Herbicide programs for seasonal windmillgrass control

by

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Abstract

Windmillgrass (*Chloris verticillata* Nutt.) is a problematic perennial grass weed commonly found in the Midwest of the United States. Currently, there are only two labeled chemical control options in turfgrass. Tenacity® (mesotrione) is labeled for two applications for control while Pylex™ (topramezone) is labeled for a single application for control. However, other herbicides could potentially provide adequate control. Also, there is no literature reported for application timing for optimal windmillgrass control. Therefore, research was conducted to determine if a single application of a common selective perennial grass herbicide would completely control windmillgrass, and to evaluate the herbicide efficacy when applied at spring, summer, or fall application timings. Single herbicide application never achieved complete control of windmillgrass; it was also determined that no differences in control was observed regardless of application timing. Previous research reported herbicide combinations as well as sequential applications could provide better control than herbicides applied alone or as a single application. Therefore, additional research trials were conducted to explore the efficacy with the addition of triclopyr to mesotrione, topramezone, and fenoxaprop as well as triclopyr alone. Sequential applications of these herbicides and herbicide combinations were also applied. It was determined that the addition of triclopyr to these herbicides provided significantly better control of windmillgrass with both single and sequential applications compared to these herbicides alone. Also, two applications of mesotrione and topramezone applied in the early fall alone provided complete control of windmillgrass by spring green up. Additional research was conducted to determine the effects of windmillgrass response to glyphosate at different rates with fall application. It was recorded at spring green up all glyphosate rates at or above 1.66 kg ae ha^{-1} provided complete control of windmillgrass.

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Chapter 1 - Herbicide and Application Timing Effects on Windmillgrass (*Chloris verticillata*) Control

Abstract

Windmillgrass (*Chloris verticillata* Nutt.) is a problematic perennial grass weed commonly found in the Midwest of the United States. Currently, Tenacity® (mesotrione) and Pylex™ (topramezone) are the only labeled chemical control options in turfgrass. Research trials were initiated in Junction City, Kansas at Rolling Meadows Golf Course and Onaga, Kansas at Cool Springs Golf course to identify additional herbicides and optimal application timings for windmillgrass control. Research trials were arranged in a three by ten factorial, randomized complete block with 4 replications. Evaluated factors were; three applications timings and ten herbicides. Application timings were summer (July 2017), fall (September 2017), and spring (May 2018). Herbicide treatments were mesotrione, fenoxaprop, topramezone, quinclorac, sulfentrazone, foramsulfuron, thiencarbazone + iodosulfuron + dicamba, flazasulfuron, trifloxysulfuron, and a non-treated control. Surfactants were added if recommended by the manufacturer. Treatments were applied to 1.5 × 1.5 m plots containing 65 to 75% windmillgrass cover using a CO_2 pressurized boom sprayer calibrated to deliver 402 L ha^{-1}. Data collection consisted of line-intersect analysis (15.24 cm spacing). Data was based off the line-intersect analysis and converted to percent windmillgrass cover for each individual plot. ANOVA was performed in SAS and means were separated according to Fisher's protected LSD at 0.05 significance level. At 6 weeks after application in the spring topramezone had 0% windmillgrass cover at Cool Spring Golf course, but that same application timing at 52 weeks after treatment topramezone had 6.6% windmillgrass cover. Therefore, windmillgrass regrowth was observed. Since no treatment completely controlled windmillgrass one year after each timing, it could take multiple applications to control windmillgrass.

Introduction

Windmillgrass (*Chloris verticillata* Nutt.) populations commonly infest turfgrass systems in the Midwest of the United States, which result in aesthetically unacceptable turfgrass stands. Windmillgrass is a warm season perennial monocot bunch-type grass (Beard & Beard, 2005). Windmillgrass spreads rapidly by stolons and by seeds produced on a panicle seedhead. The foliage grows vertically anywhere from 10 to 40 cm and the seedhead is 7 to 10 cm long (Beard & Beard, 2005). The seedhead has seven to ten slender spikes, 5 to 15 cm long, and arranged in 1 to 3 whorls (USDA, 2019). The seedhead commonly breaks away at maturity and rolls in the wind as a tumble weed (Patton & Weisenberger, 2019). As the panicle seedhead is moved by wind, seeds are dislodged and drop to the soil surface, and producing new windmillgrass plants. Windmillgrass is often found in dry compacted soils next to road sides, parking lots, and sidewalks (Patton & Weisenberger, 2019). However, windmillgrass is becoming more prevalent in desired turfgrass areas such as home lawns, golf courses, and recreational areas.

Windmillgrass is just one of several weeds becoming problematic in turfgrass cropping systems (Trewatha, 2005). Several possible explanations have been offered for why windmillgrass is becoming more prevalent. These include spreading by natural invasive characteristics, the control of previous weed competitors and developing resistance to widely used herbicides (Trewatha, 2005). Based on personal observations, windmillgrass is also able to adapt to a wide range of mowing regimes. These mowing regimes range from 15 cm down to 1.3 cm. Therefore, it has become more abundant in turfgrass systems.

Minimal information has been reported regarding postemergence herbicide options for selective control of windmillgrass in both warm- and cool-season turf (Xiong & Song, 2015). Prior to this field study, the only research trial exploring windmillgrass control with common turfgrass herbicides was conducted in a controlled greenhouse environment. Xiong and Song (2015) researched the use of seven herbicides: fenoxaprop-p-ethyl, foramsulfuron, mesotrione, quinclorac, sulfentrazone, topramezone in tank-mixture with triclopyr, and a prepackage product containing thiencarbazone-methyl, foramsulfuron, and halosulfuron-methyl, in addition to a non-treated control for windmillgrass control (Xiong & Song, 2015). Windmillgrass plants that were treated by mesotrione resulted in 50% shoot injury at 3 weeks after treatment. However, the windmillgrass plants treated by mesotrione started to recover by 4 weeks after treatment (Xiong & Song, 2015).

Prior to the initiation of Xiong and Song's study (2015) and our research study there was only one selective herbicide, Tenacity® (mesotrione), labeled for windmillgrass control (Anonymous 2011). However, in early 2018 Pylex™ (topramezone) also became labeled for control of windmillgrass (Anonymous 2018). Both Tenacity® and Pylex™ fall under the 4-hydrophenylpyruvate dioxygenase inhibitor group is 27. This group inhibits synthesis of carotenoids, which results in lipid peroxidation.

Literature on application timing and postemergence herbicide effects on windmillgrass in a non-controlled turfgrass system is sparse. Therefore, the objectives of this research were (1) to evaluate the best time to control windmillgrass and (2) to determine if a single application of a common selective perennial grass herbicide would provide complete control of windmillgrass.

