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Persistence and Bioavailability of Aminocyclopyrachlor and Clopyralid in Turfgrass Clippings: Recycling Clippings for Additional Weed Control

Dustin F. Lewis, Matthew D. Jeffries, Travis W. Gannon, Robert J. Richardson, and Fred H. Yelverton*

The synthetic auxin herbicides, aminocyclopyrachlor and clopyralid, control dicotyledonous weeds in turf. Clippings of turfgrass treated with synthetic auxin herbicides have injured off-target plants exposed to herbicide-laden clippings. Labels of aminocyclopyrachlor and clopyralid recommend that clippings of treated turfgrass remain on the turf following a mowing event. Alternative uses for synthetic auxin-treated turfgrass clippings are needed because large quantities of clippings on the turf surface interfere with the functionality and aesthetics of golf courses, athletic fields, and residential turf. A white clover bioassay was conducted to determine the persistence and bioavailability of aminocyclopyrachlor and clopyralid in turfgrass clippings. Aminocyclopyrachlor and clopyralid were each applied at 79 g ae ha^{-1} to mature tall fescue at 56, 28, 14, 7, 3.5, and 1.75 d before clipping collection (DBCC). Clippings were collected, and the treated clippings were recycled onto adjacent white clover plots to determine herbicidal persistence and potential for additional weed control. Clippings of tall fescue treated with aminocyclopyrachlor produced a nonlinear regression pattern of response on white clover. Calculated values for 50% response (GR_{50}) for visual control, for normalized difference vegetative index (NDVI), and for reduction in harvested biomass were 20.5, 17.3, and 18.7 DBCC, respectively, 8 wk after clippings were applied. Clippings of tall fescue treated with clopyralid did not demonstrate a significant pattern for white clover control, presumably because clopyralid was applied at a less-than-label rate. The persistence and bioavailability of synthetic auxin herbicides in clippings harvested from previously treated turfgrass creates the opportunity to recycle clippings for additional weed control.

Nomenclature: Aminocyclopyrachlor; clopyralid; tall fescue, *Lolium arundinaceum* (Schreb.) S.J. Darbyshire; white clover, *Trifolium repens* L. 'Dutch'.
Key words: Compost, mulch, regrassing.

Cultural management practices in actively growing, turfgrass systems require multiple mowing events per week to maintain a healthy, functional, and aesthetically pleasing turfgrass surface (Beard 1973). Turfgrass specialists recommend returning turfgrass clippings to the turf following mowing events because an estimated 25% of annual required nitrogen may be provided as the clippings decompose (Bruneau et al. 2008). Equipment failure, inclement weather, or other causes can delay scheduled mowing events, often resulting in the accumulation of turfgrass clippings. Large quantities of turfgrass clippings are undesirable in golf courses, athletic fields, and home lawn turfs because they can interfere with their functionality and aesthetics, thereby warranting clipping collection and disposal (Beard 1973). In 1984, the annual amount of turfgrass clippings collected for landfill disposal was estimated at > 7 billion kg, leading many U.S. states to ban yard-waste disposal in public landfills (Bruneau et al. 2008; Glenn 1989; Goldstein and Riggle 1990). Alternative uses for turfgrass clippings have included composting or use as gardening mulch because clippings contain high moisture and nutrient content (Bahe and Peacock 1995; Bruneau et al. 2008).

Synthetic auxin herbicides are commonly used in turfgrass settings for selective control of dicotyledonous weeds (McCarty et al. 2010; Senseman 2007). Aminocyclopyrachlor is a newly developed synthetic auxin herbicide belonging to the pyrimidine carboxylic acid herbicide family with a similar mechanism of action and chemical structure to pyridine herbicides (Claus et al. 2008; Senseman 2007). Research has indicated aminocyclopyrachlor has a favorable environmental profile with low mammalian toxicity, minimal volatility potential, and broad spectrum weed control at low application rates, compared with other synthetic auxin herbicides (Claus et al. 2008; Strachan et al. 2010).

