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Simulated controlled-release mesotrione for turfgrass tolerance and weed control

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Research Article

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Nomenclature:
Mesotrione; dandelion, *Taraxacum officinale* F.H. Wigg. TAROF; goosegrass, *Eleusine indica* L. ELEIN; nimblewill, *Muhlenbergia schreberi* J.F. Gmel. MUHSC; smooth crabgrass, *Digitaria ischaemum* Schreb. *ex* Muhl. DIGIS; white clover, *Trifolium repens* L. TRFRE; creeping bentgrass, *Agrostis stolonifera* L. AGSST; tall fescue; *Festuca arundinacea* Schreb. FESAR

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Abstract

Mesotrione typically requires multiple applications to control emerged weeds in turfgrass. As it is absorbed by both foliage and roots, a controlled-release (CR) formulation could eliminate the need for multiple applications. Research was conducted to evaluate simulated-release scenarios that mimic a potential CR mesotrione formulation. A soluble-concentrate formulation of mesotrione was titrated to produce a stepwise change in mesotrione rates, which were applied daily to mimic predetermined release scenarios over a 3-wk period. CR scenarios were compared to a broadcast treatment of mesotrione at 280 g ai ha^{-1} applied twice at 3-wk intervals, and a nontreated. Mesotrione applied in three temporal-release scenarios controlled creeping bentgrass, goosegrass, nimblewill, smooth crabgrass, and white clover equivalent to the standard sprayed mesotrione treatment in every comparison. However, each CR scenario injured tall fescue two to seven times more than the standard treatment. Soil- and foliar-initiated repeat treatments were equivalent in most comparisons. Our data indicate that mesotrione applied in a temporal range to simulate controlled-release scenarios can deliver desired weed control efficacy comparable to sequential broadcast applications. More research is needed to elucidate proper timings and release scenarios to minimize turfgrass injury.

Introduction

Mesotrione is an herbicide registered for broad-spectrum control of broadleaf and grass weeds in multiple turfgrass species (Anonymous 2011; Brewer et al. 2017; Brosnan et al. 2010; McElroy et al. 2007; Tate et al. 2019). For effective control of established weeds by mesotrione, initial herbicide application must be followed by a sequential application approximately 3 wk later (Anonymous 2011, 2018; Elmore et al. 2013). Ideally, herbicide applications would provide desired results following a single treatment without the need of a sequential application.

Controlled-release (CR) formulations allow specific amounts of herbicide to be released over a given amount of time. Controlled release of herbicides also reduces the amount of leaching and offsite movement of herbicides (Collins et al. 1973; Galán-Jiménez et al. 2020; Prado et al. 2011). Schreiber et al. (1988) reported that atrazine leaching was reduced using a CR starch granule. Similarly, Boydston (1992) reported that ^{14}C-norflurazon or ^{14}C-simazine CR starch granule applications retarded the leaching depth of both herbicides compared to conventional applications. Other CR formulations have been tested using carriers such as organic and inorganic clays (Celis et al. 2002; Hermosin et al. 2001), ethylcellulose (Sopeña et al. 2007), and zeolite and bentonite minerals modified with cetyltrimethylammonium surfactant (Shirvani et al. 2014). The pattern of herbicide release is related to particle size distribution, bead radius, polymer matrix, herbicide active ingredient, surface morphology, aqueous solubility, and lipophilicity of the herbicide or to the sorption of the herbicide to the clay mineral (Davis et al. 1996; Galán-Jiménez et al. 2020; Gerstl et al. 1998; Li et al. 2008; Sopeña et al. 2005). Sulfur coating, in a urea fertilizer, for example, releases urea via diffusion in a two-stage process that is initially constant and rapid while urea is dissolving but then decreases logarithmically after all urea has dissolved (Jarrell and Boersma 1980). Similarly, in a study by Rashidzadeh et al. (2017), 75% of paraquat was released from clinoptilolite clay in less than 48 h, whereas the same amount of release from montmorillonite clay took 168 h. Initial paraquat release in the first 24 h by both clay materials was at least 60%. Alginate polymer added to montmorillonite clay reduced the initial amount of paraquat released to as low as 40%, but total paraquat released after 60 d was only 55%. A sepiolite-based mesotrione CR formulation retained 65% of mesotrione after 96 h compared to only 29% retention of the commercial product and released mesotroine in a rate-descending pattern via controlled diffusion (Galán-Jiménez et al. 2020). Cumulative release of soil-applied fluometuron was 95% in 13 h from the commercial wettable granule formulation and was increased to 25 to 33 d using matrix granules on sequential solvent-extracted lignins (Zhao and Wilkins 2003). With bromacil, Zhao and Wilkins (2000) demonstrated a release scenario from solvent-extracted lignins that was sigmoidal. Thus, examples of varied herbicide release scenarios of herbicides have been reported (Rashidzadeh et al. 2017; Zhao and Wilkins 2000, 2003). Given its dependency on sequential applications to improve weed control efficacy, mesotrione could be a candidate herbicide for CR liquid or granular formulations.