Materials and Methods

Research Site Information

Two separate field experiments were conducted in Junction City, Kansas at Rolling Meadows Golf Course (RM) (Trial location 1) in a golf course rough area and in Onaga, Kansas at Cool Springs Golf Course (CS) (Trial location 2) in a golf course driving range. Soil was a

Holder silt loam (Fine-silty, mixed, superactive, mesic Udic Argiustolls) at RM with 2.0% organic matter and pH 5.5. Soil was a Wymore silty clay loam (fine, smectitic, mesic Auertic Argiudolls) at CS with 3.0% organic matter and pH 6.0. These studies were conducted on established tall fescue (*Schedonorus arundinaceus*) turfgrass at both locations. However, the tall fescue stands were thin and contained a diverse population of weeds. Plots were maintained at 7.6 cm with a rotary mower, mowing occurred once per week or as needed and clippings being blown away from the study area. During each study, no supplemental irrigation was directly applied to the plot area at each location. Prior to each application timing at each trial location at 2.93 kg ha^{-1} was applied with a broadcast spreader[2] to prevent new windmillgrass populations.

Herbicides and Application Timings

Field experiments were arranged in a three by ten factorial randomized complete block design with four replications. Main factors included three application timings (summer, fall and spring) and ten different herbicides. Summer applications were initiated on 14 July 2017 at RM and 18 July 2017 at CS. Fall applications were initiated on 7 September 2017 at RM and 15 September 2017 at CS. Spring applications were initiated on 24 May 2018 at RM and 25 May 2018 at CS. Each trial location was 22.9 × 12.2 m with 1.5 × 1.5 m plots four replicates were included at both locations for each treatment. Herbicide treatments consisted of and were applied based off of the highest label rate for a single application for each herbicide which include: (1) mesotrione[3] (0.28 kg ha^{-1}); (2) fenoxaprop[4] (0.19 kg ha^{-1}); (3) topramezone[5] (0.05 kg ha^{-1}); (4) quinclorac[6] (0.84 kg ha^{-1}); (5) sulfentrazone[7] (0.28 kg ha^{-1}); (6) foramsulfuron[8] (0.12 kg ha^{-1}); (7) thiencarbazone (0.03 kg ha^{-1}) + iodosulfuron (0.007 kg ha^{-1}) + dicamba [9] (0.2 kg ha^{-1}); (8) flazasulfuron[10] (0.05 kg ha^{-1}); (9) trifloxysulfuron[11] (0.027 kg ha^{-1}); and a non-treated control where no herbicides were applied. A non-ionic surfactant[12] was applied with mesotrione, fenoxaprop, and flazasulfuron at 0.25% v/v and a non-ionic surfactant was added to trifloxysulfuron at 0.5% v/v according to manufacturer label. Methylated seed oil[13] was applied with thiencarbazone + iodosulfuron + dicamba at 0.5% v/v. Methylated seed oil was added to topramezone and foramsulfuron at 1% v/v. Methylated seed oil was added to quinclorac at 1.75 L ha^{-1} according to manufacturer label.

All treatments were applied to 1.5 × 1.5 m plots using a CO_2 pressurized hand-held spray boom equipped with four 8003 flat-fan nozzles[14] on 25 cm spacing calibrated to deliver 402 L ha^{-1}.

Data Collection and Analysis

Windmillgrass percent cover was visually rated weekly at each location up to 4 weeks after herbicide application (WAA) then at 6, 8, and 52 WAA. Data included visual weed cover ratings on a scale of 0 to 100% where 0= no windmillgrass and 100= complete cover of windmillgrass. A rating grid using line intersect analysis (15.24 cm spacing) with 49 intersections was placed over each treatment plot; a count was recorded for each intersection when windmillgrass was present. Intersect counts were converted using Equation 1.1 below is based off of (Karcher & Richardson, 2013).

[1.1] % Windmillgrass Cover = [(grid intersection count at rating date / 49 total intersections) × 100]

Data presented in this project are all based off of equation 1.1. All data were subjected to ANOVA (P= 0.05). ANOVA results were used to select both main effects and interactions. Mean separations for % windmillgrass cover comparisons were accomplished using Fisher's Protected LSD ($P \leq 0.05$).

Results and Discussion

Treatments were effective at reducing windmillgrass populations; however, no treatment completely controlled windmillgrass one year after each timing.

An herbicide treatment by location interaction was significant, thus data are presented by each location. Herbicide by application timing interaction was observed for windmillgrass cover at 6 and 8 WAA at RM (Table 1.1) and at 4 and 6 WAA at CS (Table 1.2).

At both RM and CS there were rating dates when there wasn't an interaction of herbicide by application timing was not observed, but there were main effects on those dates such as timing and herbicides. At both RM and CS, timing main effect was observed at initial day of treatments. At both RM and CS, windmillgrass percent cover at initial application in the spring at RM showed less percent windmillgrass cover compared to the summer and fall timings (Table 1.5 and Table 1.6). This is likely to do with the fact that there were different populations of windmillgrass at each application timing.

Rolling Meadows

There were herbicides that had significant differences in percent windmillgrass cover when comparing differences within each active ingredient between application timings at 6 WAA. In the spring 6 WAA topramezone had less windmillgrass cover than all herbicides except fenoxaprop, and mesotrione. Topramezone with 2.6% windmillgrass cover while fenoxaprop and mesotrione with 11.2%, and 13.8% windmillgrass cover, respectively, compared to all other herbicides including the non-treated plots had 26% windmillgrass cover (Table 1.3). At the initiation of spring timing plots treated with topramezone, fenoxaprop, and mesotrione had 20.4%, 18.9%, and 23% windmillgrass cover, respectively. However, summer 6 WAA topramezone had less percent windmillgrass cover with 1.5% compared to all herbicides but fenoxaprop with 26.6% windmillgrass cover. The summer initial percent cover for plots treated with topramezone and fenoxaprop was 46.4% and 37.8% cover, respectively. In the fall 6 WAA the only significant differences between herbicides was with topramezone and thiencarbazone + iodosulfuron + dicamba with 30.6% and 51% windmillgrass cover, respectively.

Mesotrione reduced windmillgrass percent cover to 13.8, 41.4, and 37.8% windmillgrass cover at 6 WAA for spring, summer, and fall applications at RM Mesotrione with 13.8% windmillgrass cover at 6 WAA from spring application is less than 41.4% windmillgrass cover at 6 WAA from summer applications at RM (Table 1.3). At 6 WAA the non-treated had 26, 52.6, and 43.9% windmillgrass cover for spring, summer, and fall timings, respectively. Fenoxaprop reduced 11.2% windmillgrass cover 6 WAA from spring application, which is less than 6 WAA from the fall and summer application with 36.2% and 26.6% windmillgrass cover, respectively.

Topramezone in the spring 6 WAA with 2.6% windmillgrass cover and summer application 6 WAA with 1.5% windmillgrass cover 6 WAA are statistically the same (Table 1.3). Mutually 6 WAA from spring and summer applications of topramezone are statistically different than fall 6 WAA with 30.6% windmillgrass cover (Figure 1.1). All other herbicides resulted in ≥23.5% cover windmillgrass cover 6 WAA in the spring, summer, and fall at RM.