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* Former Graduate Research Assistant, Graduate Research Associate, Assistant Professor, Associate Professor, and Professor. Crop Science Department, North Carolina State University, P.O. Box 7620, Raleigh, NC 27695-7620. Corresponding author's E-mail: dustin.f.lewis@basf.com

These attributes make aminocyclopyrachlor a viable tool for broadleaf weed control in turfgrass systems (Claus et al. 2008; Curtis et al. 2009; Flessner et al. 2011; Gannon et al. 2009). Aminocyclopyrachlor was registered in 2010 for broadleaf weed control in commercial and residential turfgrass systems under the trade name Imprelis (DuPont; Anonymous 2010).

Off-target plant injury via contaminated compost and mulch has been attributed to synthetic auxin herbicides remaining in previously treated turfgrass clippings (Anonymous 2001; Bahe and Peacock 1995; Blewett et al. 2005; Burkhart and Davitt 2002; Lewis et al. 2013a; Miltner et al. 2003; Vandervoort et al. 1997). Bahe and Peacock (1995) reported tall fescue clippings previously treated with 2,4-D (21.5%) plus dicamba (11.5%) plus methylchlorophenoxypropionic acid (MCPP) (2.3%) at a total of 5 kg ai ha^{-1} reduced garden cucumber (*Cucumis sativus* L.), garden tomato [*Solanum lycopersicum* L. var *cerasiforme* (Dunal) Spooner, G.J. Anderson, & R.K. Jansen], French marigold (*Tagetes tenuifolia* Millsp.), and scarlet sage (*Salvia splendens* Sellow ex Roem. & Schult.) dry mass by 80, 73, 65, and 34%, respectively. In composting studies, 2,4-D, clopyralid, and triclopyr residues were found at 0.6, 31.9, and 0.48 mg kg^{-1} of clippings, respectively, when grass clippings were collected 128 d after application (DAA) (Vandervoort et al. 1997). In spring 2000, clopyralid gained public attention when off-target plant injury was reported in Washington, where previously treated turfgrass clippings unintentionally entered compost feedstock (Blewett et al. 2005; Burkhart and Davitt 2002; Miltner et al. 2003). Similarly clopyralid was found at between 10 and 75 μg kg^{-1} in finished compost (greater than 6 mo cured) from plant material collected on the Penn State University (Happy Valley, PA), leading the university to suspend the use of clopyralid-containing herbicides (Burkhart and Davitt 2002). Miltner et al. (2003) reported a waiting period $\geq$ 1 yr could be necessary for clopyralid-treated turfgrass to be used as compost feedstock. Lewis et al. (2013a) reported aminocyclopyrachlor and triclopyr plus clopyralid bioavailability from previously treated turfgrass clippings within aqueous environments, which led to substantial growth reductions to alligatorweed [*Alternanthera philoxeroides* (Mart.) Griseb.] and parrotfeather [*Myriophyllum aquaticum* (Vell.) Verdc.] under glasshouse conditions. Those reports indicate synthetic auxin herbicides can be highly persistent in grass clippings and remain bioavailable under various environmental conditions.

Because of the aforementioned off-target plant injury potential, many synthetic auxin herbicide labels restrict clipping collection following application (Anonymous 2008a,b, 2010). However, clipping collection may be required if regular mowing practices are not followed, creating the need to find alternative uses for synthetic auxin–treated turfgrass clippings. To date, limited research has been conducted to determine the persistence of synthetic auxin herbicides in turfgrass clippings remaining under field conditions. Because past research has indicated synthetic auxin residues can be released from turfgrass clippings, it is hypothesized clippings from previously treated turfgrass could be collected and recycled for use as an additional weed control practice. Therefore, a field bioassay was conducted to evaluate the persistence and bioavailability of aminocyclopyrachlor and clopyralid in turfgrass clippings and to determine the utility of recycling clippings for additional weed control.