Generally, granular herbicides are less effective for POST weed control than foliar sprays (Duray and Davies 1987; Koscelny and Peeper 1996). Granular herbicides have fewer points of contact with plant foliage or soil compared to foliar spray (Karnok 1986) and have limited opportunity to enter the plant through foliar absorption, especially when the foliage is dry. Foliar absorption can be enhanced by applying products when dew is present on foliage (Loughner and Nolting 2010). Although performance can be enhanced by applying to wet foliage, root-and-shoot–absorbed herbicides are less dependent on foliar absorption and tend to dominate the granular herbicide market. Granular herbicides offer advantages, such as ease of application and reduced drift (Akobundu 1981).

Mesotrione is absorbed by plant roots and foliage and possesses both PRE and POST herbicide activity (Anonymous 2011, 2018; Armel et al. 2003; Elmore et al. 2011; Mitchell et al. 2001). Because of mesotrione's soil activity, its applications are less dependent on leaf moisture for absorption. Although mesotrione is not dependent on leaf moisture for absorption, relative humidity will influence and increase turfgrass injury (Goddard et al. 2010; Gonçalves et al. 2021). Goddard et al. (2007) reported that dew presence at the time of application did not influence the control of dandelion or white clover by combination granules of mesotrione plus fertilizer in contrast to a dew-dependent granular product containing 2,4-D and MCPP.

Adapting CR technology for the production of a potential mesotrione formulation may reduce the number of applications needed to control undesirable weeds in turfgrass stands. Mesotrione would be an ideal candidate for CR liquid or granular formulations, because it is readily absorbed by foliage or roots. Therefore, the objectives of this study are to determine first the optimum mesotrione release scenario to maintain acceptable turfgrass tolerance and herbicide efficacy, and to determine further if initial application placement, to simulate foliar spray compared to granular products, affects herbicide efficacy.

Materials and Methods

Site Description and Plant Growing Conditions

Research was conducted at Virginia Tech Glade Road Research Facility (37.232017°N, 80.435746°W) at Blacksburg, VA in 2007 and 2008 to assess simulated-release scenarios that mimic a potential CR mesotrione formulation. Mature plugs of turf-type tall fescue (cv. 'Falcon III'), nimblewill, and creeping bentgrass were taken from the field and thinned to two to three tillers. Smooth crabgrass, goosegrass, and white clover were seeded into trays for establishment. Seedlings were selected for two- to three-leaf stage crabgrass and goosegrass, and one fully expanded leaf for white clover. Plants were washed to remove any excess soil before being transplanted into 10- by 10-cm pots containing steam-sterilized sand and soil (50:50 v/v). Soil type was a Groseclose–Urban Land complex (Fine, mixed, semiactive, mesic, Typic Hapludults) with 1.8% organic matter and pH 6.6. Once transplanted, plants were irrigated as needed to maintain adequate growing conditions. Each pot was fertilized biweekly using water-soluble NPK (20-20-20) fertilizer (Peters Professional 20-20-20 General Purpose Water Soluble Fertilizer; The Scotts Company, 14111 Scottslawn Road, Marysville, OH 43041). Plants were allowed to acclimate in the greenhouse for 1 wk before treatments were initiated. Experiments were maintained at average temperatures of 22 C (±2 C) in a 12/12-h day/night photoperiod supplemented by mercury vapor bulbs (trial 1) and high-pressure sodium bulbs (trial 2) during the day to ensure a minimum light intensity of 300 and 500 μmol m^{-2} s^{-1} photosynthetically active radiation in trials 1 and 2, respectively.

