolium perenne* L.). Each site contained unique soil characteristics with Raleigh consisting of a Cecil sandy loam, and Jackson Springs consisting of Candor sand. Trifloxysulfuron applications were made on an upslope herbicide-treated area of each plot to turfgrass under saturated soil conditions. Simulated rainfall events consisted of two post-application amounts (0.25 and 0.64 cm) and three timings (0, 24, and 72 h after herbicide application (HAHA)). Two experimental runs each containing 4 replicates were conducted for each site. Distance and percent of area immediately downslope was recorded for each plot. No off-target damage was observed at Jackson Springs, NC. Off-target injury was observed at Raleigh, NC, with the greatest injury being observed with 0.64 cm simulated rainfall events and events occurring immediately after herbicide application. Distance and severity of injury declined significantly 24 HAHA.

Following initial lateral movement characterization, studies were conducted in Raleigh, NC to evaluate the effectiveness of utilizing post-application irrigation to reduce distance and severity of herbicide lateral movement under saturated soil conditions. Trifloxysulfuron was applied to an upslope herbicide-treated area of each plot to turfgrass under saturated soil conditions. Treatments consisted of three irrigation schedules (PM, AM, PM + AM), each delivering a total of 0.127 cm irrigation, as well as a plot receiving herbicide but no irrigation prior to a 1.9 cm simulated rain event occurring 24 HAHA. Research findings suggest light post-application may be effective in reducing maximum distance and severity of injury downslope

due to lateral movement of herbicide off target. Findings from these trials will be useful in developing BMP's for continued safe and effective use of herbicides for control of problem weeds in turfgrass systems.

Characterization of Herbicide Fate Through Dislodgeable Foliar Residue and Lateral Movement in Turfgrass Systems

by
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DEDICATION

I dedicate this thesis to Bridgette and Theo. Thanks for helping me remember that regardless of the challenges of school and work, there is always time for ice cream and PAW Patrol.

BIOGRAPHY

Mathieu C. LeCompte was born to Joseph and Karen LeCompte in Greensboro, NC and was raised with brother, Michael. After graduating from Ragsdale High School in Jamestown, NC, Mathieu received a Bachelor of Arts degree from University of North Carolina at Chapel Hill. Shortly after graduating, Mathieu began work at The Preserve at Jordan Lake Golf Club in Chapel Hill, NC, sparking his interest in a career in turfgrass management. Within a year, Mathieu returned to North Carolina State University to receive an Associate of Applied Science degree in turfgrass management. Upon completion of this second post-secondary degree, Mathieu was employed by Governors Club in Chapel Hill, NC as an assistant golf course superintendent. Mathieu spent nearly a decade working in various golf course management positions in North Carolina, Ohio, and Virginia. During this time, Mathieu married Bridgette LeCompte. In 2018, Mathieu and Bridgette were blessed with a son, Theo, while living in Williamsburg, VA. After overseeing the restoration and reopening of Royal New Kent Golf Club in Providence Forge, VA, Mathieu, Bridgette, and Theo returned to North Carolina, where Mathieu began work towards a Master of Science degree in Crop Science.

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CHAPTER 1

Effect of Season, Product, Rate, and Sample Timing on Dislodgeability of Dicamba and 2,4-D from Hybrid Bermudagrass (*Cynodon dactylon* L x *C. transvaalensis* Burtt Davy)

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Dicamba and 2,4-D are two active ingredients commonly combined in commercial herbicide formulations for controlling broadleaf weeds in turfgrass. Previous research has investigated how factors such as irrigation, surfactants, and time of day affect dislodgeability of pesticides; however, there is a lack of research surrounding the influence of rate, seasonality, and impact of inert and active ingredients within commercially formulated products on pesticide dislodgeability. Field studies were conducted in Raleigh, NC to assess the effect of application rate, application season, commercially formulated product, and time of sample collection on dislodgeability of dicamba and 2,4-D from non-overseeded hybrid bermudagrass (*Cynodon dactylon* L x *C. transvaalensis* Burtt Davy). Trimec® Classic (PBI GORDON Corporation, Shawnee, KS, USA) and SpeedZone® (PBI GORDON Corporation, Kansas City, MO, USA) were applied at rates balancing the chemical acid equivalent load for each analyte. Each product was applied at high and low rates, delivering 2,4-D at 857 and 1120 g ae ha^{-1} and dicamba at 78 and 118 g ae ha^{-1}. Dislodgeable residue samples were collected using modified California roller methods at 0, 1, 2, 4, and 8 d after treatment (DAT). Two experimental runs were conducted in each of four seasons. Greater dislodgement of 2,4-D and dicamba was observed for high application rates compared to low rates at 1 DAT (18.23 > 16.38% dislodged of applied and 8.02 > 6.78%, respectively). Treatments with Trimec® Classic consistently produced numerically

greater dislodgeable residues 1 through 4 DAT for both dicamba and 2,4-D compared to treatments in which SpeedZone® was applied. At 1 DAT, Spring samples contained the greatest dicamba dislodged (11.79%), followed by Summer (7.45%), Fall (6.37%), and Winter (3.99%). For 2,4-D samples 1 DAT, Spring samples contained the greatest average percentage of 2,4-D dislodged (22.66%), followed by Summer (17.24%), then Fall and Winter (14.96 and 14.35%, respectively). These data provide documentation which can be used by turfgrass managers looking to mitigate risks associated with pesticide dislodgement following herbicide applications.

Introduction

Trimec® Classic and SpeedZone® are commonly applied broadleaf herbicides registered for use in turfgrass systems including athletic fields, golf courses, and residential/commercial lawns, among other use sites (Anonymous, 2023a; Anonymous, 2023b). Both herbicides contain 2,4-D [2-(2,4-dichlorophenoxy)acetic acid] and dicamba (3,6-dichloro-2-methoxybenzoic acid) among other constituents, a common combination of active ingredients for controlling broadleaf weeds in turfgrass (Jauron, 2001). These synthetic auxins mimic the natural plant hormone indole-3-acetic acid (Grossmann, 2007) causing leaf cupping, malformation, and stem epinasty (Ahrens, 1994). This leads to necrosis of terminal meristematic tissues followed by reduced root and shoot growth (Tehranchian et al., 2017; Grabińska-Sota et al., 2003), resulting in plant death. Auxin herbicides have long been used to control many weed species in turfgrass settings including common carpetgrass (*Axonopus fissifolius* (Raddi) Kuhlum), common dandelion (*Taraxacum officinale* F.H. Wigg), wild garlic (*Allium vineale* L.), and doveweed (*Murdannia nudiflora* L.) (Raudenbush et al., 2014; Atkinson et al., 2017; Henry et al., 2019; Small et al., 2019). Trimec® Classic contains 2,4-D and dicamba as dimethylamine salts, while SpeedZone® contains the 2-ethylhexyl ester form of 2,4-D, the acid form of dicamba, mecoprop-p acid [2-(4-chloro-2-methylphenoxy)propanoic acid], and carfentrazone-ethyl [ethyl 2-chloro-3-[2-chloro-5-[4-(difluoromethyl)-3-methyl-5-oxo-1,2,4-triazol-1-yl]-4-fluorophenyl]propanoate].

A report from the United States Environmental Protection Agency (USEPA) indicated 2,4-D was the most applied pesticide active ingredient in non-agricultural sectors (totaling as much as an estimated 6.8 million kg ae) during the year 2012, equating to ~14% of total pesticide use within this sector, which encompasses turfgrass (Atwood & Paisley-Jones, 2017). According to the same report, dicamba was the eighth most used pesticide active ingredient in

the home and garden market sector for the year 2012. These two pesticide active ingredients total for as much as 8.6 million kg ae applied to non – agricultural land, or nearly 17% of all pesticide active ingredients applied to this sector. The high application totals for these two active ingredients illustrate the frequency of use within this sector, warranting further research investigating potential pathways for off-target movement.

Research surrounding pathways for off-target movement is of particular importance during this era of increased scrutiny around the use of pesticides. Lawmakers and activists, alike, have led a charge to update legislation surrounding scientific review of pesticide safety and exposure trials conducted by regulatory agencies (Carter, 2021; Reynolds, 2016). Studies evaluating dislodgeable foliar residue, or turf transferable residue, are currently used by the USEPA during product registration to quantify potential occupational and residential exposure following pesticide applications (USEPA, 1996). These studies have been critical in assessing exposure risks during registration and reregistration of active ingredients which are believed to be potentially harmful to humans or applied in in large quantities.

2,4-D ester, as found in SpeedZone®, has a water solubility of 0.0867 mg L^{-1} at 20°C (Shaner, 2014). 2,4-D dimethylamine (DMA), as found in Trimec® Classic, has a water solubility of 7.29 x 10^7 mg L^{-1} at 20°C; however, it dissociates quickly into the acid form following application (Shaner, 2014). 2,4-D has a relatively low organic carbon-water partition coefficient (K_{OC} = 20 mL g^{-1}) suggesting it is weakly bound to organic matter in soil (Shaner, 2014; USEPA, 2005). This may contribute to 2,4-D being more readily dislodge from treated turfgrass systems. 2,4-D dislodgeability from turfgrass has been confirmed by multiple sources. Nishioka et al. (2001) detected 2,4-D in several areas within homes following applications to respective home lawns, raising concern of movement off application site, leading to unintended human

exposure. Dicamba acid, as found in SpeedZone®, has a water solubility of 4,500 mg L^{-1} at 25°C (Shaner, 2014). Dimethylamine salt of dicamba, as found in Trimec® Classic, has a water solubility of 720,000 mg L^{-1}. Dicamba also has a low organic carbon-water partition coefficient (K_{OC} = 2 mL g^{-1}) (Shaner, 2014) suggesting it may also possess an elevated risk for dislodgement from turf canopies following application.

Previous researchers examined the effect of various management practices on 2,4-D dislodgeability. Research to date indicates that 2,4-D dislodgement may be reduced by applying granular formulations rather than liquid-formulated herbicides, utilizing post-application irrigation, or including a surfactant when spraying herbicides (Thompson et al., 1984; Jeffries et al., 2016a; Maxwell et al., 2018). Thompson et al. (1984) reported 4.5% of the total applied 2,4-D was dislodged from Kentucky bluegrass (*Poa pratensis* L.) immediately following application and declined to 0.01% of total amount applied at 1 d after treatment (DAT) when a rainfall event (1.8 cm) occurred 1 h after treatment (HAT). The authors also reported liquid applied 2,4-D was up to 15-times more dislodgeable than granular 2,4-D in the days following application. Jeffries et al. (2016a) reported dislodgeable 2,4-D was reduced by >300% from hybrid bermudagrass following post-application irrigation occurring 24 hours after the 2,4-D application. From 2 to 7 DAT, ≤ 0.5% of applied 2,4-D was dislodged from irrigated turfgrass, while ≤ 2.3% of applied 2,4-D was dislodged when not irrigated. Finally, Maxwell et al. (2018) evaluated the effect of surfactant inclusion and sample collection time within a day on dislodgeable 2,4-D from hybrid bermudagrass overseeded with perennial ryegrass (*Lolium perenne* L.). Maxwell et al. (2018) reported 2,4-D applied with a nonionic surfactant reduced dislodgeable foliar residue compared to 2,4-D applied alone from 1 through 6 DAT. Regardless of surfactant inclusion or absence,

samples collected in the morning (0700 h) resulted in a 5- to 10-fold increase in dislodgeable 2,4-D compared to samples collected in the afternoon (1400 h) from 1 through 6 DAT.

While studies evaluating dislodgeable foliar residue have been conducted with various pesticides possessing differing physicochemical properties, reports from dislodgeable foliar residue studies are relatively few in comparison to studies evaluating other pesticide dissipation processes (e.g., runoff, leaching, volatilization, etc.). It is understood that many factors including pesticide physicochemical properties, plant uptake, foliage characteristics, surface area of plant, collection/exposure timing, and environmental conditions affect the rate at which pesticide dislodgeable residues dissipate over time (Willis & McDowell, 1987; Bates, 1990; Jeffries et al., 2016a). The objectives of this research were to quantify the impact of season, application rate, sample timings, and formulation on the dislodgeability of dicamba and 2,4-D residues from hybrid bermudagrass in hopes of improving applicator decision making in regard to rate, formulation, and seasonality of herbicide treatments. We hypothesized there would be differences in dislodgeable residues between the two tested commercial products and seasonal changes may enhance or reduce these differences depending on temperature, canopy fullness, and leaf wetness at time of sample collection. Additionally, we hypothesized that increased rates of application would result in greater dislodgeable residue.

Materials and Methods

Site Description

Field research studies were conducted on non-overseeded hybrid bermudagrass at Lake Wheeler Turfgrass Field Lab in Raleigh, NC (35°44’21.5”N 78°40’50.0”W) beginning 24 May 2021 with the final experimental run concluding on 22 February 2022. Bermudagrass was fertilized, irrigated, free of weeds and disease, maintained at a 5 cm height of cut, and managed

according to recommended practices (Miller et al., 2021). Research plots had no history of dicamba or 2,4-D applications for six months prior to the initiation of each run. Mowing and maintenance of the research area was withheld throughout the sample collection window. Additionally, no supplementary pesticides, fertilizers, plant growth regulators, or irrigation was applied to research plots following the initiation of each run through the completion of sample collection. If rain was expected, plots were covered with metal roofing panels to prevent loss of dislodgeable residue due to factors outside of the scope of this trial.

Experimental Design

Experiments were arranged in a split-plot design with the whole plot in a randomized complete block containing three replicates. Two runs were completed within each (4) season. Main plots consisted of collection timings (0, 1, 2, 4, and 8-DAT). Subplots consisted of a full factorial of two commercially formulated products (Trimec® Classic (PBI GORDON Corporation, Shawnee, KS, USA) and SpeedZone® (PBI GORDON Corporation, Kansas City, MO, USA)), each of which contained low and high application rates of both dicamba and 2,4-D. Application rates were adjusted to balance the chemical acid equivalent load of each evaluated analyte. Evaluated rates of 2,4-D included low and high rates corresponding with 857 and 1,110 g ae ha^{-1}, respectively (Table 1.1). Evaluated rates of dicamba included low and high rates corresponding with 78 and 118 g ae ha^{-1}, respectively.