Much like 6 WAA, 8 WAA from spring application at RM, topramezone resulted in less windmillgrass percent cover than every other herbicide except fenoxaprop. Topramezone with 3.1% windmillgrass cover was less than all other herbicides but fenoxaprop with 16.8% windmillgrass cover 8 WAA in the spring (Table 1.3).

Results 8 WAA from the summer applications timing at RM are very similar to the 8 WAA from the spring application timing. In the summer 8 WAA the non-treated had 57.6%

windmillgrass cover (Table 1.3). Topramezone 8 WAA from summer application resulted in less windmillgrass cover than every other herbicide except fenoxaprop. Topramezone 8 WAA from summer application, resulted in 9.7% windmillgrass cover while fenoxaprop 8 WAA from summer application resulted in 34.7% windmillgrass cover.

When comparing the differences between each active ingredient within application timing at the same WAA, topramezone 8 WAA in spring, summer, and fall application resulted in statistically the same percent windmillgrass cover. However, topramezone resulted in ≤11.7% windmillgrass cover 8 WAA all applications (Table 1.3). There were herbicides that were statistically different at each application timing, quinclorac is one of those herbicides. Quinclorac resulted in 18.9% windmillgrass cover 8 WAA from the fall application, which is significantly different than 8 WAA from both the spring and summer applications.

Cool Springs

In the spring at CS 4 WAA, topramezone resulted in 4.1% windmillgrass cover which is less cover than all the herbicides except fenoxaprop including the non-treated which was 22.9% windmillgrass cover (Table 1.4). Fenoxaprop resulted in 9.7% windmillgrass cover 4 WAA from the spring application, all other herbicides resulted in ≥17.4% windmillgrass cover 4 WAA at CS. Topramezone had 22.5% windmillgrass cover windmillgrass at spring initiation while fenoxaprop had 20.4% windmillgrass cover at spring initiation.

In the summer at 4 WAA the only significant difference was fenoxaprop with 5.1% windmillgrass cover and flazasulfuron with 34.2% windmillgrass cover. Fenoxaprop resulted in 9.7% windmillgrass cover at 4 WAA from the spring application, less than 30.1% windmillgrass cover at 4 WAA from fall application (Table 1.4). Fenoxaprop in both the summer and spring 4

WAA resulted in 5.1 and 9.7%, windmillgrass cover, respectively, which is less than the fall application with 30.1% windmillgrass cover.

In the spring 4 WAA, topramezone with 4.1% windmillgrass cover, is less than 24.5% windmillgrass cover at 4 WAA from fall application at CS (Table 1.4). However, topramezone resulted in 13.8% windmillgrass cover in the summer at 4 WAA which was statistically the same as both spring and fall.

At CS 6 WAA in the spring non-treated was 22.4% windmillgrass cover (Table 1.4). The results CS 6 WAA were very similar those at RM. Topramezone resulted in 0% windmillgrass cover 6 WAA from spring applications, less than all other herbicides 6 WAA at CS. While there are significant differences in percent windmillgrass cover during in the summer 6 WAA, many of the herbicides are statistically the same. Fenoxaprop with 17.3% windmillgrass cover at 6 WAA from the summer application, which was the least amount of windmillgrass cover. Fenoxaprop is only less cover than quinclorac, flazasulfuron, and trifloxysulfuron at 6 WAA at CS.

Main Effect

Application timing as a main effect at RM during 1, 2, 3, 4, and 52 WAA was very consistent in that the spring timing had less windmillgrass cover compared to both the fall and summer (Table 1.5). Spring windmillgrass populations were less than fall and summer at initiation, this could be attributed to much below average to average precipitation November, 2017 through April, 2018 (NOAA, 2019). While at 4 and 52 WAA there was a significant difference in herbicides (Table 1.7). Topramezone with 9.9% windmillgrass cover at 52 WAA is less than all other herbicides at RM.

Much like RM, CS is very similar with application timing as a main effect at 1, 2, 8, and 52 WAA having spring having less windmillgrass cover compared both the fall and summer (Table 1.6). While herbicides showed significant difference at 3, 8 and 52 WAA at CS, no herbicide was less than the non-treated (Table 1.8).

Conclusion

Herbicide treatments varied when comparing the locations and timings. Except for topramezone which had less windmillgrass cover at both locations 6 WAA with a spring application (Table 1.4). Although herbicide timing often has a dramatic effect on the efficacy of the herbicide application (Johnson et al. 2002; Raudenbush and Keeley, 2014; Reicher and Wiesenberger, 2007) it was also determined that no difference in control was observed regardless of application timing. Also, with a single application we did achieve complete control with a single application. Even though, at CS, topramezone applied in the spring had 0% windmillgrass cover at 6 WAA, that same spring application had 13.4% windmillgrass cover at 52 WAA (Table 1.8). Therefore, we saw regrowth of windmillgrass. No treatment completely controlled windmillgrass a year after each timing.

Results from both locations indicate that a single application of some herbicides will only reduce windmillgrass cover but not completely eradicate windmillgrass. Application timings for control does not matter. Homeowners, lawn care professionals, and golf course superintendents should use either topramezone or fenoxaprop for effective windmillgrass control but should know complete control of windmillgrass will not be achieved.

Sources of Materials

[1] Oxadiazon 2G, Control Solutions Inc. Pasadena, TX 77507

[2] SiteOne Landscape Supply. Roswell, GA 30076

[3] Tenacity® 4 SC, Syngenta Crop Protection. Greensboro, NC 27419

[4] Acclaim® Extra 0.57 EC, Bayer Environmental Science. Cary, NC 27513

[5] Pylex™ 2.8 SC, BASF Corporation. Research Triangle Park, NC 27709

[6] Drive® XLR8 1.5 SL, BASF Corporation. Research Triangle Park, NC 27709

[7] Dismiss® 4 F, FMC Corporation. Philadelphia, PA 19103

[8] Revolver® 0.19 L, Bayer Environmental Science. Cary, NC 27513

[9] Celsius® 68 WG, Bayer Environmental Science. Cary, NC 27513

[10] Katana® 25 WG, PBI Gordon. Shawnee, KS 66286

[11] Monument® 75 WG, Syngenta Crop Protection. Greensboro, NC 27419

[12] Cornbelt Premier 90® Nonionic Spreader, Van Diest Supply CO. Webster City, IA 50595