Experimental Design and Chemical Treatments

Two trials were conducted as randomized complete-block designs with four replications. Each experimental unit consisted of one pot containing one plant of a given species. Treatments included a nontreated check, a standard, and a three-by-two factorial arrangement that mimicked three hypothetical herbicide-release scenarios applied following an initial application to foliage or soil. The initial treatment was mesotrione at 280 g ai ha^{-1} applied broadcast to foliage and soil or syringed directly to soil. The release scenarios that followed consisted of an additional 280 g ai ha^{-1} mesotrione titrated at different rates applied daily to match ascending, descending, and intervallic patterns (Table 1) over a 3-wk period. Each daily treatment was carefully syringed onto the soil surface of each pot to reduce contact with the plant foliage and prevent herbicide splash during application. After daily treatments had been absorbed into the soil profile, each pot was lightly hand watered to reduce herbicide movement during watering events. Additionally, a standard treatment consisted of two broadcast applications of mesotrione at 280 g ai ha^{-1} applied at 3-wk intervals. The program consisting of 280 + 280 g ai ha^{-1} represents the maximum rate per application and the annual use limit for tall fescue turfgrass.

Herbicide Application

Treatments were applied daily for 21 d to mimic the release scenario of each CR scenario (Table 1). Plants were watered as needed throughout the study. Both foliar treatments for the standard comparison and initial foliar treatments, where applicable for the scenarios, were applied using a handheld, CO_2-pressurized boom equipped with 11004X spray tips and calibrated to deliver 280 L ha^{-1} at 206.8 kPa (11004XR Extended Range Flat Fan Spray Tip; TeeJet Technologies, P.O. Box 7900, Wheaton, IL 60187-7900, USA). Each foliar treatment was applied with a non-ionic surfactant at 0.25% v/v (Chem-Stik Nonionic Spreader-Sticker; Precision Laboratories, Inc. Waukegan, IL 60085 USA). For all CR scenarios, predetermined mesotrione rates were mixed in 5 ml of water and syringed to soil daily following initial treatment.

Data Collection

Turfgrass injury, leaf counts by color (green, pale, white, or necrotic), tiller counts, and control of creeping bentgrass, goosegrass, nimblewill, smooth crabgrass, and white clover were evaluated weekly following herbicide application. Green leaves are defined as those leaves without visible injury symptoms, pale leaves are defined as leaves with mild to moderate injury symptoms (foliar chlorosis or bleaching), white leaves are defined as leaves having severe tissue injury (completely white), and necrotic leaves are defined as leaves that are completely dead. These data are reported as a percentage of the number of leaves per plant. Tiller counts were taken for smooth crabgrass and goosegrass only.

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Table 1. Three simulated mesotrione release scenarios consisting of mesotrione rate titrations where 280 g ai ha^{-1} was applied on the first day either as a foliar spray or by adding the herbicide to 5 ml water and syringing. Between days 2 and 21, the titrated rates total an additional 280 g ai ha^{-1}, all applied via syringing.

Time after initiation	Ascending	Descending	Intervallic
d		g ai ha^{-1}	
1	280.0000	280.0000	280.0000
2	0.0003	140.0000	0.0000
3	0.0005	70.0000	0.0000
4	0.0011	35.0000	0.0000
5	0.0021	17.5000	0.0000
6	0.0043	8.7500	0.0000
7	0.0085	4.3750	0.0000
8	0.0171	2.1875	0.0000
9	0.0342	1.0938	0.0000
10	0.0684	0.5469	0.0000
11	0.1367	0.2734	0.0000
12	0.2734	0.1367	0.0000
13	0.5469	0.0684	0.0000
14	1.0938	0.0342	0.0000
15	2.1875	0.0171	0.0000
16	4.3750	0.0085	0.0000
17	8.7500	0.0043	17.5000
18	17.5000	0.0021	70.0000
19	35.0000	0.0011	105.0000
20	70.0000	0.0005	70.0000
21	140.0000	0.0003	17.5000

Injury and control ratings were recorded as a visually estimated percentage, with 0% indicating no injury or control, and 100% indicating complete death of all visible foliage or complete control (Frans 1986). After 6 wk, all aboveground vegetative growth was removed and weighed. To facilitate analysis and discussion, pale, white, green, and necrotic leaf counts data were converted to percentage discolored leaves using Equation 1:

$$((P + W + N)/T) \times 100 \qquad [1]$$

where P, W, and N represent the number of pale, white, and necrotic leaves, respectively, and T is the total number of leaves per plant.