Materials and Methods

Research was initiated June 27, 2011, and July 4, 2011, at the North Carolina State University Turf Field Laboratory in Raleigh, NC, to determine the persistence and bioavailability of synthetic auxin herbicides in previously treated turfgrass clippings by evaluating the growth response of 'Dutch' white clover. Commercially available aminocyclopyrachlor (Imprelis herbicide, E. I. DuPont de Nemours, Wilmington, DE 19805) and clopyralid (Lontrel herbicide, Dow AgroSciences, Indianapolis, IN 46268) were applied at 79 g ae ha^{-1} to mature 'Confederate' tall fescue (538 m^2 plots; 16.4 m wide by 32.8 m long) at 56, 28, 14, 7, 3.5, and 1.75 d before clipping collection (DBCC). Environmental conditions following those herbicide applications were similar in both experimental runs (Table 1). The aminocyclopyrachlor rate was selected according to label recommendation for broadleaf weed control in tall fescue (Anonymous 2010). The clopyralid rate was less than label recommendation (139 g ha^{-1}) for white clover control (Anonymous 2008b); however, that rate was selected to compare with aminocyclopyrachlor on an equal active ingredient basis. Aminocyclopyrachlor and clopyralid were applied with a CO_2-pressurized sprayer boom (CO2-pressurized sprayer, Spraying Systems Co., Wheaton, IL 60189) equipped with four TeeJet 8002 XR flat-fan nozzles (TeeJet nozzles, TeeJet Technologies, Springfield, IL 62703) on 24-cm spacings, calibrated to deliver 304 L ha^{-1} at 224 kPa.

Table 1. Environmental conditions at the Lake Wheeler Turf Field Laboratory, Raleigh, NC, surrounding herbicide applications in both experimental runs.[a]

	Run 1				Run 2			
DBCC timing[b]	Application date	Average temperature[c]	Precipitation accumulation[d]	GDD accumulation[e]	Application date	Average temperature[c]	Precipitation accumulation[d]	GDD accumulation[e]
d		C	cm			C	cm	
56	June 27, 2011	27.2	0	2,168	July 4, 2011	28.3	0	2,361
28	July 25, 2011	27.2	16.2	2,973	August 1, 2011	27.2	11.5	3,171
14	August 8, 2011	28.9	25.8	3,369	August 15, 2011	22.8	20.8	3,567
7	August 15, 2011	22.8	28.9	3,567	August 11, 2011	25.0	22.7	3,751
3.5	August 19, 2011	26.1	29.0	3,669	August 26, 2011	25.6	26.5	3,859
1.75	August 21, 2011	26.1	30.8	3,722	August 28, 2011	25.6	35.0	3,915
Foliar	August 22, 2011	25.0	30.8	3,751	August 29, 2011	23.9	39.4	3,943

[a] Abbreviations: DBCC, days before clipping collection; GDD, growing degree days.
[b] Denotes respective days after herbicide application before clipping collection.
[c] Air temperature (C) from a 2-m height.
[d] Precipitation (cm) accumulated from initial to final herbicide application timing.
[e] GDD accumulated since January 1, 2011, and based on a upper/lower limit of 30/10 C, respectively.

Before and after herbicide application, tall fescue was mown twice weekly at a 10-cm height of cut (HOC) with a push rotary mower (Honda HRC 216, American Honda Motor Co. Inc., Duluth, GA 30136). Clippings were returned to the turf following a mowing event. To minimize potential herbicide displacement, the mowing deck was cleaned of all plant residue and washed with 25 : 75 v/v ammonia : water solution before moving to adjacent tall fescue plots. This mowing methodology is similar to that described in previously published research evaluating synthetic auxin bioavailability from turfgrass clippings in aqueous environments (Lewis et al. 2013a). Other cultural practices, including fertilization, disease/insect control, and irrigation, were conducted according to state extension service recommendations for tall fescue (Bruneau 2007). In experimental runs 1 and 2, initial herbicide applications (56 DBCC) were made June 27, 2011, and July 4, 2011, respectively, and final herbicide applications (1.75 DBCC) were made August 22, 2011, and August 29, 2011, respectively. No mowing events took place for the 3.5 and 1.75 DBCC timings following herbicide application.