[13] Methylated Seed Oil, LESCO, Inc. Cleveland, OH 44114

[14] TeeJet 8003 Spraying Systems Co. Glendale Heights, IL 60139

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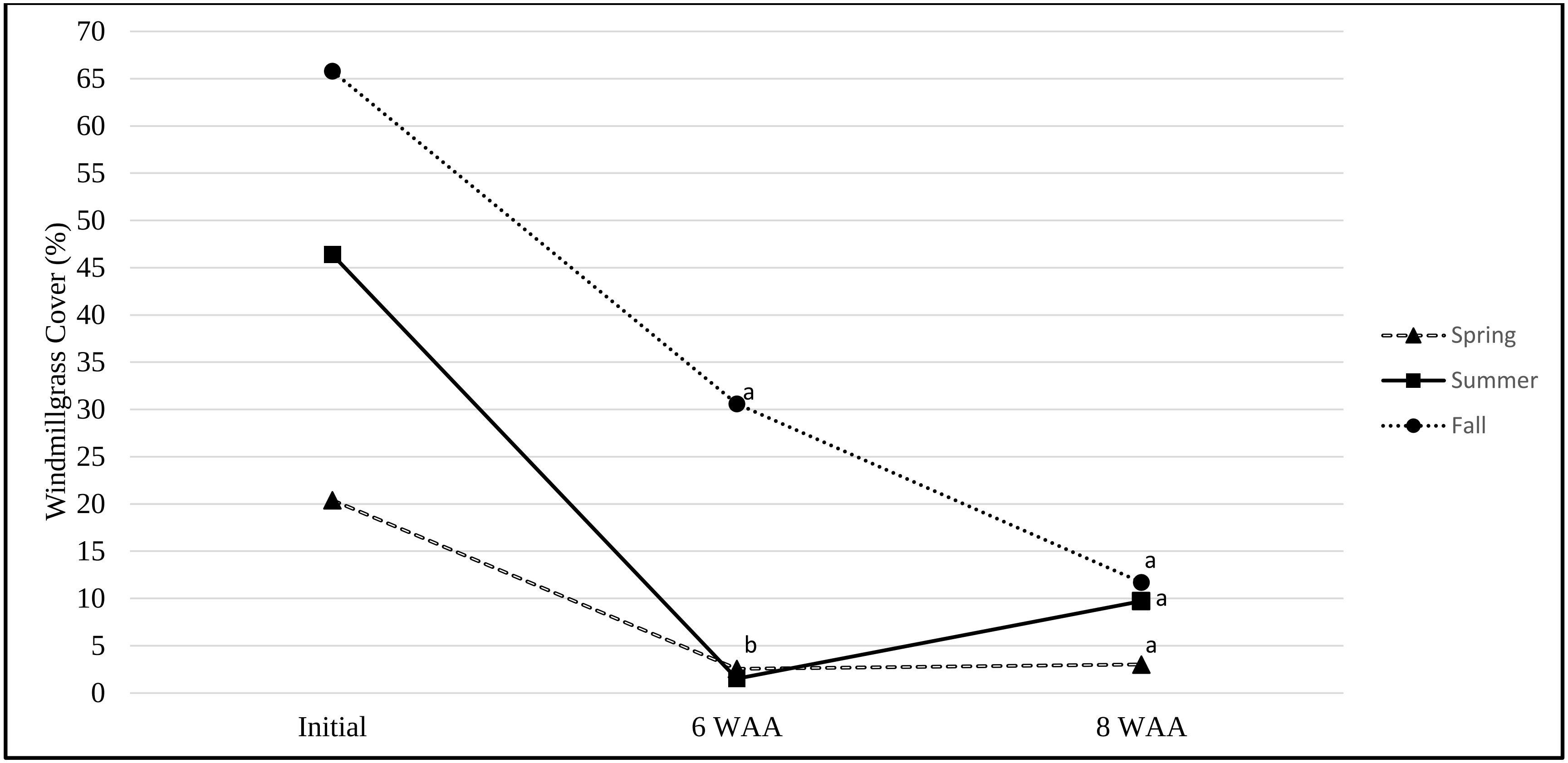
Figure 1.1 Percent windmillgrass (*Chloris verticillata* Nutt.) cover 6[y] and 8[z] weeks after application from May 24, 2018 (Spring); July 14, 2017 (Summer); Sept. 7, 2017 (Fall) applications with topramezone at 0.05 kg ha^{-1} at Rolling Meadows.



Means followed by the same letter on WAIA are not significantly different ($P \leq 0.05$) according Fisher's Protected LSD.

[y] Ratings 6 weeks after each applications timing occurred on July 3, 2018 (Spring), Aug. 25, 2017 (Summer) and Oct. 19, 2017 (Fall).

[z] Ratings 8 weeks after each applications timing occurred on July 19, 2018 (Spring), Sept. 7, 2017 (Summer) and Nov. 2, 2017 (Fall).

Table 1.1 ANOVA for percent Windmillgrass (*Chloris verticillata* Nutt.) cover at various WAA with herbicide and application timing at Rolling Meadows Golf Course in Junction City, KS.

	P-Value Associated with *F*							
	Windmillgrass Cover							
	WAA							
	0	1	2	3	4	6	8	52
Timing (T)	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Herbicide (H)	NS[a]	NS	0.0107	0.0003	<.0001	<.0001	<.0001	<.0001
T x H	NS	NS	NS	NS	NS	0.0004	0.0006	NS

Abbreviations: ANOVA, Analysis of Variance; WAA, Weeks after application; NS, not significant

[a] Significance of WAA reaction terms when data were subjected to ANOVA (P=0.05).

Table 1.2 ANOVA for percent Windmillgrass (*Chloris verticillata* Nutt.) cover at various WAA with herbicide and application timing at Cool Springs in Onaga, KS.

	P-Value Associated with *F*							
	Windmillgrass Cover							
	WAA							
	0	1	2	3	4	6	8	52
Timing (T)	0.0001	0.0003	<.0001	NS[a]	0.0177	<.0001	<.0001	<.0001
Herbicide (H)	NS	NS	NS	<.0001	<.0001	<.0001	0.0002	<.0001
T x H	NS	NS	NS	NS	0.0033	0.0038	NS	NS

Abbreviations: ANOVA, Analysis of Variance; WAA, Weeks after application; NS, not significant

[a] Significance of WAA reaction terms when data were subjected to ANOVA (P=0.05).

Table 1.3 Interaction between herbicide and application timing of Windmillgrass (*Chloris verticillata* Nutt.) percent cover at Rolling Meadows Golf Course in Junction City, KS.