Experiment Initiation

Hybrid bermudagrass plots were mowed to a height of 5 cm, clippings were collected, and plots were irrigated to saturation 24 h prior to trial initiation. Herbicide applications were made at 1400 h to plots measuring 1- by 3-m. Nontreated alleys measuring 1 m were included between blocks to minimize incidental herbicide transfer during sample collection. Treatments

were applied using a hand-held CO_2-pressurized sprayer equipped with three TeeJet XR 80015 VS nozzles (TeeJet, Spraying System Co. Wheaton, IL) calibrated to deliver 187 L ha^{-1}. Application rates were confirmed by placing chromatography paper recovery pads (350 cm^2; 0.35 mm Fisherbrand™ Pure Cellulose Chromatography Paper, Fisher Scientific International, Inc.) within application area at time of herbicide application. Recovery pads confirmed that 2,4-D was applied at 87 – 120% of intended rate across commercially formulated products, seasons, and runs. Recovery pads confirmed dicamba was applied at 90 - 104% of intended rate across commercially formulated products, seasons, and runs. Environmental conditions including temperature, relative humidity, rainfall, and leaf wetness were collected through NC CRONOS/ECONet Database using weather stations located approximately 1 km from the research site for the duration of each experimental run (Tables 1.2 – 1.5).

Sample Collection

Dislodgeable foliar residue samples were collected using modified California roller sampling method described by Fuller et al. (2001). For each collection, a 62 x 91 cm aluminum frame was fitted with a 100% cotton white sheet (249 threads 10 cm^{-2}; 70 x 99 cm). A 6 mm plastic sheet was secured to the cotton sheet to avoid cross contamination between samples. Frame and sheet were placed directly onto treated turfgrass within each plot with sheet facing down. The roller, weighing 14.5 kg and consisting of a handle affixed to a weighted rolling drum measuring 10-cm diameter by 61-cm length, was rolled over the cotton sheet five times (one down and back considered one time) at a speed of 1.6 km h^{-1} with no added downward pressure. Frame and sheet were removed from turfgrass, and debris was removed using tweezers. The sheet was removed from the frame and folded such that the side in contact with the turfgrass was in contact with itself. The sheet was subsequently placed in a glass jar and stored in a cooler, on

ice for no more than two hours until it was transferred to a freezer and stored at -20° C where it remained until processing for extraction and residue analysis. Following each sample collection, the 6 mm plastic sheet was discarded. The aluminum frame was cleaned with ammonia and water, then dried before a new cotton sheet and plastic were added for the next sample collection. Dislodged dicamba and 2,4-D residues were calculated as percent of applied using the equation:

$$\% \text{ dislodged of applied} = ([\text{CD } \mu g \text{ analyte } cm^{-2} / \text{TAR } \mu g \text{ analyte } cm^{-2}] \times 100)$$

where CD represents concentration of analyte dislodged onto sheet using modified California roller method and TAR represents target application rate for the plot from which sample was collected.

Samples collected 0 DAT were collected in the afternoon, within 5 minutes following herbicide application. These samples were excluded from final data analysis due to environmental conditions differing from the remaining collection timings. Samples collected 1, 2, 4, and 8 DAT were collected at sunrise of the corresponding day following herbicide treatment to provide a scenario in which dislodgement was most likely, as previous research by Maxwell et al. (2021) showed positive correlation between relative humidity and pesticide dislodgeability. Samples for days 1, 2, 4, and 8 DAT were collected at 0600 h during spring runs, 0800 h during fall runs, and 0700 during summer and winter runs.

Residue Analyses

Dislodgeable residues were quantified using high performance liquid chromatography coupled with diode-array and mass spectrometry detectors (HPLC-DAD-MS) (Agilent-1260

Infinity/MS6120; Agilent Technologies, Inc., Wilmington, DE, USA), following modified extraction, processing, and injection methods described by Jeffries et al. (2016a).

Frozen samples were allowed to thaw at 22° C for 30 m prior to extraction. Methanol (150 mL) was added to each sample and shaken [300 rpm (KS 501 Digital Shaker; IKA Works, Inc., Wilmington, NC, USA)] for 1 h. Samples collected at later timings were extracted with 100 mL of methanol to increase concentration of extract prior to production of aliquot. Extract was removed and samples were compressed to remove remaining solution. A second extraction was conducted with each sample, adding methanol (50 to 100 mL dependent on collection timing) and following the same procedure. Extracts were combined to produce an aliquot (50 mL) which was centrifuged (3500 rpm) for 10 m and filtered (0.45 μm nylon filter; Thermo Fisher Scientific, Inc., Pittsburgh, PA, USA) prior to injection. Extracted samples were injected within 24 h. Procedural samples (control, fortified control, and control spike) were analyzed with each set of samples to validate the efficiency of the extraction and instrument. Fortified sample recoveries were 97 – 103% for 2,4-D and 88 – 97% for dicamba. Agilent OpenLab ChemStation software C.01.04 was used to plot standard calibration curves and to quantify residue concentrations in samples based on peak area measurements. Dicamba limit of detection and limit of quantification were 0.125 and 0.25 mg L^{-1}, respectively, whereas, 2,4-D limit of detection and limit of quantification were 0.05 and 0.125 mg L^{-1}, respectively.

Statistical Analyses

Statistical analyses were conducted by analysis of variance (P=0.05) using GLIMMIX procedures in SAS (Statistical Analysis Software®, Version 9.2; SAS Institute, Inc., Cary, NC, USA). Season, commercially formulated product, rate, sample timing, and analyte were considered fixed effects. Replicate and experimental run were considered random effects. Means

were separated using Fisher's Protected LSD at P=0.05. Following initial analysis of variance, subsequent analyses were performed separately for each analyte of interest in order to characterize the effect of season, product, rate, and collection date on the dislodgeability of 2,4-D and dicamba. Main effects and their interactions are presented accordingly, with precedent given to higher order of interactions.

Results

The influence of main effects and their interactions on residue are displayed in Table 1.6. Of significance was the interaction between sample collection timing and analyte of interest. Samples collected 1, 2, and 4 DAT contained a greater percentage of 2,4-D dislodged compared to percent of dicamba dislodged of applied (Table 1.7). There was no significant difference between percent of analyte dislodged of applied at 8 d after application. Due to differences observed at 1 through 4 DAT, subsequent results are presented by analyte of interest.

Seasonal differences were observed with significant interactions between collection timing and season for both dislodged dicamba and 2,4-D. At 1 DAT, Spring samples contained the greatest percentage of dicamba dislodged at 11.79%, followed by Summer at 7.45%, Fall at 6.37%, and Winter at 3.99% (Figure 1.1). Summer contained the highest percentage of dislodged dicamba 2 DAT at 3.30%, followed by Spring (2.21%), and then Fall and Winter (1.18 and 0.60%, respectively). There was no difference in percent dislodged between Fall and Winter at 2 DAT. No significant differences were observed at 4 DAT, however, 8 DAT Summer samples contained greater dicamba dislodged than Spring, Fall, and Winter. For 2,4-D, Spring samples 1 DAT contained the greatest percentage of 2,4-D dislodged at 22.66% followed by Summer (17.24%), then Fall and Winter (14.96 and 14.35%, respectively) (Figure 1.2). There was no

difference between Fall and Winter samples. Summer had a greater percentage of dislodged 2,4-D (8.63%) 2 DAT than Spring, Fall, or Winter (4.23, 4.25, and 2.94% respectively).

Across runs, rates, and seasons, an interaction was observed between DAT and commercially formulated product (P) for amount of dicamba dislodged. At 1 DAT, treatments where Trimec® Classic was applied contained a greater percentage of dicamba dislodged (9.06%) compared to treatments where SpeedZone® was applied (5.74%) (Figure 1.3). Amount of dicamba dislodged decreased with both products over time, resulting in no significant observed differences between products at 2, 4, and 8 DAT. There were no significant interactions between collection timings and product for percent of 2,4-D dislodged of applied (Figure 1.4).

For dicamba and 2,4-D, interactions between collection timing and rate of application were observed. When dicamba was applied at 118 g ae ha^{-1}, percent dislodged was greater at 8.02% compared to 6.78% when dicamba was applied at 78 g ae ha^{-1} 1 DAT (Table 1.8). Similarly, 1 DAT when 2,4-D was applied at 1,110 g ae ha^{-1}, 18.23% of applied was dislodged compared to 16.38% dislodged when 2,4-D was applied at 857 g ae ha^{-1} (Table 1.9). No differences were observed with regard to rate and timing interaction at 2, 4, or 8 DAT for dicamba or 2,4-D.

A three-way interaction between product, rate, and season was observed for dislodged 2,4-D. General trends remain consistent with seasonal differences observed in the interaction between season and collection timing, and numerical differences between rates are mostly consistent with differences observed in the interaction between rate and collection timing. The exception to this trend was observed between high and low rates for summer samples treated with Trimec® Classic in which samples from plots receiving a low rate of Trimec® contained a greater percentage of dislodged 2,4-D (11.14%) compared to samples collected from plots

receiving a high rate of Trimec® (7.58%) (Table 1.10). Despite a similar instance where the low application rate of SpeedZone® produced a numerically greater percentage of dislodged dicamba compared to the high rate in summer samples, no significant three-way interaction was observed for dislodged dicamba (Table 1.11).

Discussion

Throughout this study, irrigation was withheld from research plots, plots were covered during forecasted rain events to prevent loss of residue, and samples were collected at sunrise, when dew was most likely to be present and dislodgeability of residue likely to be highest. Despite evaluating dislodgeable foliar residue under conditions most conducive to dislodge, dissipation of foliarly dislodgeable residue was observed with less than 1% of applied dicamba dislodged by 4 DAT and less than 1% of applied 2,4-D dislodged at 8 DAT. This is consistent with results found by Krolski et al. (2010) who noted differences in amount of pesticide dislodged between treatments until 72 h after treatment, at which point dislodged residues had decreased such that differences between treatments were not significant.

In addition to sample collection timing, the commercially formulated product used to deliver high and low rates of dicamba and 2,4-D also impacted recoveries. Treatments in which Trimec® Classic was applied delivered dicamba and 2,4-D as dimethylamine salt. Treatments in which SpeedZone® was applied delivered 2,4-D as ester and dicamba as acid. With water solubility greater for dimethylamine dicamba and 2,4-D compared to ester and acid, it is not surprising that the amount of analyte dislodged from Trimec® Classic treatments was numerically greater than the amount of analyte dislodged from SpeedZone® treatments. The inclusion of mecoprop acid and carfentrazone-ethyl in the SpeedZone® formulation may have

increased absorption, reducing dislodgeable residue for treatments in which SpeedZone® was applied.

Seasonally, more dislodged residue was collected during summer and spring compared to fall and winter. Given all samples were collected from non-overseeded bermudagrass, a full canopy of healthy turfgrass, as would be found during spring and summer samplings, is likely to intercept a greater percentage of applied liquid herbicide compared to a thinner, dormant stand of turfgrass, more common during late fall and winter months (Jeffries, 2016b). Fuller canopies of turfgrass stands would be expected to hold more dew during morning sample collections. The increased amount and persistence of dew during summer and spring morning collections support Jeffries et al. (2016a) observations suggesting that risk for dislodgement of residue increases as leaf wetness increases.

Application rate impacted dislodgeable residue. For both dicamba and 2,4-D, a greater percent of applied was dislodged 1 DAT for treatments receiving high application rates compared to low application rates. This is consistent with pesticide exposure modeling conducted by Dong & Beauvais (2013), who noted a linear correlation between amount of extractable residues from plant tissue and physical dislodgeability of pesticides via human contact.

Conclusion

The effects of season, product, rate, and timing on dislodgeable residue reiterate the importance of researching the intricacies and interactions of factors involved in making safe and effective pesticide applications. By better understanding how products interact with and can potentially be dislodged from turfgrass canopies following applications at different rates and under different seasonal conditions, land managers can more confidently make application

decisions based on product availability, target weeds and weed susceptibility, potential human or pet exposure, and risk of movement off target via foot or equipment traffic.

During this time of heightened scrutiny surrounding pesticide usage, data produced from this and future research are critical in understanding the potential exposure of individuals following chemical application to turfgrass systems. USEPA and other regulatory agencies will continue to analyze data obtained from dislodgeable foliar residue studies to evaluate potential risk of human exposure during registration and reregistration evaluations. Data from current research suggest that by restricting access to treated areas during times of heavy dew until 2 DAT, turf managers can reduce potential pesticide exposure by approximately 60% compared to 1 DAT for tested herbicides. With many other herbicides available for use in turfgrass management, future research characterizing dislodgeability of additional commonly used herbicides would be beneficial. Furthermore, it must be noted that research trials were conducted on healthy, well managed turfgrass stands. Canopies were consistent across research plots within reason and weed pressure was low. Evaluating dislodgeability from turfgrass systems under similar environmental conditions but with varying levels of weed pressure and stress may improve our understanding of the factors influencing transferable residues and broaden the scope under which this research can be applied to include turfgrass in minimally managed areas.

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Table 1.1. Herbicide treatment list, product rate, and active ingredient characterization.

Trade name[a,b]	Product rate L ha^{-1}	Active 1	Active 1 salt/acid[c]	Active 1 load g ae ha^{-1}	Active 2	Active 2 salt/acid[c]	Active 2 load g ae ha^{-1}	Analyte of interest
Trimec® Classic	3.614	2,4-D	DMA	740	dicamba	DMA	78	dicamba
Trimec® Classic	3.118	2,4-D	DMA	857	dicamba	DMA	90	2,4-D
Trimec® Classic	4.677	2,4-D	DMA	1110	dicamba	DMA	118	2,4-D
Trimec® Classic	4.677	2,4-D	DMA	1110	dicamba	DMA	118	dicamba
SpeedZone®	4.677	2,4-D	Ester	857	dicamba	Acid	78	2,4-D
SpeedZone®	4.677	2,4-D	Ester	857	dicamba	Acid	78	dicamba
SpeedZone®	6.052	2,4-D	Ester	1110	dicamba	Acid	102	2,4-D
SpeedZone®	7.015	2,4-D	Ester	1289	dicamba	Acid	118	dicamba

[a] Trimec® Classic (PBI GORDON Corporation, Shawnee, KS, USA).
[b] SpeedZone® (PBI GORDON Corporation, Kansas City, MO, USA).
[c] DMA (dimethylamine).

Table 1.2. Weather conditions for spring runs 1 and 2 at the Lake Wheeler Turf Field Lab in Raleigh, NC[a]

Date	DAT	Run	Max Temp	Min Temp	Max RH	Min RH	Precipitation	Leaf Wetness[b]
			ºC		%		cm	mV
5/24/2021	0	1	33.5	19.8	86	37	0.25*	270.9
5/25/2021	1	1	29.6	17.6	93	53	0.00	391.1
5/26/2021	2	1	34.3	18.7	91	35	0.00	275.7
5/28/2021	4	1	33.0	15.7	91	31	0.18*	278.5
6/1/2021	8/0	1/2	27.7	11.3	93	35	0.00	550.5
6/2/2021	1	2	26.6	15.1	92	62	0.69*	275.1
6/3/2021	2	2	26.6	20.2	94	72	2.54*	320.0
6/5/2021	4	2	31.3	20.1	93	35	0.00	543.2
6/9/2021	8	2	31.8	21.5	91	51	2.95*	284.5

DAT = day after treatment, Temp = temperature in ºC, RH = relative humidity in mV

* Indicates plots covered during precipitation event

[a] Weather data collected using NC CRONOS/ECONet Database; Station: Lake Wheeler Road Field Lab (LAKE).