At clipping harvest, HOC was lowered to 7.6 cm, and mulched clippings were collected by placing a plastic insert (Hefty Ultra Flex 13 Gallon Tall Kitchen Bags, Pactiv Corp., Lake Forest, IL 60045) into the mower collection bag. Harvested clippings were then recycled and spread evenly by hand onto plots of established white clover (1.5 m^2; 1 m wide $\times$ 1.5 m long) at a rate of 454 g of clippings (fresh weight) $plot^{-1}$. This recycling rate was chosen to reflect the approximate clipping mass harvested from a 1.5 m^2 area of the treated tall fescue. This mass of clippings lightly covered the clover canopy. Treatments for comparison purposes within both experimental runs were directed sprays of aminocyclopyrachlor and clopyralid (79 g ae ha^{-1}) applied at 0 DBCC, nontreated grass clippings, and a control the received no grass clippings. After clipping recycling was complete, white clover plots received 2 mm irrigation to incorporate clippings into the white clover canopy and to prevent contamination between adjacent plots. All mowing practices and irrigation practices to the white clover plots ceased following experiment initiation to ensure clipping displacement did not occur.

Experimental design was a randomized complete block in a four by seven factorial arrangement (four clipping treatments [aminocyclopyrachlor, clopyralid], nontreated mulch, and nontreated control) for seven application timings (56, 28, 14, 7, 3.5, 1.75, and 0 DBCC)] with four replications and two experimental runs. Persistence and bioavailability of aminocyclopyrachlor and clopyralid from clippings were determined weekly by visually evaluating white clover control on a 0 to 100% scale (0%, no visible injury; 100%, plant death) and recording the normalized difference vegetative index (NDVI). Research has indicated NDVI can provide nonsubjective indications of plant vigor, herbicide injury, and harvestable biomass (Bell et al. 2002; Biewer et al. 2009). The NDVI was determined using a Crop Circle ACS-210 radiometer (Crop Circle ACS-210, Holland Scientific Inc., Lincoln, NE 68516) held 1 m above the clover canopy. At 8 wk after treatment (WAT), the white clover was harvested with the previously mentioned mower

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Table 2. White clover visual control, normalized difference vegetative index (NDVI), and biomass affected by turfgrass clipping treatments and days before clipping collection (DBCC) timings.[a,b]

		White clover				
		% Control[c]		NDVI[d]		Biomass[e]
Clipping treatment	DBCC timing[f]	2 WAT	8 WAT	2 WAT	8 WAT	8 WAT
	d	%		m^2		g
AMCP[g]	56	6	16	0.818	0.841	114
	28	11	33	0.817	0.836	104
	14	10	73	0.785	0.770	55
	7	16	86	0.775	0.753	33
	3.5	11	92	0.772	0.740	38
	1.75	14	85	0.764	0.755	48
	Foliar	74	100	0.623	0.693	3
CLPY[g]	56	9	13	0.822	0.825	98
	28	3	13	0.814	0.834	115
	14	8	21	0.808	0.820	114
	7	11	32	0.809	0.837	93
	3.5	9	24	0.815	0.824	110
	1.75	10	16	0.823	0.831	120
	Foliar	67	100	0.717	0.718	19
MULCH	—	0	4	0.813	0.854	117
NT	—	0	3	0.813	0.837	116
$LSD_{(P \leq 0.01)}$	—	4	13	0.028	0.029	18

[a] Abbreviations: AMCP, aminocyclopyrachlor; CLPY, clopyralid; WAT, weeks after treatment; MLCH, nontreated mulch; NT, nontreated control.
[b] Pooled analysis over two experimental runs.
[c] Evaluated visually on a 0 to 100% scale (0%, no injury; 100%, plant death).
[d] Evaluated using Crop Circle ACS-210 radiometer (Holland Scientific, Inc., Lincoln, NE 68516).
[e] Biomass reported as dry weight collected from 0.8-m^2 area of white clover plots.
[f] Denotes respective days after herbicide application before clipping collection.
[g] AMCP and CLPY were applied at 79 g ae ha^{-1}.

(10.2 cm HOC) and a single pass (0.5 m wide) down the center of each plot (1.5 m long) for a total collection across 0.8 m^2. Biomass samples were placed in a glasshouse for 4 wk, and dry weights were recorded.