	Windmillgrass Cover (%)								
	Initial			6 WAA[a]			8 WAA		
Herbicides[b]	Spring	Summer	Fall	Spring	Summer	Fall	Spring	Summer	Fall
non-treated	28.1 Aa	46.4 Aab	58.2Aab	26.0 A[c]ab[d]	52.6 Abcd	43.9Aab	26.0 Bbc	57.6 Aab	26.5 Ba
mesotrione	23 Ba	45.9 ABab	67.4 Aa	13.8 Bbcd	41.4 Acd	37.8ABab	22.0 Bbc	49.9 Ab	15.3Bbc
fenoxaprop	18.9 Ba	37.8 ABa	51.0 Aa	11.2 Bbcd	26.6 Abde	36.2Aab	16.8 Bcd	34.7 Abc	16.8 Bbc
topramezone	20.4 Ca	46.4 Bab	65.8 Aa	2.6 Bd	1.5 Be	30.6 Ab	3.1 Ad	9.7 Ac	11.7 Ac
quinclorac	31.6 Ba	58.7 Aab	58.7Aab	34.7 Ba	67.9 Aab	37.8Bab	43.4 Ba	74.0 Aa	18.9 Cabc
sulfentrazone	22.0 Ba	56.6 Aab	61.7 Aa	28.1 Bab	55.6 Aabc	38.8 Aab	31.2Babc	60.7 Aab	20.9 Bab
foramsulfuron	24.0 Ba	59.7Aab	54.6Aab	27.5 Cab	75.5 Aab	44.9 Bab	36.8 Bab	77.1 Aa	18.9 Babc
thien+iodo+dicamba[e]	21.4 Ba	54.6 Aab	70.4Aa	30.1 Ca	80.1 Aa	51.0 Ba	35.7 Bab	77.0 Aa	23.5 Bab
flazasulfuron	28.1 Ba	64.3 Aa	28.1 Bb	37.8 Ba	72 .0 Aab	37.3 Bab	44.4 Ba	80.6 Aa	21.4 Bab
trifloxysulfuron	21.9 Ba	66.4 Aa	50.5Aab	23.5 Babc	73.5 Aab	40.3 Bab	26.5 Bbc	79.6 Aa	19.9 Babc
LSD[f]	15.4	26.2	20.9	14.5	26.4	15.3	16.5	26.5	9.1

[a] WAA= Weeks after application.

[b] Herbicides ranked no specific order.

[c] Treatment means followed by the same capital letter are not significantly different within each herbicide among application timing at the same WAA according to Fisher's protected LSD ($P \leq 0.05$).

[d] Treatment means followed by the same lower case letter are not significantly different within an application timing at each WAA according to Fisher's protected LSD ($P \leq 0.05$).

[e] thiencarbazone + iodosulfuron + dicamba.

[f] LSD is based off of lower case letters

Table 1.4 Interaction between herbicide and application timing of Windmillgrass (*Chloris verticillata* Nutt.) percent cover at Cool Springs Golf Course in Onaga, KS.

	Windmillgrass Cover (%)								
	Initial			4 WAA[a]			6 WAA		
Herbicides[b]	Spring	Summer	Fall	Spring	Summer	Fall	Spring	Summer	Fall
non-treated	13.8 Bb	34.7 Aa	26.5ABabc	22.9 A[c]bc[d]	20.4Aabc	16.8 Ac	22.4 Aab	28.1 Acd	10.2 Bb
mesotrione	30.6 Aa	30.1 Aa	40.3 Aab	17.4 Acd	17.9 Aabc	24.5 Aabc	17.2 Abcd	27.0 Acd	15.3 Aab
fenoxaprop	20.4 Aab	38.3 Aa	35.7 Aabc	9.7 Bde	5.1 Bc	30.1 Aab	10.7 ABcd	17.3 Ad	10.2 Bb
topramezone	22.5 Bab	31.1 ABa	45.4 Aa	4.1 Be	13.8 ABbc	24.5 Aabc	0.0 Be	25.0 Acd	13.8 ABab
quinclorac	26.0 Aab	32.1 Aa	29.6 Aabc	34.2 Aab	20.9 Aabc	29.1 Aab	31.6 Bab	47.4 Aabc	16.3 Cab
sulfentrazone	22.9 Bab	41.3 Aa	35.2 Aabc	32.1 Aab	14.3 Babc	26.5 Aabc	29.1 Aab	26.0 ABcd	11.3 Bb
foramsulfuron	23.5 Aab	35.2 Aa	24.0 Abc	30.1 Aab	13.8 Bbc	35.2 Aa	28.6 Aab	24.5 Acd	28.1 Aa
thien+iodo+dicamba[e]	27.1 Aab	45.4 Aa	35.7 Aabc	38.8 Aa	29.6 Aab	27.1 Aabc	35.2 Aa	39.8 Abcd	25.5 Aab
flazasulfuron	24.0 Aab	43.4 Aa	29.1 Aabc	39.8 Aa	34.2 Aa	24.0 Aabc	39.3 ABa	51.1 Aab	12.8 Bab
trifloxysulfuron	26.0 ABab	43.4 Aa	19.4 Bc	33.2 Aab	31.6 Aab	20.4 Abc	30.6 Bab	64.8 Aa	12.3 Bab
LSD[f]	16	23.9	19.7	14.5	26.4	15.3	11.2	24.5	15.9

[a] WAA= Weeks after application.

[b] Herbicides ranked no specific order.

[c] Treatment means followed by the same capital letter are not significantly different within each herbicide among application timing at the same WAA according to Fisher's protected LSD ($P \leq 0.05$).

[d] Treatment means followed by the same lower case letter are not significantly different within an application timing at each WAA according to Fisher's protected LSD ($P \leq 0.05$).

[e] thiencarbazone + iodosulfuron + dicamba.

[f] LSD is based off of lower case letters

Table 1.5 Application timing at Rolling Meadows Golf Course in Junction City, KS.

	Windmillgrass Cover (%)					
Timing	0 WAA[a]	1 WAA	2 WAA	3 WAA	4 WAA	52 WAA
Fall	57.9 a[b]	59.3 a	54.4 a	44.3 b	43.9 a	64.3 a
Summer	53.7 a	44.5 b	50.1 a	51.3 a	44.5 a	40.6 b
Spring	23.9 b	23.2 c	21.8 b	20.1 c	23.6 b	29.8 c
P-value	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
LSD	6.6	6.6	7.0	6.5	7.7	10.5

[a] WAA= Weeks after application.

[b] Treatment means followed by the same letter are not significantly different between each timing within each WAIA according to Fisher's protected LSD ($P \leq 0.05$).

Table 1.6 Application timing at Cool Springs Golf Course in Onaga, KS.

	Windmillgrass Cover (%)				
Timing	0 WAA[a]	1 WAA	2 WAA	8 WAA	52 WAA
Fall	32.7 a[b]	26.8 a	25.3 a	23.9 a	24.0 a
Summer	32.7 a	26.8 a	25.3 b	23.9 b	24.0 a
Spring	24.8 b	18.0 b	19.5 c	11.7 c	13.7 b
P-value	0.0004	0.0004	<.0001	<.0001	<.0001
LSD	6.4	5.4	5.2	6.4	4.7

[a] WAA= Weeks after application.

[b] Treatment means followed by the same letter are not significantly different between each timing within each WAIA according to Fisher's protected LSD ($P \leq 0.05$).

Table 1.7 Herbicide at Rolling Meadows Golf Course in Junction City, KS.

	Windmillgrass Cover (%)			
Herbicide	4 WAA[a]		52 WAA	
flazasulfuron	47.3	a[b]	59.9	a
thien+iodo+dicamba[c]	46.4	a	57.1	a
quinclorac	46.1	a	54.3	ab
trifloxysulfuron	46.1	a	59.9	a
foramsulfuron	43.5	a	45.9	abc
sulfentrazone	42.9	a	50.5	ab
non-treated	40.3	ab	47.1	abc
mesotrione	27.2	bc	29.9	c
fenoxaprop	18.5	c	35.0	bc
topramezone	14.8	c	9.9	d
P -value	<.0001		<.0001	
LSD	13.4		19.5	

[a] WAA= Weeks after application.