[b] Leaf wetness data collected at time of morning collection, 0600 h on respective date.

Table 1.3. Weather conditions for summer runs 1 and 2 at the Lake Wheeler Turf Field Lab in Raleigh, NC[a]

Date	DAT	Run	Max Temp	Min Temp	Max RH	Min RH	Precipitation	Leaf Wetness[b]
			ºC		%		cm	mV
8/2/2021	0	1	28.8	21.4	93	44	0.00	275.7
8/9/2021	1	1	32.3	20.4	93	45	0.00	512.5
8/10/2021	2	1	32.5	22.4	93	52	0.00	394.4
8/12/2021	4	1	34.9	23.1	91	46	0.00	305.6
8/16/2021	8	1	30.6	21.9	94	62	0.48*	313.8
8/23/2021	0	2	32.2	20.4	93	50	0.00	558.2
8/24/2021	1	2	34.9	21.8	93	44	0.00	509.7
8/25/2021	2	2	33.5	22.0	93	52	0.00	442.9
8/27/2021	4	2	32.4	21.0	92	45	0.00	430.6
8/31/2021	8	2	32.7	21.3	91	45	0.00	310.5

DAT = day after treatment, Temp = temperature in ºC, RH = relative humidity in mV

* Indicates plots covered during precipitation event

[a] Weather data collected using NC CRONOS/ECONet Database; Station: Lake Wheeler Road Field Lab (LAKE).

[b] Leaf wetness data collected at time of morning collection, 0700 h on respective date.

Table 1.4. Weather conditions for fall runs 1 and 2 at the Lake Wheeler Turf Field Lab in Raleigh, NC[a]

Date	DAT	Run	Max Temp	Min Temp	Max RH	Min RH	Precipitation	Leaf Wetness[b]
			ºC		%		cm	mV
10/25/2021	0	1	25.7	15.8	92	58	3.35*	422.5
10/27/2021	1	1	20.5	7.6	90	48	0.00	270.5
10/28/2021	2	1	21.9	9.1	92	51	1.02*	411.9
10/30/2021	4	1	14.8	9.1	89	64	0.00	388.0
11/1/2021	0	2	20.5	7.1	91	45	0.00	477.5
11/2/2021	1	2	20.2	7.3	92	51	0.03*	449.5
11/3/2021	8/2	1/2	12.6	7.7	85	39	0.00	273.9
11/5/2021	4	2	10.9	3.1	87	36	0.00	272.7
11/9/2021	8	2	23.9	4.2	91	30	0.00	559.0

DAT = day after treatment, Temp = temperature in ºC, RH = relative humidity in mV

* Indicates plots covered during precipitation event

[a] Weather data collected using NC CRONOS/ECONet Database; Station: Lake Wheeler Road Field Lab (LAKE).

[b] Leaf wetness data collected at time of morning collection, 0800 h on respective date.

Table 1.5. Weather conditions for winter runs 1 and 2 at the Lake Wheeler Turf Field Lab in Raleigh, NC[a]

Date	DAT	Run	Max Temp	Min Temp	Max RH	Min RH	Precipitation	Leaf Wetness[b]
			ºC		%		cm	mV
2/8/2022	0	1	8.7	0	91	52	0.00	308.9
2/9/2022	1	1	13.8	-2.1	91	28	0.03*	290.6
2/10/2022	2	1	17.9	0	84	25	0.00	286.4
2/12/2022	4	1	20.6	4.6	72	30	0.00	269.9
2/14/2022	0	2	9.1	-3.9	91	31	0.00	293.3
2/15/2022	1	2	10.6	-4.2	76	31	0.00	268.8
2/16/2022	8/2	1/2	17.3	-1.6	86	45	0.00	324.1
2/18/2022	4	2	20.6	3.5	86	39	0.61*	296.2
2/22/2022	8	2	21.6	13.5	89	61	0.03*	284.6

DAT = day after treatment, Temp = temperature in ºC, RH = relative humidity in mV

* Indicates plots covered during precipitation event

[a] Weather data collected using NC CRONOS/ECONet Database; Station: Lake Wheeler Road Field Lab (LAKE).

[b] Leaf wetness data collected at time of morning collection, 0700 h on respective date.

Table 1.6. Partial ANOVA for the effect of season, sampling timing, product, and rate on percent of applied dicamba and 2,4-D dislodged from hybrid bermudagrass at $\alpha = 0.05$. Full model containing dicamba and 2,4-D as well as ANOVA sorted by active ingredient presented.

Source of variation	Dicamba and 2,4-D	Dicamba	2,4-D
Season (S)	<0.0001	<0.0001	<0.0001
Day After Treatment (D)	<0.0001	<0.0001	<0.0001
D x S	<0.0001	<0.0001	<0.0001
Product (P)	<0.0001	<0.0001	<0.0001
P x S	0.0121	0.4230	0.0082
P x D	<0.0001	<0.0001	0.1347
P x S x D	0.9912	0.8155	0.9748
Rate (R)	0.1171	0.0452	0.2244
R x S	0.1589	0.6159	0.1411
R x D	0.0022	0.0063	0.0254
R x S x D	0.1806	0.1096	0.3151
P x R	0.0169	0.0924	0.0360
P x R x S	0.0005	0.0664	0.0040
P x R x D	0.6206	0.7238	0.4844
P x R x S x D	0.8483	0.5736	0.8051
Analyte (A)	<0.0001	—	—
A x D	<0.0001	—	—

S = Season, D = Day after treatment, P = Product, R = Rate, A = Analyte

Table 1.7. DAT-by-active ingredient interaction on percent of active ingredient dislodged.

	1 DAT	2 DAT	4 DAT	8 DAT
		% dislodged of applied[a]		
Dicamba[b]	7.40	1.82	0.73	0.34
2,4-D[c]	17.30	4.99	1.77	0.51
$LSD_{(0.05)}$[d]		0.76		

[a] Data pooled over two experimental runs, two products, two rates, and four seasons. Dicamba applied at nominal rate = 78 and 118 g ae ha^{-1} for low and high application rates respectively. Recovery rate was 90 – 104% of nominal application rate across experimental runs. 2,4-D applied at nominal rate = 857 and 1110 g ae ha^{-1} for low and high application rates respectively. Measured spray application rate was 87 – 120% of nominal application rate across experimental runs. % of analyte dislodged of applied = average residue dislodged / total applied.

[b] Dicamba applied in the form of dimethylamine salt (DMA) and acid.

[c] 2,4-D applied in the form of dimethylamine (DMA) and ester salts.

[d] Fisher's Protected LSD conducted at P = 0.05.

Table 1.8. DAT-by-rate interaction on percent of dicamba dislodged.

	1 DAT	2 DAT	4 DAT	8 DAT
	% of dicamba dislodged of applied[a]			
78 g ae ha^{-1} [b]	6.78	1.58	0.64	0.55
118 g ae ha^{-1}	8.02	2.06	0.91	0.04
$LSD_{(0.05)}$[c]	0.72			

[a] Data pooled over two experimental runs, two products, and four seasons. Dicamba applied at nominal rate = 78 and 118 g ae ha^{-1} for low and high application rates respectively. Recovery rate was 90 – 104% of nominal application rate across experimental runs. % of dicamba dislodged of applied = average residue dislodged / total applied.
[b] Dicamba applied in the form of dimethylamine salt (DMA) and acid.
[c] Fisher's Protected LSD conducted at P = 0.05.

Table 1.9. DAT-by-rate interaction on percent of 2,4-D dislodged.

	1 DAT	2 DAT	4 DAT	8 DAT
	% of 2,4-D dislodged of applied[a]			
857 g ae ha^{-1} [b]	16.38	5.00	1.48	0.93
1110 g ae ha^{-1}	18.23	4.97	2.06	0.09
LSD $_{(0.05)}$[c]	1.26			

[a] Data pooled over two experimental runs, two products, and four seasons. 2,4-D applied at nominal rate = 857 and 1110 g ae ha^{-1} for low and high application rates respectively. Recovery rate was 87 – 120% of nominal application rate across experimental runs. % of 2,4-D dislodged of applied = average residue dislodged / total applied.

[b] 2,4-D applied in the form of dimethylamine (DMA) and ester salts.

[c] Fisher's Protected LSD conducted at P = 0.05.

Table 1.10. Product-by-rate-by-season interaction on percent of 2,4-D dislodged.[a]

	Trimec Classic[bc]		SpeedZone[de]	
	Low[f]	High[g]	Low	High
	% of 2,4-D dislodged of applied			
Winter	4.87	5.08	3.67	4.53
Spring	7.45	8.65	6.16	6.74
Summer	11.14	7.58	4.88	6.69
Fall	5.13	6.14	4.28	5.28
LSD $_{(0.05)}$[h]	1.78			

[a] Data pooled over two experimental runs. 2,4-D applied at nominal rate = 857 and 1110 g ae ha^{-1} for low and high application rates respectively. Recovery rate was 87 – 120% of nominal application rate across experimental runs. % of 2,4-D dislodged of applied = average residue dislodged / total applied, pooled across 3 reps and 2 runs.
[b] Trimec® Classic (PBI GORDON Corporation, Shawnee, KS, USA).
[c] 2,4-D in the form of dimethylamine salt (DMA).
[d] SpeedZone® (PBI GORDON Corporation, Kansas City, MO, USA).
[e] 2,4-D in the form of ester salt.
[f] 2,4-D applied at 857 g ae ha^{-1}.
[g] 2,4-D applied at 1110 g ae ha^{-1}.
[h] Fisher's Protected LSD conducted at P = 0.05.

Table 1.11. Product-by-rate-by-season interaction on percent of dicamba dislodged.[a]

	Trimec Classic[bc]		SpeedZone[de]	
	Low[f]	High[g]	Low	High
	% of dicamba dislodged of applied			
Winter	1.25	1.75	0.81	1.13
Spring	4.40	4.45	2.92	3.18
Summer	3.16	4.47	3.28	2.28
Fall	2.17	3.03	1.13	1.78
LSD $_{(0.05)}$[h]	NS[i]			

[a] Data pooled over two experimental runs. Dicamba applied at nominal rate = 78 and 118 g ae ha^{-1} for low and high application rates respectively. Recovery rate was 90 – 104% of nominal application rate across experimental runs. % of dicamba dislodged of applied = average residue dislodged / total applied, pooled across 3 reps and 2 runs.
[b] Trimec® Classic (PBI GORDON Corporation, Shawnee, KS, USA).
[c] Dicamba in the form of dimethylamine salt (DMA).
[d] SpeedZone® (PBI GORDON Corporation, Kansas City, MO, USA).
[e] Dicamba in the form of acid.
[f] Dicamba applied at 78 g ae ha^{-1}.
[g] Dicamba applied at 118 g ae ha^{-1}.
[h] Fisher's Protected LSD conducted at P = 0.05.
[i] NS indicates no statistically significant difference.

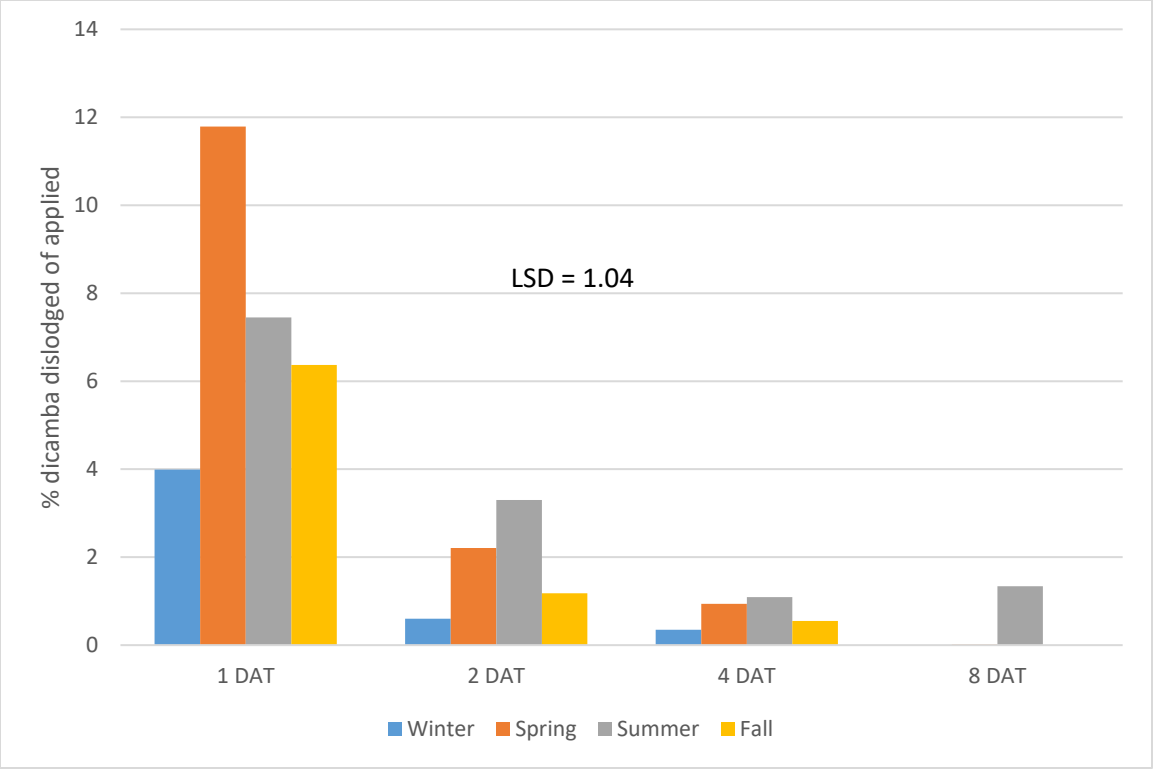

Figure 1.1. DAT-by-season interaction on percent of dicamba dislodged. Data pooled over two experimental runs, two products, and two rates. Dicamba applied at nominal rate = 78 and 118 g ae ha^{-1} for low and high application rates respectively. Recovery rate was 90 – 104% of nominal application rate across experimental runs. % of dicamba dislodged of applied = average residue dislodged / total applied. Dicamba applied in the form of dimethylamine salt (DMA) and acid. Fisher's Protected LSD conducted at P = 0.05.