ANOVA was conducted using mixed-model methodology (SAS statistical software, Version 9, SAS Institute Inc., Cary, NC 27513), and means were separated using Fisher's Protected LSD ($P \leq 0.05$). Clipping treatment and DBCC timing were considered fixed variables in the model. Clipping treatment by DBCC timing was evaluated to determine whether there was an interaction. Experimental run was considered a random variable, allowing for the comparison of treatment means and interactions over multiple environments (Carmer et al. 1989). Experimental run, replication, and interactions between these effects were considered random effects in the model. Visual white clover control, NDVI, and dry biomass means from respective aminocyclopyrachlor and clopyralid clippings were subject to nonlinear regression analysis in SigmaPlot (Systat Software Inc., San Jose, CA 95110) using the four parameter logistic equation:

$$Y = \min + \left\{ (\min - \max) \Big/ \left[1 + (X/GR_{50})^b \right] \right\} \quad [1]$$

where Y is the dependent variable, min and max correspond to the lower and upper asymptotes, X is the independent variable, GR_{50} is the DBCC timing halfway between the max and min asymptotes, and b is the slope of the line. Foliar-directed spray applications of aminocyclopyrachlor and clopyralid, as well as the nontreated mulch and nontreated control, were omitted from the regression analysis to demonstrate the persistence and bioavailability of aminocyclopyrachlor and clopyralid in turfgrass clippings on white clover.

Results and Discussion

The ANOVA determined a significant ($P \leq 0.05$) interaction between clipping treatment and DBCC timings on white clover visual control, NDVI, and dry biomass; therefore, the interaction is reported, rather than the main effects (Table 2).

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Table 3. Parameters of the four-parameter logistic equation for aminocyclopyrachlor clippings to determine the days before clipping collection timing required to induce a 50% growth response (GR_{50}) to white clover visual control, NDVI value, and dry biomass. Data are means ± standard errors.[a,b]

Dependent variable (Y)	Min	Max	GR_{50}	b	R^2
Control	14.1 ± 4.5	88.1 ± 2.1	20.5 ± 1.5	−3.5 ± 0.7	0.99*
NDVI	0.749 ± 0.005	0.841 ± 0.008	17.3 ± 2.5	5.7 ± 3.1	0.99*
Biomass	39.4 ± 4.7	113.9 ± 8.6	18.7 ± 3.0	4.7 ± 2.1	0.98*

[a] Abbreviations: NDVI, normalized difference vegetative index.

[b] Equation $Y = \min + \{(\max - \min)/[1 + (X/GR_{50})^b]\}$, where Y is the dependent variable, min and max correspond to the lower and upper asymptotes, X is the independent variable, GR_{50} is the days before clipping collection timing halfway between the min and max asymptotes, and b is the slope of the line.

* Regression model significant below the 0.05 level of probability.

Nonlinear regression analysis (Equation 1) of white clover visual control, NDVI, and dry biomass was significant ($P < 0.05$) for aminocyclopyrachlor clippings, and GR_{50} values were calculated to determine DBCC timing required to induce a 50% growth reduction (Table 3). However, regression analysis on clopyralid clippings was nonsignificant and, consequently, will not be reported.

Visual White Clover Control. At 2 WAT, epinastic symptomology indicative to synthetic auxin herbicide activity was observed from aminocyclopyrachlor and clopyralid clippings at all corresponding DBCC timings. White clover control ranged from 6 to 14% and 3 to 11% from aminocyclopyrachlor and clopyralid clipping, respectively, at 56 to 1.75 DBCC (Table 2). Foliar-direct spray applications of aminocyclopyrachlor and clopyralid controlled white clover the greatest at 74 and 67%, respectively, whereas no herbicidal activity was noted from the nontreated mulch and nontreated control.

At 8 WAT, aminocyclopyrachlor clippings demonstrated greater white clover control than clopyralid clippings did when applied at 28 to 1.75 DBCC (Table 2). No differences in white clover control were evident from aminocyclopyrachlor or clopyralid clippings when applied at 56 DBCC. White clover control was 33, 73, 86, 92, and 85% from aminocyclopyrachlor clippings treated at 28, 14, 7, 3.5, and 1.75 DBCC, respectively, whereas clopyralid clippings treated at the same DBCC timings controlled white clover 13, 21, 32, 24, and 16%, respectively. Aminocyclopyrachlor and clopyralid foliar-directed spray applications provided 100% white clover control. The nontreated mulch and nontreated control indicated 4 and 3% white clover control, which may have been due to lateral relocation of the synthetic auxin herbicides from rainwater. Aminocyclopyrachlor clippings followed a nonlinear regression pattern ($R^2 = 0.99$; $P < 0.01$) with the GR_{50} for white clover control determined as 20.5 DBCC (Figure 1). Based on visual observations, Strachan et al. (2011) reported that 1 g ha^{-1} aminocyclopyrachlor resulted in a 25% growth reduction (GR_{25}) to white clover when applied PRE to a silty clay loam soil under glasshouse conditions. By extrapolating the white clover GR_{25}, the aminocyclopyrachlor rate reported by Strachan et al. (2011) to the clipping amount recycled from the previously treated tall fescue area, it can be speculated the aminocyclopyrachlor concentration in tall fescue clippings was ≥ 0.33 mg kg clipping^{-1} when treated at ≤ 33 DBCC.