[b] Treatment means followed by the same letter are not significantly different between each herbicide within the same WAA according to Fisher's protected LSD ($P \leq 0.05$).

[c] thiencarbazone + iodosulfuron + dicamba.

Table 1.8 Herbicide at Cool Springs Golf Course in Onaga, Ks.

	Windmillgrass Cover (%)					
Herbicide	3 WAA[a]		8 WAA		52 WAA	
quinclorac	34.0	a[b]	26.2	abc	18.0	bc
flazasulfuron	30.4	ab	26.4	abc	26.2	a
thien+iodo+dicamba[c]	28.4	ab	29.9	ab	26.7	a
trifloxysulfuron	28.1	ab	32.7	a	26.9	a
foramsulfuron	25.8	abc	24.8	abc	20.4	ab
sulfentrazone	25.0	bc	23.5	abc	21.3	ab
mesotrione	18.5	cd	17.7	cd	17.7	bc
non-treated	17.7	cd	18.4	bcd	18.4	bc
topramezone	16.3	d	10.9	d	13.4	bc
fenoxaprop	16.2	d	15.7	cd	12.1	c
P -value	<.0001		0.0138		0.0006	
LSD	8.6		12.2		7.8	

[a] WAA= Weeks after application.

[b] Treatment means followed by the same letter are not significantly different between each herbicide within the same WAA according to Fisher’s protected LSD ($P \leq 0.05$).

[c] thiencarbazone + iodosulfuron + dicamba.

Chapter 2 - Influence of Herbicide Combinations and Sequential Applications on Windmillgrass (*Chloris verticillata*) Control

Abstract

Windmillgrass (*Chloris verticillata* Nutt.) is a problematic perennial grass weed commonly found in the Midwest of the United States. At time of trial initiation, Tenacity® (mesotrione) was the only herbicide labeled for windmillgrass control with two applications two to three weeks after the first application. Field research trials were initiated in Manhattan, KS at Rocky Ford Turfgrass Research Center to identify the effect of single versus sequential applications of postemergent herbicides as well as tank-mixing triclopyr with HPPD^{-} and ACCase^{-} inhibitor herbicides on windmillgrass control. Treatments were arranged in a 2 by 8 factorial design, with 4 replications and repeated in time. Evaluated factors were 2 application timings (single or sequential) and 8 herbicide combinations. Application timings were 16 August 2018 (trial 1) and 11 September 2018 (trial 2). The sequential application was applied on 9 September 2018 (trial 1) and 2 October 2018 (trial 2). Herbicide treatments were topramezone, mesotrione, fenoxaprop, triclopyr, topramezone + triclopyr, mesotrione + triclopyr, fenoxaprop + triclopyr, and a non-treated control. Surfactants were added if recommended by the manufacturer. Treatments were applied to 1.22 × 1.22 m plots containing 60 to 70% windmillgrass cover using a CO_2 pressurized 4 nozzle hand-held boom sprayer calibrated to deliver 402 L ha^{-1}. Windmillgrass grass percent control was based off of line-intersect analysis (15.24 cm spacing). Data was based off the line-intersect analysis and converted to percent windmillgrass control for each individual plot. ANOVA was performed in SAS and means were separated according to Fisher's protected LSD at 0.05 significance level. Throughout both trials, it was determined that two sequential applications of an herbicide or herbicide combinations except fenoxaprop alone will provide complete control of windmillgrass. Also, tank-mixing with triclopyr to each herbicide improved the efficacy of each herbicide.

Introduction

Currently limited options are available for windmillgrass control in turfgrass systems. Tenacity® (mesotrione) and Pylex™ (topramezone) are the two herbicides currently available for turfgrass managers that are labeled for windmillgrass control. The Tenacity® manufacturer label recommends a second application two to three weeks after initial application (Anonymous 2011). Additionally, studies have shown the addition of triclopyr to of 4-hydroxyphenylpyruvate dioxygenase ($HPPD^-$) inhibitors increases windmillgrass control in a controlled environment (Smeda & Xiong, 2019). Prior research indicated that triclopyr tank-mixed with topramezone improves grass control (Cox et al. 2017; Brosnan & Breeden, 2013; Brosnan et al. 2014). The combination of topramezone with triclopyr reduced whitening symptoms on susceptible plant species while increasing both grass and broadleaf weed control (Venner et al. 2013). Research conducted by Smeda & Xiong (2019) in a controlled environment, at the University of Missouri did two different studies. The first study was to evaluate a single application of seven selected postemergent herbicides for controlling windmillgrass. Windmillgrass that received fenoxaprop-p-ethyl or topramezone tank-mixed with triclopyr resulted in 100% windmillgrass control four weeks after application (Smeda & Xiong, 2019). All herbicides but fenoxaprop-p-ethyl and topramezone tank-mixed with triclopyr, resulted in ≥50% injury four weeks after treatment, with the exception of mesotrione at 66% injury (Smeda & Xiong, 2019).

The second study explored the efficacy of 4-hydroxyphenylpyruvate dioxygenase ($HPPD^-$) inhibitors for windmillgrass control. The research was conducted under greenhouse conditions. In this study six different treatments were applied at the label-suggested rate. Similar to their first study, Smeda & Xiong (2019) reported, triclopyr tank-mixed with topramezone and mesotrione resulted in 100% windmillgrass control.

Mesotrione and topramezone each applied alone only resulted in 40 to 50% control when compared to the non-treated control at four weeks after treatment. Windmillgrass that received $HPPD^-$ inhibitor herbicides alone, showed regrowth six weeks after treatment. In comparison, the windmillgrass that had the tank-mixture of $HPPD^-$ inhibitor herbicides plus triclopyr still showed complete control at six weeks after treatment. Also, triclopyr alone showed greater than 90% injury to windmillgrass just two weeks after treatment. Triclopyr resulted in 91% windmillgrass control. Overall, using $HPPD^-$ herbicides in a tank-mixture with triclopyr shows acceptable control of windmillgrass in a controlled environment.

Research results indicate that weed control in a controlled environment often results better control than in a field. Glenn et al. (2015) study, resulted that in a controlled environment that sodium bicarbonate at 374 L ha^{-1} resulted in 66% southern crabgrass (*Digitaria ciliaris*) at one-two leaf stage 7 days after initial treatment. While in the field experiment sodium bicarbonate also at 374 L ha^{-1} resulted in 44% southern crabgrass (*Digitaria ciliaris*) at one-two leaf stage 7 days after initial treatment.

Therefore, the objectives of this research were to (1) evaluate the single versus a sequential application of postemergent herbicides and (2) addition of triclopyr to $HPPD^-$ and $ACCase^-$ inhibitor herbicides on windmillgrass control in field experiments.