Statistical Analyses

Variance was tested for homogeneity by plotting residuals in SAS 9.2 (SAS 9.2 software; SAS Institute Inc., Cary, NC 27513-2414, USA). Data were subjected to a combined ANOVA with sums of squares partitioned to reflect trial effects and the factorial treatment arrangement. Trial was considered random, and the mean squares of placement, time-release scenario, and placement-by-time release scenario were tested using the mean square associated with their interaction with trial (McIntosh, 1983). Appropriate means for significant main effects or interactions within the factorial treatment structure were separated using Fisher's Protected LSD at $P = 0.05$. Comparison treatments were measured against appropriate means generated following ANOVA on the factorial treatments with single-degree-of-freedom contrasts.

Results and Discussion

Weed Control

At 3 and 6 wk after initial treatment (WAIT), trial, CR scenario, and application placement were not significant for creeping bentgrass, goosegrass, nimblewill, and white clover control; therefore, data were pooled for comparison to the standard and check (Table 2).

Regardless of scenario or application placement, treatments designed to mimic CR effectively controlled creeping bentgrass, goosegrass, nimblewill, and white clover greater than 87% at 6 WAIT and equivalent to the standard treatment. For smooth crabgrass, differences were observed for trial and application placement (Table 2). At 3 WAIT for trial 2, regardless of release scenario, initial treatment to soil controlled smooth crabgrass 91%, which was significantly less than initial treatment to foliar plus soil (98%). Although significant, these differences may be of minimal biological relevance as both application placements led to 100% control by 6 WAIT. The inconsistency noted between trials at 3 WAIT caused the trial-by-placement-by-CR scenario interaction for smooth crabgrass control. Galán-Jiménez et al. (2020) recently reported a CR mesotrione formulation based on a sepiolite clay sorption method. The CR formulation created by Galán-Jiménez et al. (2020) was rate-descending based on water-release kinetics, but the release scenario did not exactly match that of the rate-descending simulation in this study. Similar to our results, the CR formulation in the Galán-Jiménez et al. (2020) study injured weedy sunflower (*Helianthus annuus* L.) equivalent to or more than the commercial formulation.

Tall Fescue Injury

Tall fescue injury was significantly influenced by initial application placement but not by trial or scenario (Table 2). Initial soil applications injured tall fescue less than foliar-plus-soil applications at 3 and 6 WAIT. All treatments designed to mimic time-release scenarios injured tall fescue two to seven times greater than the standard comparison treatment. Comparison treatments injured tall fescue 7% and 18% at 3 and 6 WAIT, respectively. All CR scenarios injured tall fescue at least 34% regardless of application placement. This increased injury could have occurred because more mesotrione was available to plants from 0 to 3 WAIT. Had release scenarios been initiated 1 to 2 wk after initial treatments, tall fescue injury might have been decreased. More research is needed to assess other release scenarios to reduce turfgrass injury.

Leaf Color

Trial repetition, application placement, and mesotrione release scenario had no effect on percentage discolored leaves of nimblewill, smooth crabgrass, and white clover 2 WAIT; therefore, data were pooled for comparison to the standard and nontreated check (Table 3). Regardless of initial application placement or release scenario, CR scenarios discolored 46%, 76%, and 72% of nimblewill, smooth crabgrass, and white clover leaves, respectively, and equivalent to the standard mesotrione treatment 2 WAIT. Both the average of CR treatments and the standard had more discolored leaves than the nontreated check. Tall fescue leaf discoloration was influenced by CR scenarios and trial but not by initial application placement (Table 3).