White Clover NDVI. At 2 WAT, turfgrass clippings treated with aminocyclopyrachlor 7 to

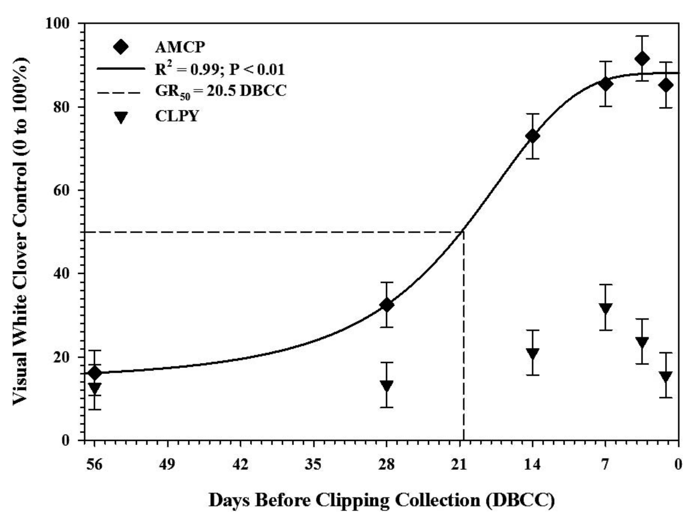

Figure 1. Nonlinear regression of white clover injury affected by tall fescue clippings from previously treated with aminocyclopyrachlor and days before clipping collection (DBCC) timing of 8 wk after treatment, using the equation $Y = \min + \{(\max - \min)/[1 + (X/GR_{50})^b]\}$. Data points are mean ± standard error.

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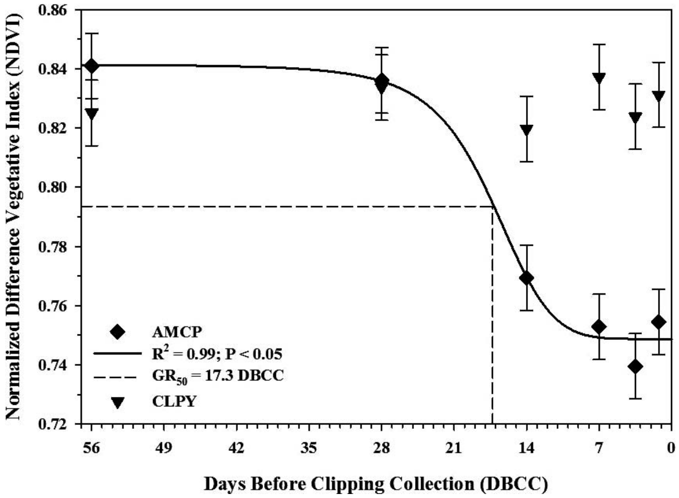

Figure 2. Nonlinear regression of white clover normalized difference vegetative index (NDVI) affected by tall fescue clippings previously treated with aminocyclopyrachlor and days before clipping collection (DBCC) timing at 8 wk after treatment, using the equation $Y = \text{min} + \{(\text{max} - \text{min})/[1 + (X/GR_{50})^b]\}$. Data points are mean ± standard error.