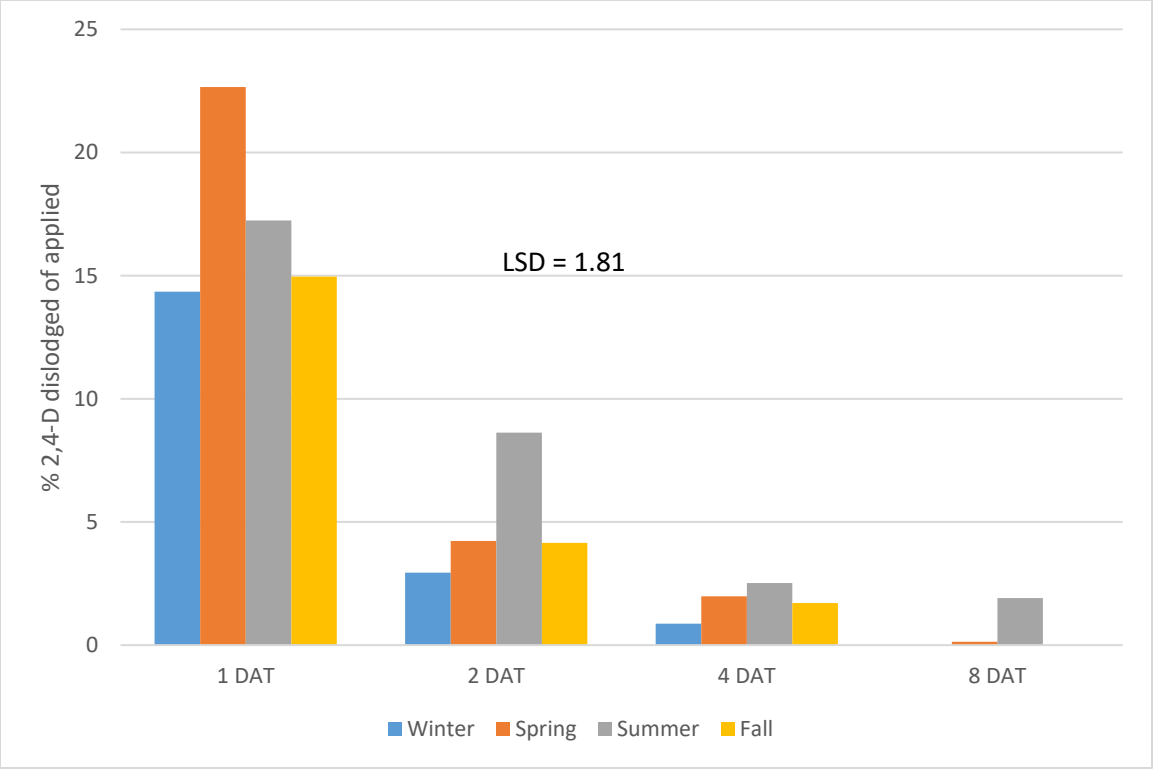

Figure 1.2. DAT-by-season interaction on percent of 2,4-D dislodged. Data pooled over two experimental runs, two products, and two rates. 2,4-D applied at nominal rate = 857 and 1110 g ae ha^{-1} for low and high application rates respectively. Recovery rate was 87 – 120% of nominal application rate across experimental runs. % of 2,4-D dislodged of applied = average residue dislodged / total applied. 2,4-D applied in the form of dimethylamine (DMA) and ester salts. Fisher's Protected LSD conducted at P = 0.05.

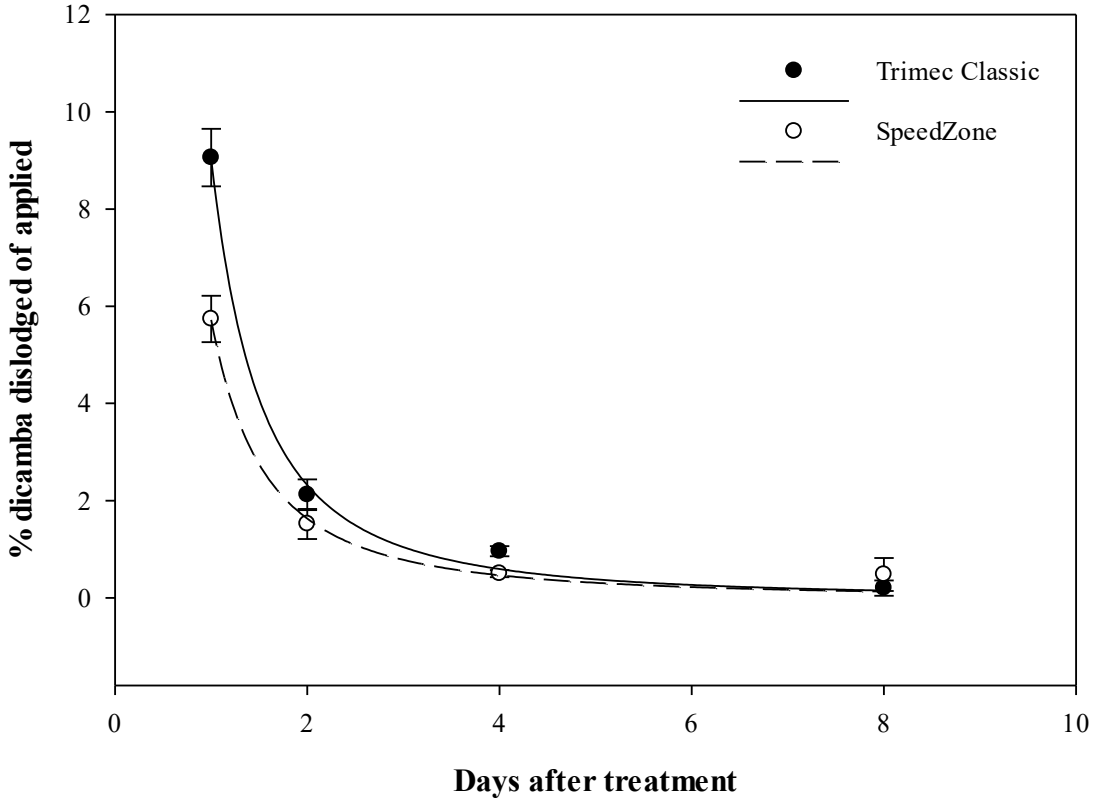

Figure 1.3. DAT-by-product interaction on percent of dicamba dislodged. Data pooled over two experimental runs, two rates, and four seasons. Dicamba applied at nominal rate = 78 and 118 g ae ha^{-1} for low and high application rates respectively. Recovery rate was 90 – 104% of nominal application rate across experimental runs. % of dicamba dislodged of applied = average residue dislodged / total applied.

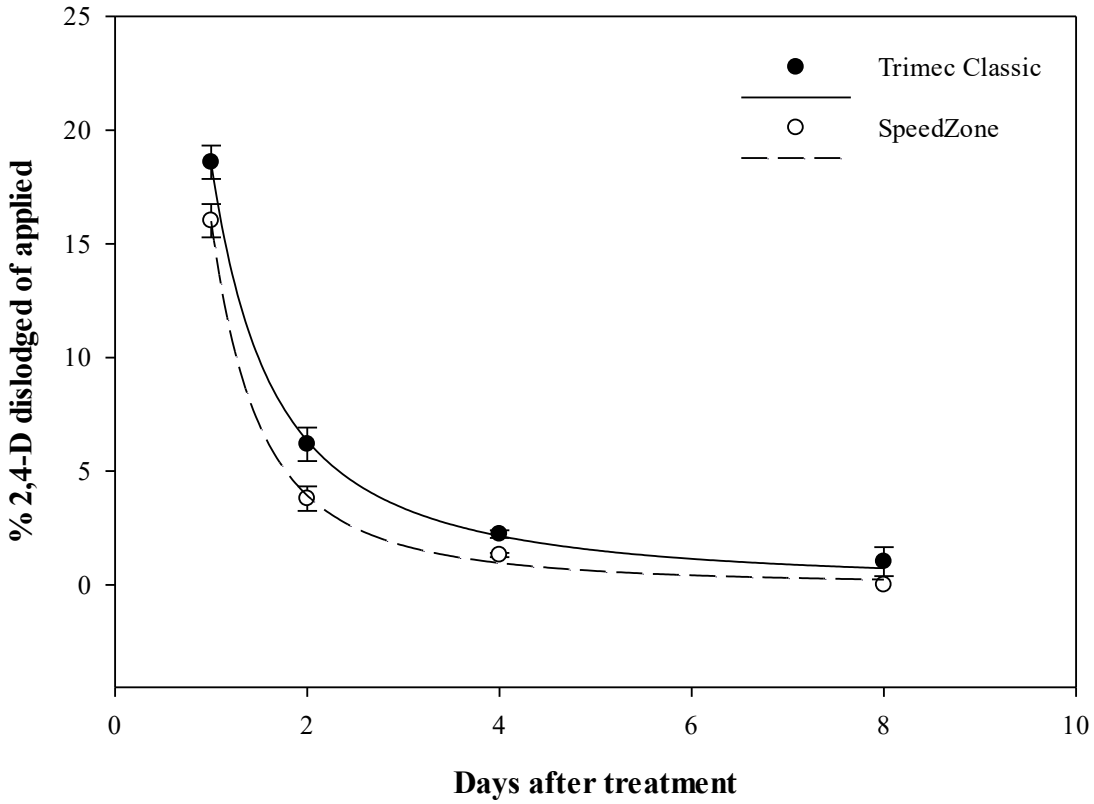

Figure 1.4. DAT-by-product interaction on percent of 2,4-D dislodged. Data pooled over two experimental runs, two rates, and four seasons. 2,4-D applied at nominal rate = 857 and 1110 g ae ha^{-1} for low and high application rates respectively. Recovery rate was 87 – 120% of nominal application rate across experimental runs. % of 2,4-D dislodged of applied = average residue dislodged / total applied.

CHAPTER 2

Characterizing herbicide lateral movement in turfgrass systems under saturated soil conditions

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Physicochemical characteristics of herbicides paired with edaphic conditions and mixtures of grass species often associated with heightened weed pressure in turfgrass lead to an increased propensity for herbicides to move laterally off-target, particularly in sloped landscapes and when herbicide applications are made to turfgrass systems under saturated soil conditions. The objective of this study was to evaluate the effects of simulated rainfall timing and amount on lateral herbicide movement following applications to turfgrass under saturated soil conditions. Field studies to characterize herbicide lateral movement were conducted in Raleigh and Jackson Springs, NC on dormant hybrid bermudagrass (*Cynodon dactylon* L. x *C. transvaalensis* Burtt Davy cv. 'Tifway 419') overseeded with perennial ryegrass (*Lolium perenne* L.). Trifloxysulfuron applications were made on an upslope herbicide-treated area of each plot to turfgrass under saturated soil conditions. Simulated rainfall events consisted of two post-application amounts (0.25 and 0.64 cm) and three timings (0, 24, and 72 h after herbicide application (HAHA)). Data pertaining to maximum distance of perennial ryegrass injury downslope of herbicide application and percent of perennial ryegrass exhibiting herbicide injury within an observation area directly downslope of herbicide-treated area were collected 6 weeks after treatment (WAT). No off-target damage was observed at either experimental run conducted in Jackson Springs, NC. Injury to perennial ryegrass was observed in Raleigh, NC a maximum

distance of 2.40 m downslope from spray swath in research plots receiving 0.64 cm of simulated rainfall and 1.59 m for plots receiving 0.25 cm of simulated rain. Additionally, simulated rainfall administered 0 HAHA resulted in visual herbicide injury 3.01 m off-target, while rainfall occurring 72 HAHA resulted in approximately 60% decrease in maximum distance of off-target damage. Greater than 70% of perennial ryegrass injury was observed within 330 cm from spray swath for plots receiving 0.64 cm of simulated rainfall immediately following herbicide application. Only 64% of injury was observed within 30 cm for plots receiving 0.64 cm of simulated rainfall 72 HAHA and no injury was observed beyond 120 cm in plots receiving 0.25 cm of simulated rainfall 72 HAHA. Data suggest damage caused by lateral movement of trifloxysulfuron and similar herbicides applied to turfgrass under saturated soil conditions can be greatly reduced by timing herbicide applications that avoid rain events for 72 h following herbicide application.

Introduction

Weeds are known to decrease functionality and aesthetics of landscapes, athletic fields, parks, and various other turfgrass systems. Weeds often exhibit reduced wear tolerance, shorter life cycles, and less consistent growth habits, resulting in increased risks for seasonal erosion and a general inability to maintain contiguous surfaces compared to turfgrass (McElroy & Martins, 2013). Pesticide-free weed control methods (e.g., cultural, biological, and mechanical) in turfgrass have limited efficacy and are often more labor intensive compared to chemical weed control (Jensen et al., 2014; Hahn et al., 2020). As a result, herbicides are an integral component of many effective integrated weed management programs (Owen et al., 2015).

Off-target pesticide movement is of particular importance when applications are made near people or their dwellings, often the location of highly managed turfgrass systems. Years of research focused developing management practices to reduce pesticide off-target movement into sensitive areas of increased human exposure such as groundwater (Mahoney et al., 2015; Smith & Bridges, 1996). Damage to sensitive fruit and vegetable gardens, vineyards, and various other landscapes is observed from unintended herbicide off-target movement (Branham & Lickfeldt, 1997; Busey et al., 2003; Read & Gamet, 2016). Lateral movement is a common way pesticides move off-target. Lateral movement can occur through surface runoff (Haith, 2010), subsurface lateral flow (Kahl et al., 2007; Peyrard et al., 2016), or a combination of these processes. Despite efforts, off-target lateral herbicide movement can occur following application. Off-target lateral herbicide movement has been noted in the contamination of surface water, with expressed concern regarding its impact on environmental quality (Cohen, 1999). Additionally, lateral herbicide movement can create undesirable, costly, and permanent damage if herbicides move into areas of susceptible turfgrass or ornamental species (Utah State University, n.d.)

Herbicide physicochemical characteristics, such as soil sorption affinity, water solubility, and chemical half-life, can provide information regarding the propensity of an herbicide to move laterally following application. Decreased soil sorption, increased water solubility, and increased persistence can equate to an increase in an herbicide's potential to move laterally off-target. Additionally, edaphic factors such as soil porosity and moisture can affect herbicide movement across or through the soil. Research conducted by Smith et al. (2002) showed that increasing soil volumetric water content (VWC) at application can increase pesticide movement via runoff. Furthermore, Brown et al. (2001) noted this increase in VWC can also increase pesticide movement through the soil via leaching. Weather conditions at and following pesticide application are a major factor in pesticide lateral movement (Haith & Duffany, 2007). Untimely or high intensity rains shortly following application can increase movement off application site, into sensitive areas.