Materials and Methods

Research Site Information

Two separate field experiments were initiated at Rocky Ford Turfgrass Center (RF) in Manhattan, KS. The soil was a Chase silty clay loam (fine, smectitic, mesic Aquertic Argiudolls) with 6.8 pH and 2.7% organic matter. Both trials were conducted on tall fescue (*Schedonorus arundinaceus*) at RF. Plots were maintained at 7.6 cm with a rotary mower and mowing occurred once per week or as needed. Clippings were removed from the study area. During each study, no supplemental irrigation was applied. Prior to each trial initiation oxadiazon[1] at 2.93 kg ha^{-1} was applied with a broadcast spreader[2] to prevent new windmillgrass populations and other summer annual weeds.

Herbicides and Application Timings

Separate field experiments were initiated on 16 August 2018 (trial 1) and 11 September 2018 (trial 2). The sequential application was applied on 9 September 2018 (trial 1) and 2 October 2018 (trial 2). Field experiments were arranged in a two by eight factorial design with four replications. Plots were 1.22 × 1.22 m. Main factors included two application strategies (single or sequential application), and eight herbicide combinations. A non-treated control was included for comparison for a total of 15 individual treatments.

Treatments applied were based on labeled rates and include: (1) topramezone[3] (0.05 kg ha^{-1}); (2) mesotrione[4] (0.28 kg ha^{-1}); (3) fenoxaprop[5] (0.19 kg ha^{-1}); (4) triclopyr[6] (1.12 kg ae ha^{-1}); (5) topramezone (0.05 kg ha^{-1}) + triclopyr (1.12 kg ae ha^{-1}); (6) mesotrione (0.28 kg ha^{-1}) + triclopyr (1.12 kg ae ha^{-1}); (7) fenoxaprop (0.19 kg ha^{-1}) + triclopyr (1.12 kg ae ha^{-1}); (8) non-treated control where no herbicides were applied. A non-ionic surfactant[7] was applied with mesotrione, fenoxaprop, mesotrione + triclopyr, and fenoxaprop + triclopyr at 0.25% v/v. Methylated seed oil[8] was added to topramezone and topramezone + triclopyr at 1% v/v.

All treatments were applied to 1.22 × 1.22 m plots using a CO_2 pressurized hand-held spray boom equipped with four 8003 flat-fan nozzles[9] on 25 cm spacing calibrated to deliver 402 L ha^{-1}.

Data Collection and Analysis

Windmillgrass grass percent cover was collected weekly up to 6 weeks after initial application (WAIA) for each trial due to windmillgrass entering dormancy. Ratings were also collected on June 1, 2019 at spring green up for both trials. Weed control was visually rated on a scale of 0 to 100% where 0= no windmillgrass and 100= complete cover of windmillgrass. A rating grid using line intersect analysis (15.24 cm spacing) with 49 intersections was placed over each treatment plot; a count was recorded for each intersection when windmillgrass was present. Intersect counts were converted using Equation 2.1 below is based off of (Karcher & Richardson, 2013).

[2.1] % Windmillgrass Control = [(grid intersection counts at initial rating date – grid intersection counts at rating date / grid intersection counts at initial rating date) × 100]

All data were subjected to ANOVA (P= 0.05). ANOVA results were used to select both main effects and interactions. Mean separations for % windmillgrass control comparisons were accomplished using Fisher's Protected LSD ($P \leq 0.05$).

Results and Discussion

Complete windmillgrass control was achieved as soon as 3 weeks after the first application and maintained 100% windmillgrass control the following spring at green up when the windmillgrass was coming out of winter dormancy on June 1, 2019 for both trials. Measurements on June 1, 2019 were 41 and 37 WAIA for trial 1 and trial 2, respectively.

A herbicide by application timing interaction was significant, thus data are presented by single vs. sequential application for each trial (P<.0001). A herbicide treatment by trial interaction was significant, due to late initiation of trial 2 thus data are presented by each trial

(P<.0001). A herbicide treatment by application interaction was observed for trial 1 at 5, 6, and 41 WAIA (Table 2.1) and for trial 2 at 4, 5, 6, and 37 WAIA (Table 2.2).

Trial 1

The first week through the third week after initial application there was no significant differences between a single and a sequential application for all herbicide differences. The sequential applications were applied at 3 WAIA. At 4 WAIA the first significant difference occurred between a single versus a sequential application of a herbicide (Table 2.3). Mesotrione with sequential applications provided 100% windmillgrass control compared to a single application of mesotrione with 15.7% windmillgrass control. Also, at 4 WAIA topramezone tank-mixed with triclopyr resulted in 100% windmillgrass control which is better than all the herbicides.

At 5 WAIA treatments fenoxaprop tank-mixed with triclopyr resulted in 46.4% windmillgrass control, less than the sequential applications of fenoxaprop + triclopyr resulted in 100% windmillgrass control (Table 2.3). Triclopyr resulted in 62.1% windmillgrass control at 5 WAIA, less than the sequential applications triclopyr resulted in 100% windmillgrass control. Mesotrione resulted in 10.7% windmillgrass control at 5 WAIA, less than the sequential applications mesotrione resulted in 100% windmillgrass control.

At 6 WAIA all treatments that contained topramezone resulted in no significant differences between single and sequential application. (Table 2.3). Fenoxaprop resulted in 27.2% windmillgrass control at 6 WAIA, less than the sequential applications of fenoxaprop resulted in 93.8% windmillgrass control. Fenoxaprop tank-mixed with triclopyr resulted in 45.2% windmillgrass control at 6 WAIA, less than the sequential applications of fenoxaprop tank-mixed with triclopyr resulted in 100% windmillgrass control. Triclopyr resulted in 69.5% windmillgrass control at 6 WAIA, less than the sequential applications triclopyr resulted in 100% windmillgrass control. Mesotrione resulted in 16.9% windmillgrass control at 6 WAIA, less than the sequential applications mesotrione resulted in 100% windmillgrass control. Mesotrione tank-mixed with triclopyr resulted in 88% windmillgrass control at 6 WAIA, less than the sequential applications of fenoxaprop tank-mixed with triclopyr resulted in 100% windmillgrass control.

At 41 WAIA once all windmillgrass broke winter dormancy, all single applications and applications that did not have triclopyr tank-mixed did not achieve complete control of windmillgrass (Table 2.3). However, triclopyr and topramezone alone resulted in 88.6% and 93.8% windmillgrass control, respectively. Fenoxaprop resulted in 42.5% windmillgrass control at 41 WAIA, less than the sequential applications of fenoxaprop resulted in 90.6% windmillgrass control. Fenoxaprop + triclopyr resulted in 82.4% windmillgrass control at 41 WAIA, less than the sequential applications of fenoxaprop tank-mixed with triclopyr that resulted in 100% windmillgrass control. Mesotrione resulted in 52.5 % windmillgrass control at 41 WAIA, less than the sequential applications of mesotrione alone resulted in 100% windmillgrass control.