The standard mesotrione comparison treatment discolored 37% and 18% of tall fescue leaves in trials 1 and 2, respectively (Table 3). As most of the discolored leaves were pale leaves, the percentage discolored leaves should not be viewed as percentage injury, which was only 7% from the comparison treatment at 3 WAIT when averaged over trials (Table 2). In each case, percentage discolored leaves from the standard comparison was less than that sustained from the simulated CR scenarios. In trial 1, the simulated CR scenarios did not differ from each other, but in trial 2, the

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Table 2. Effect of initial mesotrione placement on tall fescue injury (%) and smooth crabgrass control (%) in two trials averaged over time-release scenarios. Placement, scenario, and trial were insignificant for creeping bentgrass, goosegrass, nimblewill, and white clover, so data were pooled for comparison with the standard treatment.[a]

		3 WAIT[b]			6 WAIT		
Species	Initial placement[c]	Average	Trial 1	Trial 2	Average	Trial 1	Trial 2
		%					
Tall fescue	Soil only	34*			35*		
	Foliar + soil	48*			51*		
	Standard	7			18		
	LSD (P = 0.05)	10			11		
Smooth crabgrass	Soil only		60	91		87	100
	Foliar + soil		57	98		94	100
	Standard		72			100	
	LSD (P = 0.05)		NS	7		NS	NS
Goosegrass		55			87		
Standard		41			80		
Creeping bentgrass		69			89		
Standard		61			86		
Nimblewill		49			91		
Standard		53			79		
White clover		81			97		
Standard		71			91		

[a]Means followed by an asterisk are different from the standard comparison treatment (two applications of mesotrione applied at 280 g ai ha^{-1} at 3-wk intervals).
[b]Abbreviations: NS, not significant; WAIT, wk after initial treatment.
[c]Initial placement indicates that the initial mesotrione treatment of 280 g ai ha^{-1} was applied only to soil (to mimic a granular treatment) or to foliar plus soil (to mimic a broadcast spray). Regardless of the initial application placement, all time-release scenarios were achieved by diluting titrated mesotrione rates in 5 ml water and syringing them to soil daily over a 3-wk period.

Table 3. Average effect of time-release scenarios and application placement compared to standard treatment and nontreated check on percentage discolored leaves at 2 WAIT of nimblewill, smooth crabgrass, and white clover and effect of release scenario and trial on the percentage discolored leaves of tall fescue.[a]

	Percentage discolored leaves				
			Tall fescue		
Treatment	Nimblewill	Smooth crabgrass	Trial 1	Trial 2	White clover
	%				
Avg. time-release[b]	46	76	–	–	72
Standard	47	57	37	18	69
Nontreated	13	5	0	1	15
Rate ascending[c]	–	–	60	27	–
Rate descending	–	–	55	51	–
Rate intervallic	–	–	53	38	–
LSD (P = 0.05)	16	25	14	7	31

[a]Percentage discolored leaves based on leaf counts of necrotic, pale, and white leaves converted to a percentage of total leaves per plant.
[b]Significant differences were not observed among the factorial structure of mesotrione time-release scenarios and application placement for nimblewill, smooth crabgrass, and white clover; therefore, data were pooled for comparison to the nontreated check and standard treatment (two applications of mesotrione applied at 280 g ai ha^{-1} at 3-wk intervals).
[c]Time-release scenarios included mesotrione rate titrations that were added to 5 ml water and syringed to soil each day during a 3-wk period. The titrated rates totaled 280 g ai ha^{-1} and were applied in a logarithmic ascent between day 2 and day 21 ("rate ascending"), a logarithmic descent between day 2 and day 21 ("rate descending"), and a curved pattern between day 17 and day 21 ("intervallic").

rate-descending release scenario resulted in the most discolored leaves 2 WAIT. Although CR scenarios were insignificant for tall fescue injury in Table 2, the percentage leaf discoloration indicates that increased mesotrione rate in the first 3 wk could be responsible for tall fescue discoloration observed in these trials. The rate-descending pattern applies the equivalent of over 525 g ai ha^{-1} mesotrione in the first 4 d as a result of the logarithmic pattern chosen. It may be possible to reduce turfgrass injury by delaying CR treatments for at least 1 to 2 wk after the initial application or by reducing the initial rate, but more research is needed to test this theory. A sepiolite-based CR mesotrione formulation did not injure corn (*Zea mays* L.) when compared to a commercial formulation, but these treatments were applied at only 100 g ai ha^{-1} (Galán-Jiménez et al. 2020).