Certain sulfonylurea herbicides such as trifloxysulfuron have proven highly effective in controlling many problematic turfgrass weeds such as annual bluegrass (*Poa annua* L.) (Breeden et al., 2017; Toler et al., 2007) and yellow nutsedge (*Cyperus esculentus* L.) (Burke et al., 2008; Gannon et al., 2012). Often, these and other problematic weeds thrive in areas with high VWC, posing a challenge for land managers attempting to control weeds chemically. Under certain environmental conditions, herbicides with physicochemical properties conducive to lateral movement should be used with caution to avoid off-target damage. Trifloxysulfuron (N-[(4,6-dimethoxy-2-pyrimidinyl)amino]carbonyl]-3-(2,2,2- trifluoroethoxy)-2-pyridinesulfonamide) was applied in this study due to its broad spectrum weed control as well as its activity on certain cool season turfgrass species (Anonymous, 2021). Trifloxysulfuron is an acetolactate synthase-inhibitor herbicide used for selective control of broadleaf and grassy weeds as well as sedges in

select turfgrass systems. Trifloxysulfuron is weakly sorbed to soils with a K_{oc} of 29-574 mL g^{-1} (Shaner, 2014). It is highly water soluble with a K_s of 5016 mg L^{-1} and has a moderate half-life (DT_{50} = 13-36 d) (Matocha & Senseman, 2007; Shaner, 2014). These characteristics suggest trifloxysulfuron and similar herbicides have a likelihood of movement laterally on and through soil, particularly when herbicide applications are made to saturated soil conditions.

The objective of this study was to better characterize herbicide lateral movement in turfgrass under saturated soil conditions as it relates to timing and amount of simulated rainfall being added to the turfgrass system following herbicide application. In doing so, this data can be used to develop best management practices to guide applicators in treating problem weeds while minimizing risks of off-target herbicide movement into sensitive areas. We hypothesize that avoiding simulated rainfall events for 72 h following application will reduce lateral herbicide movement. Furthermore, we hypothesize that reducing the amount of simulated rainfall will result in less distance and amount of downslope visual herbicide injury compared to plots receiving heavier simulated rainfall events.

Materials and Methods

Site Description

Field studies were conducted at Lake Wheeler Turfgrass Field Lab in Raleigh, NC (35°44’28.3”N 78°40’47.7”W) and at Sandhills Research Station in Jackson Springs, NC (35°11’16.8”N 79°40’11.6”W) from November of 2020 to May of 2021. Lake Wheeler Turfgrass Field Lab plots consisted of a Cecil sandy loam (fine, kaolinitic, thermic Typic Kanhapludult) soil with 33.2% clay, 23.8% silt, 43.0% sand, pH of 6.6, and 9.5% slope. Organic matter content was approximately 5.59% by weight in the top 7.6 cm. Sandhills Research Station plots consisted of Candor sand (sandy, kaolinitic, thermic Grossarenic Kandiudults) soil with 9%

clay, 7.1% silt, 83.9% sand, pH of 6.4, and 7.8% slope. Organic matter content was approximately 4.18% by weight in the top 7.6 cm.

At both locations, trials were conducted on dormant hybrid bermudagrass (*Cynodon dactylon* L. x *C. transvaalensis* Burtt Davy, cv. 'Tifway 419') overseeded with perennial ryegrass (*Lolium perenne* L.) (Pure Sport Perennial Ryegrass Blend, Pure Seed, Canby, OR, USA) at 976 kg seed ha^{-1}. Perennial ryegrass served as a downslope bioindicator for lateral movement due to its sensitivity to trifloxysulfuron deposited by herbicide runoff (Jester et al., 2022). Ryegrass seed blend consisted of 33.38% 'Carly', 32.78% 'Brightstar SLT', and 32.72% 'Estelle' perennial ryegrass. Overseed was applied to entire research area on 26 August 2020 for experiments initiated on 3 November 2020 and 5 April 2021 at Sandhills Research Station. Overseed was applied on 27 August 2020 and 25 February 2021 for experiments initiated on 4 November 2020 and 6 April 2021, respectively, at Lake Wheeler Turfgrass Field Lab. Plots consisted of an upslope herbicide-treated area measuring 2.13 wide by 1.22 m long and an observation area, immediately downslope of the herbicide-treated area, measuring 2.13 m wide by 3.35 m long, with long side of plots oriented in line with predominant slope. Plots were maintained at 5 cm height of cut until experiment initiation, at which time mowing was withheld until completion of experimental run.

Experimental Design

Experiments were conducted as a complete randomized block design with four replicates of a 2-by-3 factorial arrangement for each run. Two experimental runs were conducted at each location. Factor combinations consisted of 2 post-application simulated rainfall amounts (0.25 and 0.64 cm) and 3 simulated rainfall timings (0, 1, and 3 d after treatment (DAT)). Rainfall timings of 0, 1, and 3 DAT correspond to 0 (immediate), 24, and 72 hours after herbicide

application (HAHA). A nontreated experimental control was included in each experimental block.

Experiment Initiation

Perennial ryegrass was mown, clippings collected, and research areas were irrigated 48 h prior to initiation. Beginning 24 h prior to initiation, irrigation was applied using overhead irrigation to bring soil to saturation. VWC was monitored utilizing FieldScout^{TM} 300 TDR Soil Moisture Meter (Spectrum Technologies, Inc., Aurora, IL, USA) fitted with 7.6 cm probes. Plot irrigation schedules continued until herbicide application, targeting soil saturation (48% and 40% VWC +/- 3% at Lake Wheeler Turfgrass Field Lab and Sandhills Research Station, respectively). At 1400 h on the day of experiment initiation, trifloxysulfuron (Monument 75WG®; Syngenta, Greensboro, NC) was applied to upslope, herbicide-treated areas of each water-saturated plot at the maximum labeled single application rate of 27.8 g ai ha^{-1} with a non-ionic surfactant (0.25% v v^{-1}). Herbicide applications were performed using a hand-held CO_2-pressurized sprayer equipped with four XR 8003 VS flat-fan nozzles (TeeJet Flat-Fan Nozzles®, Spraying Systems Co., Wheaton, IL) calibrated to deliver 405 L ha^{-1}, consistent with common herbicide application carrier volumes used by turfgrass managers. A spray barrier comprised of corrugated plastic sheeting was utilized during herbicide application to prevent overspray into the downslope, observation area of plots.

Following herbicide application, simulated rainfall was administered using a hand-held irrigation wand equipped with a digital water meter (Great Plains Industries, Inc.; Wichita, KS, USA) to deliver precise irrigation amounts to entire plots (treated and downslope observation areas) corresponding to simulated rainfall timing and amount. Post-application simulated rainfall was administered at an approximate rate of 2.58 L m^{-2} per 5 minutes. No additional irrigation

was administered to plots until 5 d after herbicide application, at which time irrigation was supplemented to maintain plant health. For research conducted at Lake Wheeler Turfgrass Field Lab, soil VWC was 42 – 46% 0 HAHA, 35 – 42% 24 HAHA, and 24 – 42% at 72 HAHA simulated rainfall event. Decrease in soil VWC occurred more rapidly at Sandhills Research Station with 38 – 39%, 26 – 27%, and 19 – 26% at 0, 24, and 72 HAHA, respectively, simulated rainfall events.

Visual injury of perennial ryegrass was estimated weekly for weeks 1 through 6. Six weeks after treatment (WAT), grid count data were collected using modified methods previously described by Leon et al. (2016) to quantify percent of area exhibiting visual herbicide injury in downslope, observation area of each plot. Grids consisted of 495 10 by 10 cm cells. Cells containing visual injury consistent with herbicidal damage were noted and percent of area exhibiting visual injury downslope was calculated using the equation:

% area exhibiting injury = ([number of cells exhibiting herbicide injury / total cells in observation area] x 100)

Distance of visual herbicide damage in observation area was measured from the edge of treated area to the bottom edge of visually damage perennial ryegrass using fiberglass measuring tape. Maximum distance (m) of herbicide injury from edge of spray swath was recorded for each plot.

Statistical Analysis

Lateral movement data from trials conducted at Lake Wheeler Turfgrass Field Lab were subjected to analysis of variance (P=0.05) using GLIMMIX procedures in SAS (Statistical

Analysis Software®, Version 9.2; SAS Institute, Inc., Cary, NC, USA). Main effects and the interactions between simulated rainfall amount, simulated rainfall timing, and experimental run were tested as fixed effects. Following initial analysis, treatments were pooled over runs as the effect of experimental run was not significant. Replicate was considered random effect. Simulated rainfall events were further analyzed as unique combinations of simulated rainfall amount and timing, representing real world precipitation events. Percent of area exhibiting herbicide damage was calculated for each unique combination of simulated rainfall amount and timing in (11) 30 cm increments downslope from spray swath. Means were separated using Fisher's Protected LSD at P=0.05.

Results and Discussion

No injury to perennial ryegrass downslope of application area was observed for either run conducted at Sandhills Research Station [Candor sand (sandy, kaolinitic, thermic Grossarenic Kandiudults)] (Table 2.1). This suggests that there is limited risk of off-target damage to similarly sensitive species when herbicides with similar physicochemical characteristics to trifloxysulfuron are applied within labeled rate to soils under comparable edaphic conditions, slope ≤ 7.8%, and when rain events following application are ≤ 0.64 cm. Because no off-target injury was observed at this location, data from Sandhills Research Station were omitted from subsequent data analysis.

Differences in injury downslope between the two locations are consistent with previous research. In research surrounding pesticide transport through field soils, Flury (1996) discusses the inverse relationship between pesticide leaching and runoff. As leaching potential of a pesticide within a soil increases, runoff potential decreases. While investigating effects of soil texture on leaching potential of pesticides, Fogg et al. (2004) found pesticide leaching potential

to be greater in sandy soils compared to soils with higher silt and clay concentrations. The leaching of herbicide through the courser textured soil at Sandhills Research Station may have contributed to the reduced lateral herbicide movement resulting in lack of visual damage to perennial ryegrass in the downslope area at this research location. Furthermore, consistent with research conducted by Want et al. (2021), the more rapid decrease in soil VWC in sandy soil at Sandhills Research Station may have contributed in the differences in observed off-target injury as a result of simulated rainfall events occurring at lower VWC at Sandhills Research Station.

Injury to perennial ryegrass downslope of application area was observed at Lake Wheeler Turfgrass Field Lab [Cecil sandy loam (fine, kaolinitic, thermic Typic Kanhapludult)]. This suggests potentially elevated risk of off-target damage due to lateral herbicide movement when trifloxysulfuron and herbicides with similar physicochemical properties are applied to turfgrass systems under similar edaphic conditions when rain events are expected in the amount of ≥ 0.25 cm within the first days following application. Lateral trifloxysulfuron movement off-target was influenced by both simulated rainfall timing and amount (Table 2.2). As there was no statistical difference between experimental runs, subsequent analyses pooled data across runs. No contamination was observed between adjacent plots.

Not surprisingly, damage caused by lateral herbicide movement was greater at Lake Wheeler Turfgrass Field Lab when simulated rainfall was administered at 0.64 cm compared to 0.25 cm (Tables 2.3 and 2.4). Injury to perennial ryegrass was observed a maximum distance of 2.40 m downslope from the edge of herbicide application swath for plots receiving 0.64 cm of simulated rain. This was different from and more than 50% greater than the maximum distance of 1.59 m downslope for plots receiving 0.25 cm of simulated rainfall. When considering the percentage of area damaged within the downslope observation area, 46.67% of the observation

area exhibited off-target injury to perennial ryegrass consistent with herbicide damage for research plots receiving 0.64 cm of simulated rainfall. This is greater than the observed 28.50% of area exhibiting injury for research plots receiving 0.25 cm of simulated rain.

These data are consistent with research findings of Potter et al. (2014), who observed greater pesticide runoff in peanut production during months with greater average rainfall totals (August and September) compared to months with lower average rainfall totals (May). Modeling of shallow lateral overland flow within soil showed an increase in subsurface lateral flow with increased rainfall intensities (Sarkar & Dutta, 2015). Results from this study coincide with prior research, suggesting a positive correlation between increased runoff and subsurface lateral flow of pesticides with an increase in rainfall amount.

Data showed that the time at which simulated rainfall was applied affected distance of off-target visual damage downslope from the upslope herbicide-treated spray swath (Table 2.5). Simulated rainfall administered immediately following herbicide application resulted in maximum visual injury of 3.01 m off-target, while simulated rain 24 HAHA resulted in less herbicide movement with a 37% decrease in distance with a maximum of 1.89 m. Less movement was observed at 72 HAHA with a maximum distance of 1.09 m. When comparing percentages of downslope damage across days, a decrease in visual off-target injury was observed as simulated rainfall events occurred further from time of herbicide application (Table 2.6). An average of 69.38% of downslope observation area exhibited off-target injury to perennial ryegrass for simulated rainfall events occurring immediately following herbicide treatment. Events occurring 24 HAHA resulted in less injury with 31.25% of downslope area exhibiting downslope injury. Less downslope area exhibited injury at 72 HAHA, with 12.13% downslope area injury.

Previous research supports these findings. Increasing the interval between time of herbicide application and rainfall runoff event has been shown to reduce losses of herbicide due to surface runoff (Baker & Mickelson, 1994). Adsorption greatly reduces lateral herbicide movement by limiting plant available herbicides within soils (Carter, 2020). Additionally, studies have found by increasing the interval between herbicide application and rainfall event, increased soil adsorption may occur. Research conducted by Walker et al. (1999) found adsorption equilibrium of herbicides may not be reached until after 24 HAHA.

To further characterize the effect of rainfall amount and timing on the lateral herbicide movement, each combination of simulated rainfall amount and timing was analyzed as a unique event, as they would occur in typical turfgrass management situations. Data showed 83.70% of downslope observation area exhibited ryegrass injury when 0.64 cm of simulated rainfall was administered immediately following herbicide application to saturated soil. This is greater compared to 55.00% when 0.25 cm simulated rainfall was administered immediately after herbicide application (Figure 2.1). Both simulated rainfall events produced greater percentages compared to plots receiving 0.64 cm of simulated rainfall 24 HAHA (39.00%). This was similar to the 23.50% injury observed in plots receiving 0.25 cm of simulated rainfall 24 HAHA. Similar to plots receiving 0.25 cm 24 HAHA, at 72 HAHA 17.30% and 7% of downslope damage were observed for plots receiving 0.64 and 0.25 cm of simulated rainfall, respectively. Furthermore, there was no significant difference between percent of downslope area exhibiting visual herbicide injury for research plots receiving 0.25 cm of simulated rain 72 HAHA and the nontreated control which exhibited no herbicide injury. Visual observations of distance moved followed similar trends with maximum observed injury occurring 3.35 m off-target and downslope for plots receiving 0.64 cm immediately following herbicide application (Figure 2.2).