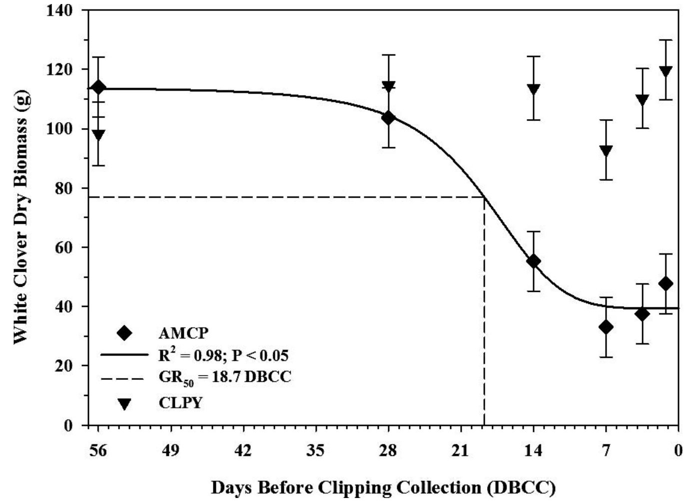

Figure 3. Nonlinear regression of white clover biomass affected by tall fescue clippings previously treated with aminocyclopyrachlor and days before clipping collection (DBCC) timing at 8 wk after treatment, using the equation $Y = \text{min} + \{(\text{max} - \text{min})/[1 + (X/GR_{50})^b]\}$. Data points are mean ± standard error.

1.75 DBCC had lower NDVI values than clopyralid treated clippings did when applied at the same respective DBCC timings (Table 2). No differences in NDVI were apparent from aminocyclopyrachlor and clopyralid clippings applied at 56 to 14 DBCC. NDVI from the clopyralid-treated clippings was not different than the nontreated mulch and nontreated control. Foliar-directed aminocyclopyrachlor and clopyralid applications resulted in the lowest NDVI values (0.623 and 0.717, respectively), which corresponded to the high level of clover control and the consequential bermudagrass [*Cynodon dactylon* (L.) Pers.] release from the formerly clover-dominant plots.

At 8 WAT, aminocyclopyrachlor clippings from 14 to 1.75 DBCC had lower NDVI values than clopyralid clippings did when applied at the same DBCC timings (Table 2). The NDVI from aminocyclopyrachlor and clopyralid clippings from 56 and 28 DBCC were not different from the nontreated mulch or nontreated control. Aminocyclopyrachlor clippings at 14, 7, 3.5, and 1.75 DBCC resulted in lower NDVI than found in the nontreated mulch and nontreated control, whereas only clopyralid applied at 3.5 DBCC produced lower NDVI than the nontreated mulch. Foliar aminocyclopyrachlor and clopyralid applications continued to produce the lowest recorded NDVI, which can be attributed to the high level of clover control. As observed with visual control, aminocyclopyrachlor clippings followed a nonlinear regression pattern ($R^2 = 0.99$; $P < 0.05$), with the GR_{50} for NDVI determined as 17.3 DBCC (Figure 2). Past research has also found NDVI to be indicative of overall plant health because higher NDVI values are associated with greater photosynthetically active radiation being absorbed by plant material (Bell et al. 2002). Biewer et al. (2009) also employed field spectroscopy to predict total biomass of a mixed white clover/perennial ryegrass (*Lolium perenne* L.) sward, suggesting a strong relationship ($r^2 = 0.90$) between NDVI and biomass yield.

White Clover Dry Biomass. Aminocyclopyrachlor clippings applied at 14 to 1.75 DBCC had less biomass than respective clopyralid clippings at 8 WAT (Table 2). No differences in white clover biomass were detected from either herbicide applied at 56 and 28 DBCC. Biomass from nontreated mulch and the nontreated control were 117 and 116 g, respectively, which was greater than the amount of aminocyclopyrachlor clippings applied ≤ 14 DBCC and clopyralid clippings at 7 DBCC. White clover biomass was the least from foliar aminocyclopyrachlor and clopyralid applications, with mass measuring 3 and 19 g, respectively. Biomass reduction from aminocyclopyrachlor clippings followed a nonlinear regression pattern ($R^2 = 0.98$; $P < 0.05$) with the GR_{50} for biomass determined as 18.7 DBCC (Figure 3). The white clover biomass reduction observed from aminocyclopyrachlor clippings was comparable to biomass reduction reported from Bahe and Peacock (1995) who used clippings previously treated with 2,4-D plus dicamba plus MCPP. Although biomass measurements provide insight to synthetic auxin activity, quantifying plant injury by dry weight only can be insensitive to sublethal synthetic auxin levels that can stimulate significant growth responses (Fauci et al. 2002).