A three-way interaction of trial, application placement, and mesotrione release scenario was observed for creeping bentgrass 2 WAIT (Table 4). In trial 1, complete control of creeping bentgrass was observed for each application placement, release scenario, and standard mesotrione comparison treatment. In trial 2, differences in application placement and release scenario were observed. For the rate-ascending release scenario, foliar-initiated treatments were more effective (80%) than soil-initiating treatments (68%). The foliar-initiated ascending treatment was also more effective than the foliar-applied, rate-descending treatment, the soil-applied, rate-intervallic treatment, and the standard-comparison treatments. The differences noted between trials could be due to changes in supplemental lighting between the two years in which these trials were conducted. In the second trial, high-pressure sodium lights provided almost twice the photosynthetic active radiation of the mercury vapor lights used in trial 1. Increased heat of underlying surfaces of the high-pressure sodium lights or increased light intensity may have contributed to the trial

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Table 4. Effect of release scenario and application placement of mesotrione on discolored leaves of creeping bentgrass and goosegrass. Significant differences in trial were observed for creeping bentgrass.

Initial placement[a]	Release scenario	Percentage discolored leaves: Creeping bentgrass Trial 1	Creeping bentgrass Trial 2	Goosegrass
		%		
Foliar + soil	Rate ascending	100	80	57
	Rate descending	100	69	72
	Rate intervallic	100	76	55
Soil only	Rate ascending	100	68	62
	Rate descending	100	75	58
	Rate intervallic	100	67	66
Foliar + soil	Standard	100	69	56
Nontreated		0	0	0
	LSD (P = 0.05)	–	10	22

[a]Initial placement indicates that the initial mesotrione treatment of 280 g ai ha^{-1} was applied only to soil (to mimic a granular treatment) or to foliar + soil (to mimic a broadcast spray). Regardless of the initial application placement, all time-release scenarios were achieved by diluting titrated mesotrione rates in 5 ml water and syringing them to soil daily over a 3-wk period. Time-release scenarios included mesotrione rate titrations that were added to 5 ml water and syringed to soil each day during a 3-wk period. The titrated rates totaled 280 g ai ha^{-1} and were applied in a logarithmic ascent between day 2 and day 21 ("rate ascending"), a logarithmic descent between day 2 and day 21 ("rate descending"), and a curved pattern between day 17 and day 21 ("intervallic").

Table 5. Average effect of time-release scenarios and application placement compared to standard treatment and nontreated check on aboveground fresh-plant weight of creeping bentgrass, nimblewill, smooth crabgrass, and white clover and effect of release scenario on aboveground fresh-plant weight of goosegrass and tall fescue.

	Creeping bentgrass	Goosegrass	Nimblewill	Smooth crabgrass	Tall Fescue	White clover
Release scenario	g					
Avg. time-release[a]	0.26	–	0.13	0.04	–	0.03
Standard	0.24	0.62	0.18	0	1.88	0.09
Nontreated	3.74	4.37	1.33	4.19	2.32	1.86
Rate ascending[b]	–	0.35	–	–	0.97	–
Rate descending	–	0.32	–	–	0.78	–
Rate intervallic	–	0.37	–	–	1.19	–
LSD (0.05)	0.48	0.77	0.34	0.87	0.51	1.16

[a]Significant differences were not observed among the factorial structure of mesotrione time-release scenarios and application placement for creeping bentgrass, nimblewill, smooth crabgrass, and white clover; therefore, data were pooled for comparison to the nontreated check and standard treatment (two applications of mesotrione applied at 280 g ai ha^{-1} at 3-wk intervals).
[b]Time-release scenarios included mesotrione rate titrations that were added to 5 ml water and syringed to soil daily during a 3-wk period. The titrated rates totaled 280 g ai ha^{-1} and were applied in a logarithmic ascent between day 2 and day 21 ("rate ascending"), a logarithmic descent between day 2 and day 21 ("rate descending"), and a curved pattern between day 17 and day 21 ("intervallic").

interaction. Goosegrass leaf discoloration did not differ between treatments (Table 4).