Distance of movement in plots receiving 0.25 cm of simulated rainfall 0 HAHA were similar at 2.67 m off-target. Similar to observations from 0.25 cm and less than 0.64 cm 0 HAHA, 2.36 m of off-target damage was observed for 0.64 cm of simulated rainfall at 24 HAHA. Maximum movement of 1.41 m was observed for 0.25 cm simulated rainfall 24 HAHA, similar to movement observed for plots receiving 0.64 cm simulated rainfall 24 HAHA. Maximum movement at 72 HAHA was not different from 0.25 cm 24 HAHA with maximum distance of observed injury 1.49 and 0.69 m for plots receiving 0.64 and 0.25 cm of simulated rainfall, respectively. Similarly, there was no significant difference between distance of observed movement for plots receiving 0.25 cm of simulated rainfall 3 DAT and the nontreated control which exhibited no observed off-target injury.

By delineating percent of downslope area exhibiting herbicide injury by distance from spray swath, we see > 70% injury at distances through 330 cm for plots receiving 0.64 cm simulated rainfall 0 HAHA (Table 2.7). Injury for this simulated rainfall event was greater than all other rainfall events for observation areas 181 through 330 cm from edge of spray swath. Less than 50% of area exhibited herbicide injury beyond 180 cm for plots receiving 0.25 cm 0 HAHA. Additionally, less than 50% of area exhibited injury beyond 60 cm for plots receiving simulated rainfall events 24 HAHA at both rainfall amounts. Less area exhibited injury compared to 0.25 cm events 0 HAHA at distances between 31 and 180 cm from edge of spray swath. At 72 HAHA, approximately 64% of area exhibited herbicide injury between 0 and 30 cm and approximately 38% of area exhibiting injury for plots receiving 0.64 and 0.25 cm of simulated rainfall, respectively.

While there are situations with zero tolerance for lateral movement of herbicide outside of the spray swath, data suggest that under conditions comparable to those tested in these studies,

there is limited risk for substantial damage caused by lateral movement > 1 m off-target to perennial ryegrass or similarly sensitive species when rainfall events are avoided for 72 h after herbicide application and deliver precipitation ≤ 0.25 cm within tested experimental parameters. Avoiding rainfall for the first 24 HAHA resulted in less than half of the downslope area exhibiting herbicide injury compared to injury observed for rainfall occurring immediately following herbicide application at both simulated precipitation amounts. Furthermore, distance of visual damage downslope was reduced by 0.99 and 1.26 m by delaying simulated rainfall event for 24 h compared to rainfall movement events occurring immediately following herbicide application. By timing herbicide applications such that rain events are not expected in the days immediately following herbicide application and utilizing buffer areas between treated areas and sensitive environments such as those described by Cole et al. (1997), applicators can greatly reduce risks associated with off-target damage cause by lateral herbicide. As made evident by the differences in findings between experimental locations within this study and through prior research conducted by Haith et. al (2008), each combination of pesticide and site is unique, resulting in variable levels of risk for lateral movement of pesticides between locations. Future research evaluating additional herbicides, soil textures, organic matter contents, and weather conditions will be critical in better understanding factors influencing surface runoff and subsurface lateral flow.

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Table 2.1. Effect of simulated rainfall movement event on percent of area exhibiting visual herbicide injury in perennial ryegrass (*Lolium perenne*) downslope of trifloxysulfuron applied to turfgrass under saturated soil conditions at Sandhills Research Station, Jackson Springs, NC.[a]

Simulated rainfall event	% area exhibiting injury[b]
0.25 cm 0 DAT[cd]	0
0.64 cm 0 DAT	0
0.25 cm 1 DAT	0
0.64 cm 3 DAT	0
0.25 cm 1 DAT	0
0.64 cm 3 DAT	0
Control	0

[a] Trifloxysulfuron-sodium applied as Monument® 75WG (Syngenta Crop Protection, LLC, Greensboro, NC, USA) at 27.8 g ai ha^{-1} with non-ionic surfactant (0.25% v v^{-1}) to turfgrass at 40% volumetric water content +/- 3%. Data pooled over two experimental runs conducted at Sandhills Research Station, Jackson Springs, NC [Candor sand (sandy, kaolinitic, thermic Grossarenic Kandiudults)]. Data collected 42 d after herbicide application.
[b] % area exhibiting injury calculated using 10 x 10 cm grids downslope of treated area where % area exhibiting injury = (number of cells containing ryegrass exhibiting visual herbicide damage / total number of cells) x 100)) in 2.1 x 3.4 m downslope evaluation area.
[c] Simulated movement event describes a unique combination of irrigation amount and irrigation timing applied to research plot.
[d] DAT = days after trifloxysulfuron treatment where 0 DAT represents simulated rainfall added immediately following herbicide application.

Table 2.2. Partial ANOVA for visual injury in perennial ryegrass (*Lolium perenne*) downslope of trifloxysulfuron applied to turfgrass under saturated soil conditions at Lake Wheeler Turfgrass Field Lab, Raleigh, NC.

		Maximum distance of damage		% area exhibiting injury	
Source of variation	Df	F-value	Pr > F	F-value	Pr > F
Experimental run (R)	1	0.01	0.9091	2.68	0.1113
Rainfall amount (A)	1	10.57	0.0026	14.71	0.0005
A x R	1	2.64	0.1135	1.23	0.2757
Rainfall timing (T)	2	19.94	<0.0001	50.49	<0.0001
T x R	2	1.04	0.3646	1.34	0.2757
T X A	2	0.10	9.091	1.35	0.2730
A x T x R	2	0.03	0.9670	0.06	0.9450

R = experimental run, R = rainfall amount, T = rainfall timing

Table 2.3. Effect of simulated rainfall amount on maximum distance of visual herbicide damage in perennial ryegrass (*Lolium perenne*) downslope of trifloxysulfuron applied to turfgrass under saturated soil conditions.[a]

Simulated rainfall amount (cm)	Maximum distance of damage downslope (m)
0.25	1.59
0.64	2.40
LSD $_{(0.05)}$[b]	0.50

[a] Trifloxysulfuron-sodium applied as Monument® 75WG (Syngenta Crop Protection, LLC, Greensboro, NC, USA) at 27.8 g ai ha^{-1} with non-ionic surfactant (0.25% v v^{-1}) to turfgrass at 48% volumetric water content +/- 3%. Data pooled over three simulated rainfall timings and two experimental runs conducted at Lake Wheeler Turf Field Lab, Raleigh, NC [Cecil sandy loam (fine, kaolinitic, thermic Typic Kanhapludult)]. Data collected 42 d after herbicide application.

[b] Fisher's Protected LSD conducted at P = 0.05.

Table 2.4. Effect of simulated rainfall amount on percent of area exhibiting visual herbicide injury in perennial ryegrass (*Lolium perenne*) downslope of trifloxysulfuron applied to turfgrass under saturated soil conditions.[a]

Simulated rainfall amount (cm)	% area exhibiting injury[b]
0.25	28.50
0.64	46.67
LSD $_{(0.05)}$[c]	10.71

[a] Trifloxysulfuron-sodium applied as Monument® 75WG (Syngenta Crop Protection, LLC, Greensboro, NC, USA) at 27.8 g ai ha^{-1} with non-ionic surfactant (0.25% v v^{-1}) to turfgrass at 48% volumetric water content +/- 3%. Data pooled over three simulated rainfall timings and two experimental runs conducted at Lake Wheeler Turf Field Lab, Raleigh, NC [Cecil sandy loam (fine, kaolinitic, thermic Typic Kanhapludult)]. Data collected 42 d after herbicide application.

[b] % area exhibiting injury calculated using 10 x 10 cm grids downslope of treated area where % area exhibiting injury = ((number of cells containing perennial ryegrass exhibiting visual herbicide damage / total number of cells) x 100) in 2.1 x 3.4 m downslope evaluation area.

[c] Fisher's Protected LSD conducted at P = 0.05.

Table 2.5. Effect of simulated rainfall timing on maximum distance of visual herbicide damage in perennial ryegrass (*Lolium perenne*) downslope of trifloxysulfuron applied to turfgrass under saturated soil conditions.[a]

Days after herbicide application	Maximum distance of damage downslope(m)
0[b]	3.01
1	1.89
3	1.09
LSD $_{(0.05)}$[c]	0.61

[a] Trifloxysulfuron-sodium applied as Monument® 75WG (Syngenta Crop Protection, LLC, Greensboro, NC, USA) at 27.8 g ai ha^{-1} with non-ionic surfactant (0.25% v v^{-1}) to turfgrass at 48% volumetric water content +/- 3%. Data pooled over two simulated rainfall amounts and two experimental runs conducted at Lake Wheeler Turf Field Lab, Raleigh, NC [Cecil sandy loam (fine, kaolinitic, thermic Typic Kanhapludult)]. Data collected 42 d after herbicide application.

[b] 0 days after herbicide application represents simulated rainfall added immediately following herbicide application.

[c] Fisher's Protected LSD conducted at P = 0.05.

Table 2.6. Effect of simulated rainfall timing on percent of area exhibiting visual herbicide injury in perennial ryegrass (*Lolium perenne*) downslope of trifloxysulfuron applied to turfgrass under saturated soil conditions.[a]

Days after herbicide application	% area exhibiting injury[b]
0[c]	69.38
1	31.25
3	12.13
LSD $_{(0.05)}$[d]	13.11

[a] Trifloxysulfuron-sodium applied as Monument® 75WG (Syngenta Crop Protection, LLC, Greensboro, NC, USA) at 27.8 g ai ha^{-1} with non-ionic surfactant (0.25% v v^{-1}) to turfgrass at 48% volumetric water content +/- 3%. Data pooled over two simulated rainfall amounts and two experimental runs conducted at Lake Wheeler Turf Field Lab, Raleigh, NC [Cecil sandy loam (fine, kaolinitic, thermic Typic Kanhapludult)]. Data collected 42 d after herbicide application.

[b] % area exhibiting injury calculated using 10 x 10 cm grids downslope of treated area where % area exhibiting injury = (number of cells containing ryegrass exhibiting visual herbicide damage / total number of cells) x 100)) in 2.1 x 3.4 m downslope evaluation area.

[c] 0 days after herbicide application represents simulated rainfall added immediately following herbicide application.

[d] Fisher's Protected LSD conducted at P = 0.05.

Table 2.7. Effect of simulated rainfall event on percentage of downslope area exhibiting visual herbicide injury in perennial ryegrass (*Lolium perenne*) by distance from spray swath of trifloxysulfuron applied to turfgrass under saturated soil conditions.[a]

		Distance from edge of spray swath (cm)										
		0 – 30	31-60	61 – 90	91 – 120	121 – 150	151 – 180	181 – 210	211 – 240	241 – 270	271 – 300	301 – 330
Irrigation amount (cm)[c]	Days after herbicide application[d]	% area exhibiting injury[b]										
0.25	0	91.68	86.11	83.89	76.68	68.61	62.49	46.95	29.18	22.79	19.44	20.83
0.25	1	66.67	62.23	37.78	22.51	11.68	8.34	8.05	9.16	11.11	9.45	10.00
0.25	3	37.79	23.90	11.13	3.34	0	0	0	0	0	0	0
0.64	0	97.50	96.11	90.01	87.79	84.15	82.79	81.10	79.01	75.84	75.28	74.16
0.64	1	77.50	53.34	48.61	38.89	32.78	31.68	32.21	32.23	31.38	30.28	24.99
0.64	3	64.43	46.65	31.39	14.71	11.10	7.49	5.00	4.18	0.84	0.84	0.84
LSD $_{(0.05)}$[e]		21.02										

[a] Trifloxysulfuron-sodium applied as Monument® 75WG (Syngenta Crop Protection, LLC, Greensboro, NC, USA) at 27.8 g ai ha^{-1} with non-ionic surfactant (0.25% v v^{-1}) to turfgrass at 48% volumetric water content +/- 3%. Data pooled over two experimental runs conducted at Lake Wheeler Turf Field Lab, Raleigh, NC [Cecil sandy loam (fine, kaolinitic, thermic Typic Kanhapludult)]. Data collected 42 d after herbicide application.

[b] % area exhibiting injury calculated using 10 x 10 cm grids downslope of treated area where % area exhibiting injury = (number of cells containing ryegrass exhibiting visual herbicide damage / total number of cells) x 100)).

[c] Simulated movement event describes a unique combination of irrigation amount and irrigation timing applied to research plot.

[d] 0 days after herbicide application represents simulated rainfall administered immediately following herbicide application.

[e] Fisher's Protected LSD conducted at P = 0.05.

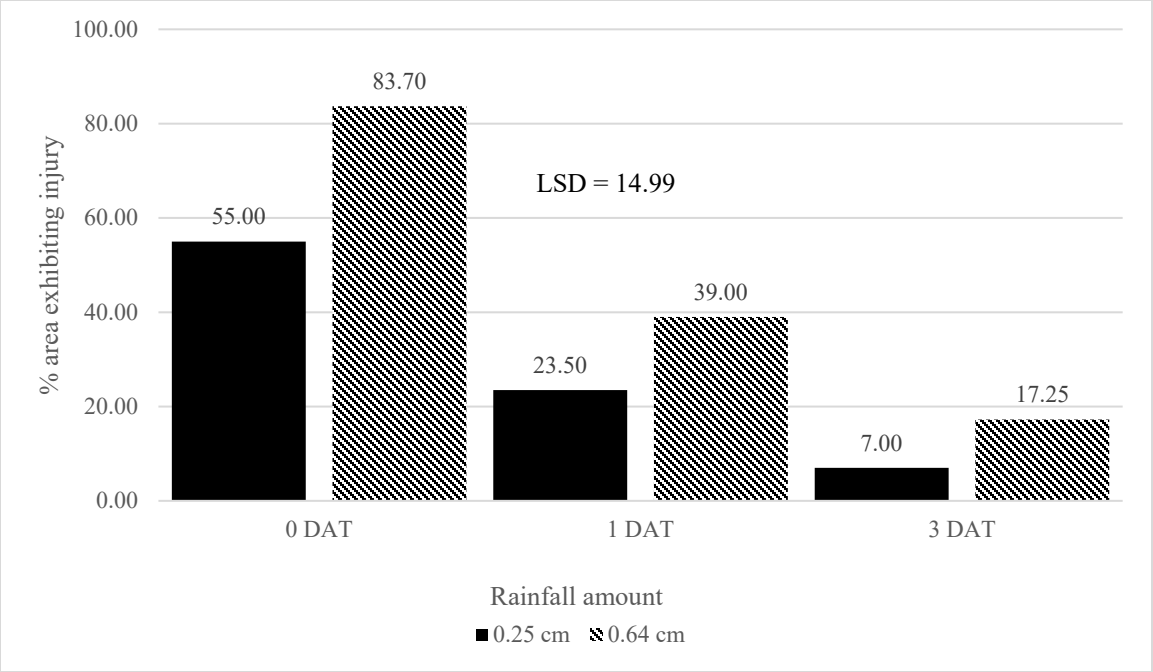

Figure 2.1. Effect of simulated rainfall event on percent of visual damage in perennial ryegrass (*Lolium perenne*) downslope of trifloxysulfuron applied to turfgrass under saturated soil conditions at Lake Wheeler Turfgrass Field Lab, Raleigh, NC [Cecil sandy loam (fine, kaolinitic, thermic Typic Kanhapludult)]. DAT = days after trifloxysulfuron treatment where 0 DAT represents simulated rainfall added immediately following herbicide application. Fisher's Protected LSD conducted at P = 0.05.