Pearson's Correlation Coefficients. Pearson's correlation coefficients were analyzed between white clover visual control, NDVI, and biomass data taken 8 WAT. Correlation of visual control with NDVI ($r = -0.84$; $P < 0.001$) and biomass ($r = -0.80$; $P < 0.001$) was strongly negative, indicating an increase in visual control was equated to decreased NDVI and biomass values. These results are similar to previous research reporting a strong correlation between visual ratings and nonsubjective rating assessments, thus supporting visual evaluation as an effective measure for these plant responses in the scientific community (Lewis et al. 2010; Yelverton et al. 2009). Correlation between NDVI and biomass showed a strong, positive relationship ($r = 0.76$; $P < 0.001$), indicating increased biomass with greater NDVI values. These results are congruent with those of Biewer et al. (2009) who found NDVI to be predictive of harvestable biomass. However, sublethal synthetic auxin levels cannot be quantified accurately by plant dry weight alone and should be supplemented with additional evaluation methods (Fauci et al. 2002).

This research indicated that aminocyclopyrachlor is persistent and bioavailable in clippings of tall fescue previously treated with the herbicide. Recycling clippings laden with aminocyclopyrachlor provides additional broadleaf weed control because aminocyclopyrachlor applied at ≤ 14 DBCC controlled white clover $> 70\%$ and reduced NDVI and biomass $> 50\%$. Further, nonlinear regression analysis of aminocyclopyrachlor clippings determined the GR_{50} for visual control, NDVI, and reduction in biomass as 20.5, 17.3, and 18.7 DBCC, respectively. That similarity of results from three data collection methods in conjunction with strong Pearson correlation coefficients validate the experimental methodology and the initial hypothesis that aminocyclopyrachlor, when present in grass clippings, is persistent and bioavailable. Analytical research has indicated ^{14}C-aminocyclopyrachlor remains unmetabolized within tall fescue for a 192-h period (Lewis et al. 2013b). Those researchers proposed cyclic movement of aminocyclopyrachlor in a tall fescue environment; aminocyclopyrachlor that was present in the treated foliage was released into the soil profile as the clippings decomposed, was then reabsorbed by tall fescue roots, and was translocated back to the aboveground foliage. That cycle allows aminocyclopyrachlor and other synthetic auxin herbicides to persist in clippings of turfgrass even after repeated mowing events (Lewis et al. 2013b; Miltner et al. 2003). Based on this hypothesis, it is probable that the roots of white clover absorbed aminocyclopyrachlor as the treated clippings decomposed and released intact aminocyclopyrachlor. Additional evidence to support delayed bioavailability of aminocyclopyrachlor until grass clipping decomposed is the greater herbicidal response observed at 8 WAT relative to 2 WAT (Table 2).

Clippings of tall fescue treated with clopyralid had minimal effect on white clover. This may be attributed to the lower application rate used in this study to compare the aminocyclopyrachlor and clopyralid on an equal active ingredient basis. Future research should be conducted using the recommended clopyralid labeled rate (≥ 139 g ha^{-1}) to better determine its persistence and potential bioavailability in recycled tall fescue clippings.

Shortly following initiation of these experiments, the Environmental Protection Agency issued a stop sale order to Imprelis because of widespread off-target plant injury, especially on coniferous tree species (USEPA 2011). Although aminocyclopyrachlor is no longer registered for use in commercial or residential turfgrass settings, there are still numerous synthetic auxin herbicides labeled for use on tall fescue within these systems (Senseman 2007). Therefore, recycling clippings of turfgrass treated with synthetic auxin herbicides would allow turfgrass managers an alternative method for clipping disposal while providing additional broadleaf weed control. Adoption of this practice may also reduce the total number of herbicide applications needed to maintain a desirable turfgrass stand, as well as reduce fertility inputs. Conversely, turfgrass managers who choose to recycle clippings of turfgrass treated with synthetic auxin herbicides should first be fully cognizant of the persistence and bioavailability of these compounds to avoid potential nontargeted plant injury and negative environmental impacts.

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