Fresh Weights

Trial repetition, application placement, and mesotrione release scenario had no effect on plant fresh weight for creeping bentgrass, nimblewill, smooth crabgrass, and white clover 7 WAIT; therefore, data were pooled (Table 5). In each case, nontreated plant weights were significantly greater than the standard comparison or the average of application placement and mesotrione release scenario, which were statistically similar. In each case, mesotrione treatments were effective at controlling these species. The average of application placement and mesotrione release scenario reduced plant weight 93%, 90%, 99%, and 98%, whereas the standard treatment reduced plant weight 94%, 86%, 100%, and 95% for creeping bentgrass, nimblewill, smooth crabgrass, and white clover, respectively. For goosegrass, application placements were similar; therefore, data were pooled. Standard mesotrione application and the mesotrione release scenarios were similar and reduced plant weight 86% or greater when compared to the nontreated check (Table 5).

Mesotrione CR scenarios reduced tall fescue fresh weight at least 51%. Each of these release scenarios was more injurious than the standard mesotrione treatment. Standard mesotrione treatments reduced tall fescue weight by 20% and were not different from the nontreated check.

In these studies, leaf discoloration was reported in Table 3 for the nontreated plants within nimblewill, smooth crabgrass, and white clover species. This injury was predominantly necrosis or chlorosis but occasionally consisted of a small amount of bleaching. Substantial effort was made during these trials to reduce the potential for herbicide movement from one plant to the other. Potential volatility of mesotrione has been observed in field and greenhouse trials at Virginia Tech (C.G. Gonçalves and S.D. Askew, personal observation). Species highly sensitive to mesotrione located in areas around field plots, such as *Oxalis* sp. and small *Brassica* sp., have been injured, although herbicide was applied with a shield to reduce drift potential. According to Dumas et al. (2017), mesotrione is weakly acidic, nonvolatile, and highly soluble in water. Though volatility is suspected, no reports of mesotrione volatility are known to exist. The high water solubility suggests co-distillation as a possible mechanism of movement in confined greenhouse conditions. Researchers evaluating other bleaching herbicides have reported volatility in their trials (Locke et al. 1996; Thelen et al. 1988). Other causes of leaf phytotoxicity in nontreated plants could be due to tip necrosis following salt-concentrated guttation water or other stress factors, such as supplemental greenhouse lighting.

Tall fescue was injured more by treatments designed to mimic CR scenarios than by the standard comparison. This occurrence was unexpected but could be due to increased herbicide rate during the first 5 d following the CR treatments. The three release scenarios were chosen based on discussion with a Syngenta formulation chemist (L. Galiano, personal communication). The ascending, descending, and intervallic patterns are indicative of various formulations technologies available to a formulations chemist, and each CR scenario involves different technology and costs (Galán-Jiménez et al. 2020; Rashidzadeh et al. 2017; Zhao and Wilkins 2000, 2003). For example, impregnating herbicide onto a clay or peanut hull carrier that imparts a rate-descending CR scenario will be less expensive that a micro-encapsulated formulation designed for intervallic release by microbial degradation. Information about the extent of bioefficacy from each pattern can enable economically viable choices to be made for any future work on CR mesotrione formulations. The patterns were designed to apply 280 g ai ha^{-1} initially and another 280 g ai ha^{-1} over the next 21 d. Because the standard mesotrione broadcast treatment consists of two 280 g ai ha^{-1} treatments at a 21-d interval, a better choice might be to initiate the release scenarios at 2 WAIT and have them extend over a period of time between 2 and 5 WAIT. Such a release scenario could conceivably be produced using microbially degraded encapsulation.

In conclusion, a recent sepiolite-based CR mesotrione formulation with a rate-descending release scenario demonstrated that soil loading of mesotrione at 0 to 10 cm was dramatically increased, presumably as a result of changes in foliar absorption rates (Galán-Jiménez et al. 2020). Our results align with those of the sepiolite-based formulation in that simulations based on mesotrione CR scenarios applied singly with or without foliar exposure can control weeds as well as single or repeated foliar treatments. Although we did not identify an optimum CR scenario in this work, the data suggest that rate-descending patterns and soil-plus-foliar treatments may cause more leaf discoloration or injury to tall fescue when compared to rate-ascending, rate-intervallic, and soil-only treatments. Our work further demonstrates that mesotrione can control a variety of weeds when released into the soil environment in different ways.

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No conflicts of interest have been declared.

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