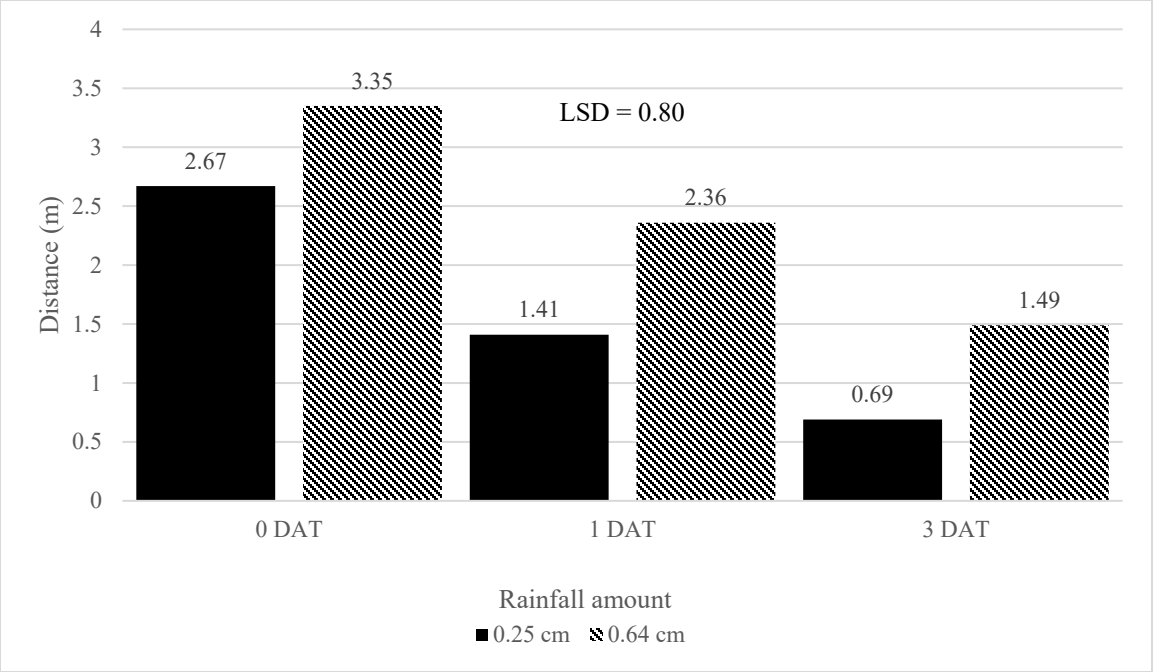

Figure 2.2. Effect of simulated rainfall event on maximum distance of visual damage in perennial ryegrass (*Lolium perenne*) downslope of trifloxysulfuron applied to turfgrass under saturated soil conditions Lake Wheeler Turfgrass Field Lab, Raleigh, NC [Cecil sandy loam (fine, kaolinitic, thermic Typic Kanhapludult)]. DAT = days after trifloxysulfuron treatment where 0 DAT represents simulated rainfall added immediately following herbicide application. Fisher's Protected LSD conducted at P = 0.05.

CHAPTER 3

Use of irrigation following herbicide applications to reduce off-target lateral movement

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Despite a propensity for certain herbicides to move laterally on and through soil, prior research suggests that lateral movement may be reduced if herbicide is irrigated into thatch prior to rainfall movement events. Field studies were conducted in Raleigh, NC on dormant hybrid bermudagrass (*Cynodon dactylon* L. x *C. transvaalensis* Burtt Davy, cv. 'Tifway 419') overseeded with a perennial ryegrass blend (*Lolium perenne* L.) to determine if light post-application irrigation schedules could reduce distance and severity of off-target damage caused by lateral movement of herbicides. Trifloxysulfuron applications were made to an upslope herbicide-treated area of each plot to turfgrass under saturated soil conditions. Treatments consisted of three irrigation schedules (PM, AM, PM + AM), each delivering a total of 0.127 cm irrigation, as well as a plot receiving herbicide but no irrigation prior to a simulated rain event. A simulated rain event occured 24 h after herbicide application, delivering 1.9 cm irrigation over 6 h. Data pertaining to maximum distance of visual herbicide injury to perennial ryegrass downslope and percent area exhibiting injury within observation area directly downslope of herbicide-treated area were collected 6 weeks after treatment (WAT). Damage was observed 2.17 m downslope from herbicide application in plots receiving no post-application irrigation prior to simulated movement event. Distance of visual damage was reduced by 53% when light irrigation was administered in the afternoon, 3 h following herbicide application. Distance of visual damage was reduced by 72% when light irrigation was administered at 0730 h the

following morning and by 79% when split between 3 h following herbicide application and 0730 h the following morning. Data pertaining to percent of downslope area exhibiting herbicide injury follow similar trends. Plots receiving post-application irrigation contained < 20% of downslope area exhibiting herbicide injury beyond 90 cm. Plots not receiving post-application irrigation prior to simulated movement event contained ≥ 20% observed herbicide injury through 330 cm from spray swath. Findings of this study suggest that light post application reduces distance and severity of damage caused by lateral movement of trifloxysulfuron.

Introduction

Lateral movement of pesticides applied to turfgrass is a concern for potential negative impacts to the health of surrounding sensitive ecosystems (Haith, 2010; Haith & Rossi, 2003; Leon, 2016). Herbicides, when applied to sloped surfaces, can move laterally through surface runoff (Rosenthal & Hipp, 1993; Watschke et al., 1999), as a result of subsurface flow through soils (Kahl et al., 2007; Peyrard et al., 2016; Potter et al., 2015), or a combination of both. Lateral movement potential in soil is impacted by the affinity of an herbicide to adsorb to soil particles and organic matter, an herbicide's water solubility, soil texture, soil organic matter content, landscape topography, and frequency, amount, and intensity of irrigation and rainfall events (Gish et al., 2011; Müller et al., 2006). Research conducted by Cohen et al. (1999) found lateral movement of pesticides leading to concerning groundwater contamination. Under conducive environmental conditions, movement of certain herbicides into sensitive ornamental plants, turfgrass species, or waterbodies such as ponds and creeks can create costly damage, adversely affecting aesthetics and ecological networks (Haith, 2010; Haith & Rossi, 2003; Rice et al., 2010).

Herbicide use has remained an important component of weed management in turfgrass systems due to time, efficacy, and cost efficiencies compared to herbicide-free management approaches (Hahn, 2020). Americans spent an estimated $910 million USD on synthetic herbicides for use in non-agricultural settings in 2012 (Atwood & Paisley-Jones, 2017). Balancing the contrasting realities between turf managers' reliance upon synthetic herbicides and acknowledgement of concern surrounding off-target movement into sensitive environments requires that pesticide applicators understand factors that contribute to increased risks of off-target movement and implement practices to reduce these risks. While lateral herbicide

movement can occur under several environmental conditions, movement from herbicide applications on sloped terrain present additional risks. This research focuses on reducing risks associated with herbicide use in sloped environments, although many factors may be applicable in other scenarios.

Several herbicide active ingredients commonly used in turfgrass management have been found to move laterally under certain environmental conditions (Lee et al., 2000, Leon et al., 2016; Rice et al., 2010). Trifloxysulfuron (N-[(4,6-dimethoxy-2-pyrimidinyl)amino]carbonyl]-3-(2,2,2- trifluoroethoxy)-2-pyridinesulfonamide) was applied in this study due to its control of an array of problematic weeds as well as its activity on certain cool-season grasses (Anonymous, 2021). Trifloxysulfuron is an acetolactate synthase-inhibitor herbicide commonly used for selective control of broadleaf and grassy weeds as well as sedge species in select turfgrass systems. This herbicide is weakly sorbed to organic matter in soils with a K_{oc} of 29-574 mL g^{-1}, highly water soluble with a K_s of 5016 mg L^{-1} and has a moderate half-life (DT_{50} = 13-36 d) (Matocha & Senseman, 2007; Shaner, 2014). These characteristics suggest trifloxysulfuron may move laterally on and through soil, particularly when herbicide applications are made to turfgrass systems under saturated soil conditions.

Irrigating root absorbed herbicides after application effectively reduced injury to desired turfgrasses while maintaining efficacy in controlling target weeds (Kerr et al., 2019a, 2019b; Brewer et al., 2022). This strategy may prove useful for mitigating herbicide lateral movement by moving herbicide into the thatch layer following application, where sorption to organic matter is more likely to occur. According to Matocha et al. (2006), trifloxysulfuron has greater runoff potential when applied to plant material compared to bare ground due to low herbicide absorption and high foliar washoff. In a study investigating dissipation and mobility of

sulfonylurea herbicides in soil, Grey et al. (2012) observed increased sorption and decreased lateral soil mobility of sulfonylurea herbicides as soil organic matter increases. These findings suggest moving herbicides off turfgrass canopies and into thatch and soil could reduce damage caused by lateral movement.

The objective of this study was to determine the effectiveness of using light, post-application irrigation schedules to reduce lateral herbicide movement of herbicides applied to turfgrass under saturated soil conditions. We hypothesize that by moving herbicide off canopy foliage and into turfgrass thatch with light irrigation, we can increase the amount of herbicide adsorbed to organic matter and soil. By increasing adsorbed herbicide, we aim to substantially reduce the distance and severity of damage caused by off-target lateral movement downslope, providing additional application strategies for safe and effective herbicide applications.

Materials and Methods

Site Description

Field research was conducted from 31 March to 20 May 2022 at Lake Wheeler Turfgrass Field Lab in Raleigh, NC (35°44’28.3”N 78°40’47.7”W). Lake Wheeler research plots consist of Cecil sandy loam (fine, kaolinitic, thermic Typic Kanhapludult) soil with 33.2% clay, 23.8% silt, 43.0% sand, pH of 6.6, approximately 5.59% organic matter by weight in the top 7.6 cm, and 9.5% slope. Trials were conducted on dormant hybrid bermudagrass (*Cynodon dactylon* L. x *C. transvaalensis* Burtt Davy, cv. ‘Tifway 419’) overseeded with perennial ryegrass (*Lolium perenne* L.) (Pure Sport Perennial Ryegrass Blend, Pure Seed, Canby, OR, USA). Perennial ryegrass served as a downslope bioindicator for lateral movement due to its sensitivity to trifloxysulfuron deposited by herbicide runoff (Jester et al., 2022). Ryegrass seed blend consisted of 33.38% ‘Carly’, 32.78% ‘Brightstar SLT’, and 32.72% ‘Estelle’ perennial ryegrass. Overseed

was applied at 976 kg seed ha^{-1} to entire research area on October 15, 2021. For each treatment, plots consisted of an upslope herbicide-treated area measuring 1.52 wide by 1.22 m long and an observation area, immediately downslope of the herbicide-treated area, measuring 1.52 wide by 3.35 m long, with long side oriented in line with predominant slope. Plots were maintained at 5 cm height of cut until experiment initiation, at which time mowing was withheld until trial completion.

Experimental Design

Experiments were conducted as a randomized complete block design with 4 replicates and 2 experimental runs. Three irrigation schedules totaling 0.127 cm were administered following herbicide application. Schedules included 0.127 cm irrigation administered 3 h after herbicide application (HAHA), 0.127 cm irrigation at 0730 h the morning following herbicide application (17 HAHA), and 0.064 cm irrigation administered 3 HAHA with an additional 0.064 cm 17 HAHA. A fourth plot in each replicate received no post-application irrigation prior to a simulated rainfall movement event applied to entirety of trial plots. An experimental control receiving no herbicide application was included.

Experiment Initiation

Perennial ryegrass was mown, clippings collected, and research area irrigated 48 h prior to initiation. Beginning 24 h prior to initiation, irrigation was applied using overhead irrigation to bring soil to saturation. Volumetric water content (VWC) was monitored utilizing FieldScout™ 300 TDR Soil Moisture Meter (Spectrum Technologies, Inc., Aurora, IL, USA) fitted with 7.6 cm probes. Plot irrigation schedules continued until herbicide application, targeting soil saturation (48% VWC +/- 3%). At 1430 h on the day of experiment initiation, trifloxysulfuron (Monument 75WG®; Syngenta, Greensboro, NC) was applied at the maximum labeled single

application rate of 27.8 g ai ha^{-1} with a non-ionic surfactant (0.25% v v^{-1} of spray solution) to upslope, herbicide-treated area of each plot with soil VWC measuring 47.6 – 48.1%. Herbicide applications were made using a hand-held CO_2-pressurized sprayer equipped with four XR 8003 VS flat-fan nozzles (TeeJet Flat-Fan Nozzles®, Spraying Systems Co., Wheaton, IL) calibrated to deliver 405 L ha^{-1} consistent with common herbicide application carrier volumes used by turfgrass managers. A spray barrier comprised of corrugated plastic sheeting was used during herbicide application to prevent overspray into the downslope, observation area of plots.

Following herbicide application, irrigation was administered using a hand-held irrigation wand equipped with a GPI digital water meter (Great Plains Industries, Inc.; Wichita, KS, USA) to deliver precise irrigation amounts to entire plots (upslope and downslope) corresponding to treatment timing and amount. Irrigation was administered slowly, at a rate of 1.45 L m^{-2} over approximately 4 minutes, minimizing surface runoff. Afternoon irrigation events (3 HAT) occurred at soil VWC 44.8 – 47.6%. Soil VWC decreased to 42.3 – 45.3% by morning irrigation event, 17 HAHA. At 24 HAHA (soil VWC 40.7 – 45.3%), a simulated rainfall movement event delivering 1.9 cm irrigation over 6 h was applied to the entire experimental area using overhead irrigation, equating to approximately 2.5x the available pore space within the top 15 cm of soil when evaluated soil is at field capacity.

Visual perennial ryegrass injury was estimated weekly for weeks 1 through 6. Six weeks after treatment (WAT), grid count data were collected using modified methods previously described by Leon et al. (2016) to quantify percent of area exhibiting visual herbicide injury in downslope area of each plot. Grids consisted of (55) 30 by 30 cm cells. Cells containing visual herbicide injury were noted and percent of area injured downslope calculated using the equation:

% area exhibiting injury = ([number of cells exhibiting herbicide injury / total cells downslope] x 100)

Distance of visual herbicide damage in observation area was measured from the edge of treated area to the bottom edge of visually damage perennial ryegrass using fiberglass measuring tape. Maximum distance (m) of herbicide injury from edge of spray swath was recorded for each plot.

Statistical Analyses

Analyses of variance were performed using GLIMMIX procedure in SAS software (Statistical Analysis Software®, Version 9.2; SAS Institute, Inc., Cary, NC, USA). Main effects of irrigation timing and experimental run were tested as fixed effects. Following initial analysis, treatments were pooled over runs as the effect of experimental run was not significant. Replicate was considered a random effect. Experimental control was excluded from statistical analysis. Irrigation schedules were further analyzed, calculating percent of area exhibiting herbicide injury in (11) 30 cm increments downslope from herbicide application. Means were separated using Fisher's protected least significant difference at P=0.05.

Results and Discussion

No reduction in control of perennial ryegrass was observed in the herbicide treated area for any post-application irrigation application. No contamination was observed between adjacent plots. Timing of post-application irrigation significantly affected both distance and percent of area exhibiting visual herbicide injury in perennial ryegrass (Table 3.1). Damage downslope from herbicide application was observed within plots receiving no post-application irrigation prior to the 1.9 cm simulated rainfall movement event, with a maximum downslope distance of

visual damage 2.17 m from edge of spray swath (Table 3.2). Distance of visual damage from spray swath was less with for all plots receiving post-application irrigation prior to simulated rainfall event. Distance of visual damage was reduced by 53% when light irrigation was administered 3 HAHA. Distance of visual damage was reduced by 72% and 79% when light irrigation was administered at 0730 h the following morning and when split between 3 HAHA and 0730 h the following morning, respectively. By comparing plots receiving post-application irrigation, differences in distance of visual damage were observed between irrigation applied 3 h after application (1.03 m) and irrigation applied the following morning (0.61 m) or split between 3 h after application and the following morning (0.46). There were no differences between irrigation applied the following morning or split between 3 h after application and the following morning.

The effect of post-application irrigation was highlighted when considering % of area exhibiting visual injury downslope of herbicide application. Injury of perennial ryegrass averaged 36.36% when post-application irrigation was not administered (Table 3.3). All plots receiving post-application irrigation exhibited less downslope injury compared to plots not receiving post-application irrigation prior to simulated rainfall event. Downslope injury was reduced to 14.09% of area when irrigation was administered 3 h following herbicide application. Percent of visual injury was further reduced to 7.84% and 5.00% when irrigation was administered at 0730 h the following morning and when split between 3 h following herbicide application and 0730 h the following morning, respectively. Differences between irrigation timings were observed in percent of visual injury with 14.09% of downslope area exhibiting injury for treatments receiving irrigation 3 h after application compared to 7.84% and 5.00% exhibiting injury for treatments receiving irrigation the morning after and treatments receiving

irrigation split between 3 HAHA and the morning after herbicide application, respectively. There were no differences in percent injury observed between irrigation applied the following morning and irrigation split between 3 HAHA and the morning after herbicide application.

These data support previous research investigating management practices for reducing lateral off-target herbicide movement. Previous trials observed the first irrigation or rainfall event following pesticide application being the most likely to affect pesticide runoff (Lee et al., 2000; White et al., 1976). Light irrigation or rainfall events shortly following herbicide applications have been shown to help reduce lateral movement during subsequent rainfall runoff events (Bell & Moss, 2008; Jester et al. 2022; Potter et al., 2008). Additionally, sorption to grass thatch has proven effective in reducing movement within soils following herbicide application. While researching the effect of thatch on herbicide sorption, Raturi et al. (2001) observed a 21% decrease in dicamba concentration passing through experimental columns containing grass thatch compared to bare soil. In a similar study mefenoxam and propiconazole fungicides, moved deeper through cylinders containing bare soil compared to turfgrass when receiving equal irrigation treatments over a 64 d during the evaluation of the effect of turfgrass cover on soil mobility and dissipation (Gardner & Branham, 2001).

Within treatments receiving light post-application irrigation, differences in distance of visual damage were observed between irrigation applied 3 h after application (1.03 m) and irrigation applied the following morning (0.61 m) or split between 3 h after application and the following morning (0.46) (Table 3.2). Similarly, differences were observed in % of visual injury with 14.09% of downslope area exhibiting injury for treatments receiving irrigation 3 h after application compared to 7.84% and 5.00% exhibiting injury for treatments receiving irrigation

the morning after and treatments receiving irrigation split between 3 HAHA and the morning after herbicide application, respectively (Table 3.3).

In further delineating percent of area exhibiting herbicide injury by distance from spray swath, we observed 40% of downslope area exhibiting herbicide injury at 180 cm from spray swath and ≥ 20% injury through 330 cm from spray swath for plots not receiving light post-application irrigation prior to simulated rainfall movement event (Table 3.4). For plots receiving PM irrigation prior to the 1.9 cm movement event, approximately 33% or downslope area exhibited herbicide injury at 90 cm from spray swath and only approximately 8% of area exhibited injury between 91 and 120 cm from edge of herbicide spray swath. No more than 5% of area exhibited herbicide injury beyond 60 cm of spray swath for plots receiving post-application irrigation the morning after herbicide application or split between 3 HAHA and the morning after herbicide application. No herbicide injury was observed beyond 150 cm from spray swath for any plot receiving light post-application irrigation.

When comparing the differences in timing of light post-application irrigation, we must first consider the natural drying of the soil. As noted by Hofmeister et al. (2016), runoff risk is increased with increasing VWC. Although irrigation was < 0.15 cm at 3 h after application, with the soil near saturation at time of irrigation, the likelihood of applied water moving herbicide across the surface rather than infiltrating the soil surface is increased as there is limited pore space within the soil profile for additional water. With the natural percolation and drying of the soil surface over time, VWC will be lower the following morning, decreasing the risk of surface runoff until soil water storing capacity is once again exceeded due to subsequent rain or irrigation events (Dunne, 1970). Taking into consideration only soil VWC, irrigating after soil

VWC decreases may result in a lower risk of lateral movement from the addition of water into the turfgrass system as compared to irrigating at higher VWC.

Additionally, herbicide movement from turfgrass canopy into thatch and upper soil layers is critical for the sorption of available herbicide (Carrol, 2008). Maxwell et al. (2018) observed through their research that pesticide was more readily dislodged from turfgrass canopy at 0700 h, in the presence of dew, compared to from a dry canopy at 1400 h. This increase in dislodgement during morning hours when dew is more likely present may facilitate greater movement of available, resolubilized herbicide from the turfgrass canopy into the thatch and upper soil layers when light post application irrigation is administered. By moving more herbicide into the soil profile, we can achieve greater sorption, thus reducing damage caused by lateral movement on and in the soil if heavier, movement events occur.

Conclusion

Findings of these and previous studies suggest the addition of light post application irrigation is effective in reducing the distance and severity of damage caused by lateral movement of herbicides following heavy simulated rain events. Light irrigation at all tested timings within the first 24 h following herbicide application showed significant decreases in herbicide injury to downslope perennial ryegrass. Light irrigation in the morning or split between afternoon and morning provided greater decrease in movement compared to irrigation only in the afternoon on the day of application. The use of multiple light irrigation applications should be considered after herbicide application and prior to rainfall movement events to reduce damage caused by lateral movement, if efficacy of applied pesticide is not affected. By expanding future trials to include multiple successive irrigation applications and additional injury reduction strategies, herbicide injury from lateral movement may be further reduced and risk of downslope

injury more effectively mitigated. Future research should explore additional lateral movement reduction strategies, pesticides, and edaphic conditions to provide applicators additional tools to make pesticide applications more safely, confidently, and responsibly.

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Table 3.1. Partial ANOVA for visual injury in perennial ryegrass (*Lolium perenne*) downslope of trifloxysulfuron applied to turfgrass under saturated soil conditions at Lake Wheeler Turfgrass Field Lab, Raleigh, NC.

Source of variation	Df	Maximum distance of damage		% area exhibiting injury	
		F-value	Pr > F	F-value	Pr > F
Experimental run (R)	1	0.45	0.5091	0.01	0.9429
Irrigation timing (T)	3	20.96	<0.0001	13.41	<0.0001
T x R	3	0.15	0.9269	0.01	0.9994

R = experimental run, T = irrigation timing

Table 3.2. Effect of post-application irrigation schedules on maximum distance of visual herbicide damage to perennial ryegrass (*Lolium perenne*) downslope of trifloxysulfuron applied to turfgrass under saturated soil conditions.[a]

Irrigation timing	Maximum distance of damage downslope (m)		
No irrigation[bc]	2.17	A	
Afternoon	1.03	B	a
Morning	0.61	BC	b
Afternoon + morning	0.46	C	b
LSD $_{(Full)}$ [de]		0.50	
LSD $_{(Irrigated)}$ [f]			0.29

[a] Trifloxysulfuron-sodium applied as Monument® 75WG (Syngenta Crop Protection, LLC, Greensboro, NC, USA) at 27.8 g ai ha^{-1} with non-ionic surfactant (0.25% v v^{-1}) to turfgrass at 48% volumetric water content +/- 3%. Data pooled over two experimental runs conducted at Lake Wheeler Turf Field Lab, Raleigh, NC [Cecil sandy loam (fine, kaolinitic, thermic Typic Kanhapludult)]. Simulated movement event occurred 24 h after herbicide application, delivering 1.9-cm irrigation over 6 h. Data collected 42 d after herbicide application.

[b] Afternoon, morning, and afternoon + morning schedules delivered a total of 0.127-cm irrigation to treated plots and downslope evaluation areas prior to 1.9-cm simulated rainfall movement event.

[c] No irrigation indicates that no irrigation was applied prior to simulated movement event. Afternoon indicates 0.127-cm irrigation applied 3 h after herbicide application. Morning indicates 0.127-cm irrigation applied at sunrise the day following herbicide application (17 h after herbicide application). Afternoon + morning indicates 0.064-cm irrigation applied 3 h after application and an additional 0.064-cm irrigation applied at sunrise the day following herbicide application.

[d] Fisher's Protected LSD conducted at $P = 0.05$.

[e] Least significant difference for full model, including plots receiving and not receiving post-application irrigation prior to simulated rainfall event.

[f] Least significant difference only for plots receiving post-application irrigation prior to simulated rainfall event.

Table 3.3. Effect of post-application irrigation schedules on percent of area exhibiting visual herbicide injury in perennial ryegrass (*Lolium perenne*) downslope of trifloxysulfuron applied to turfgrass under saturated soil conditions.[a]

Irrigation timing	% area exhibiting injury[b]		
No irrigation[cd]	36.36	A	
Afternoon	14.09	B	a
Morning	7.84	B	b
Afternoon + morning	5.00	B	b
LSD $_{(Full)}$[ef]	10.87		
LSD $_{(Irrigated)}$[g]			3.68

[a] Trifloxysulfuron-sodium applied as Monument® 75WG (Syngenta Crop Protection, LLC, Greensboro, NC, USA) at 27.8 g ai ha^{-1} with non-ionic surfactant (0.25% v v^{-1}) to turfgrass at 48% volumetric water content +/- 3%. Data pooled over two experimental runs conducted at Lake Wheeler Turf Field Lab, Raleigh, NC [Cecil sandy loam (fine, kaolinitic, thermic Typic Kanhapludult)]. Simulated movement event occurred 24 h after herbicide application, delivering 1.9-cm irrigation over 6 h. Data collected 42 d after herbicide application.

[b] % area exhibiting injury calculated using 30 x 30 cm grids downslope of treated area where % area exhibiting injury = ((number of cells containing perennial ryegrass exhibiting visual herbicide damage / total number of cells) x 100) in 1.5 x 3.4 m downslope evaluation area.

[c] Afternoon, morning, and afternoon + morning schedules delivered a total of 0.127-cm irrigation to treated plots and downslope evaluation areas prior to 1.9-cm simulated rainfall movement event.

[d] No Irrigation indicates that no irrigation was applied prior to simulated movement event. Afternoon indicates 0.127-cm irrigation applied 3 h after herbicide application. Morning indicates 0.127-cm irrigation applied at sunrise the day following herbicide application (17 h after herbicide application). Afternoon + morning indicates 0.064-cm irrigation applied 3 h after application and an additional 0.064-cm irrigation applied at sunrise the day following herbicide application.

[e] Fisher's Protected LSD conducted at P = 0.05.

[f] Least significant difference for full model, including plots receiving and not receiving post-application irrigation prior to simulated rainfall event.

[g] Least significant difference only for plots receiving post-application irrigation prior to simulated rainfall event.

Table 3.4. Effect of post-application irrigation on percentage of downslope area exhibiting visual herbicide injury in perennial ryegrass (*Lolium perenne*) by distance from spray swath of trifloxysulfuron applied to turfgrass under saturated soil conditions.[a]

Irrigation timing	Distance from edge of spray swath (cm)										
	0 – 30	31-60	61 – 90	91 – 120	121 – 150	151 – 180	181 – 210	211 – 240	241 – 270	271 – 300	301 – 330
	% area exhibiting injury[b]										
No post-application irrigation[c]	75.00	72.50	57.50	37.50	30.00	40.00	25.00	15.00	20.00	20.00	20.00
PM	60.00	52.50	32.50	7.50	0	0	0	0	0	0	0
AM	60.00	20.00	5.00	0	0	0	0	0	0	0	0
PM + AM	32.50	12.50	2.50	2.50	2.50	0	0	0	0	0	0
LSD $_{(0.05)}$[d]	15.08										

[a] Trifloxysulfuron-sodium applied as Monument® 75WG (Syngenta Crop Protection, LLC, Greensboro, NC, USA) at 27.8 g ai ha^{-1} with non-ionic surfactant (0.25% v v^{-1}) to turfgrass at 48% volumetric water content +/- 3%. Data pooled over two experimental runs conducted at Lake Wheeler Turf Field Lab, Raleigh, NC [Cecil sandy loam (fine, kaolinitic, thermic Typic Kanhapludult)]. Simulated movement event occurred 24 h after herbicide application, delivering 1.9-cm irrigation over 6 h. Data collected 42 d after herbicide application.

[b] % area exhibiting injury calculated using 30 x 30 cm grids downslope of treated area where % area exhibiting injury = ((number of cells containing perennial ryegrass exhibiting visual herbicide damage / total number of cells) x 100) in 1.5 x 3.4 m downslope evaluation area.

[c] PM indicates 0.127-cm irrigation applied 3 h after herbicide application. AM indicates 0.127-cm irrigation applied at sunrise the day following herbicide application (17 h after herbicide application). PM + AM indicates 0.064-cm irrigation applied 3 h after application and an additional 0.064-cm irrigation applied at sunrise the day following herbicide application.

[d] Fisher's Protected LSD conducted at $P = 0.05$.