Trial 2

Much like trial 1, the first week through the third week after application there was no significant differences between a single and sequential applications. The sequential application was applied at 3 WAIA. Although there were no differences in the 1, 2, and 3 WAIA between single and sequential applications, a single application of topramezone tank-mixed with triclopyr provided 100% windmillgrass control at 3 WAIA (Table 2.6) and still had 100% control at 37 WAIA (Table 2.4).

At 5 WAIA the first significant differences occurred between single versus sequential applications of herbicides (Table 2.4). Fenoxaprop tank-mixed with triclopyr resulted in 45%

windmillgrass control at 5 WAIA, less than the sequential applications of fenoxaprop tank-mixed with triclopyr resulted in 100% windmillgrass control. Mesotrione resulted in 31.3% windmillgrass control at 5 WAIA, less than the sequential applications mesotrione resulted in 100% windmillgrass control.

At 6 WAIA a single application of fenoxaprop alone resulted in 42.2 % windmillgrass control, less than the sequential applications of fenoxaprop alone that resulted in 95% windmillgrass control (Table 2.4). Fenoxaprop tank-mixed with triclopyr resulted in 49.8% windmillgrass control at 6 WAIA, less than the sequential applications of fenoxaprop tank-mixed with triclopyr that resulted in 100% windmillgrass control. Mesotrione resulted in 58.8% windmillgrass control at 6 WAIA, less than the sequential applications of mesotrione alone resulted in 100% windmillgrass control.

At 37 WAIA once all windmillgrass broke winter dormancy, all single applications and applications that did not have triclopyr combinations didn't achieve complete control of windmillgrass (Table 2.4). However, topramezone and triclopyr alone resulted in 94.5% and 85.8% windmillgrass control, respectively Fenoxaprop resulted in 41.5% windmillgrass control at 37 WAIA, less than the sequential applications of fenoxaprop resulted in 89.8% windmillgrass control. Fenoxaprop tank-mixed with triclopyr resulted in 82.9% windmillgrass control at 37 WAIA, significantly less than the sequential applications of fenoxaprop tank-mixed with triclopyr resulted in 100% windmillgrass control. Mesotrione resulted in 54 % windmillgrass control at 37 WAIA, less than the sequential applications mesotrione resulted in 100% windmillgrass control.

Conclusions

Tenacity® with active ingredient of mesotrione, label calls for windmillgrass control requires a second application two to three weeks after the first application (Anonymous 2011). Mesotrione in both trials resulted in ≤ 54% windmillgrass control with a single application by 41 WAIA, which is less than 100% windmillgrass control with sequential applications in both trials (Table 2.3 and 2.4). Therefore, in order to achieve complete windmillgrass control with Tenacity® two applications are required.

Two applications of triclopyr, topramezone, topramezone tank-mixed with triclopyr, and mesotrione tank-mixed with triclopyr all resulted in 100% windmillgrass control by spring green up in both trials. The only single application that resulted in complete control of windmillgrass was when triclopyr was tank-mixed with topramezone.

In both trials at all WAIA except the first week, triclopyr in combination with the other herbicides provided significantly better control than herbicides without triclopyr tank-mixed (Figure 2.1 and 2.2). A single application of the tank-mixture triclopyr and topramezone resulted in 100% windmillgrass control as early as 3 WAIA (Table 2.5 and 2.6) and that tank mixture provided complete control through the winter until spring green up in both trials (Table 2.3 and 2.4). Also, in both trials it was determined that there was a difference when comparing single versus sequential applications of fenoxaprop tank-mixed with triclopyr. The sequential applications resulted in complete windmillgrass control, while a single application of fenoxaprop tank-mixed with triclopyr did not.

Previous researchers found in a controlled environment, that windmillgrass that treated with topramezone tank-mixed with triclopyr reached 100% windmillgrass control four weeks after application (Smeda and Xiong, 2019). Much like our results in the field, it was also determined that a single application of the topramezone tank-mixed triclopyr resulted in 100% windmillgrass control as early as 3 WAIA (Table 2.5 and 2.6).

Although smooth crabgrass (*Digitaria ischaemum*) is a summer annual weed while Windmillgrass (*Chloris verticillata* Nutt.) is a perennial weed, results show that mesotrione often has the same effect on both weeds when looking at single versus sequential applications. Mesotrione alone only controlled smooth crabgrass 66% by 6 weeks after treatment, while tank mixtures of triclopyr at 560 or 1,120 g ae ha^{-1} with mesotrione at 140 g ha^{-1} applied singly provided excellent control (> 90%) of smooth crabgrass (Yu & McCullough 2016). These results are very similar to the results found in this study. During trial 1 6 WAIA mesotrione alone had 16.9% windmillgrass control while tank-mixing triclopyr with mesotrione resulted in 88% control. With trial 2 mesotrione alone had 58.8% windmillgrass control and tank mixing triclopyr with mesotrione resulted in 90% 6 WAIA.

While white clover (*Trifolium repens*) is a perennial broadleaf weed while Windmillgrass (*Chloris verticillata* Nutt.) is perennial grass weed, results show that mesotrione often has the same effect on both perennial weed species when comparing mesotrione alone versus mesotrione tank-mixed with triclopyr. Mesotrione alone at 175 g ha^{-1} only controlled white clover 14% by 4 weeks after treatment. While tank mixtures of triclopyr at 560 g ae ha^{-1} of with mesotrione at 175 g ha^{-1} improved control 89% of white clover (Rana et al. 2014). These results are very similar to the results found in this study. During trial 1 4 WAIA mesotrione alone had 15.7% windmillgrass control while tank-mixing triclopyr with mesotrione resulted in 89.8% windmillgrass control (Table 2.3). While in trial 2 at 4 WAIA mesotrione alone had 37.9% windmillgrass control and tank mixing triclopyr with mesotrione resulted in 90.8% windmillgrass control (Table 2.6).

Results from both trials indicate that sequential applications of certain herbicides or a single application of topramezone tank-mixed with triclopyr will result in complete windmillgrass control. Homeowners, lawn care professionals, and golf course superintendents should do sequential applications of mesotrione, topramezone, or triclopyr for complete windmillgrass control. Also, a single application of topramezone tank-mixed with triclopyr will provide complete windmillgrass control.

Sources of Materials

[1] Oxadiazon 2G, Control Solutions Inc. Pasadena, TX 77507

[2] SiteOne Landscape Supply. Roswell, GA 30076

[3] Pylex™ 2.8 SC, BASF Corporation. Research Triangle Park, NC 27709

[4] Tenacity® 4 SC, Syngenta Crop Protection. Greensboro, NC 27419

[5] Acclaim® Extra 0.57 EC, Bayer Environmental Science. Cary, NC 27513

[6] Alligare 4 AE, Alligare LCC. Opelika, AL 36801

[7] Cornbelt Premier 90® Nonionic Spreader, Van Diest Supply CO. Webster City, IA 50595

[8] Methylated Seed Oil, LESCO, Inc. Cleveland, OH 44114

[9] TeeJet 8003 Spraying Systems Co. Glendale Heights, IL 60139

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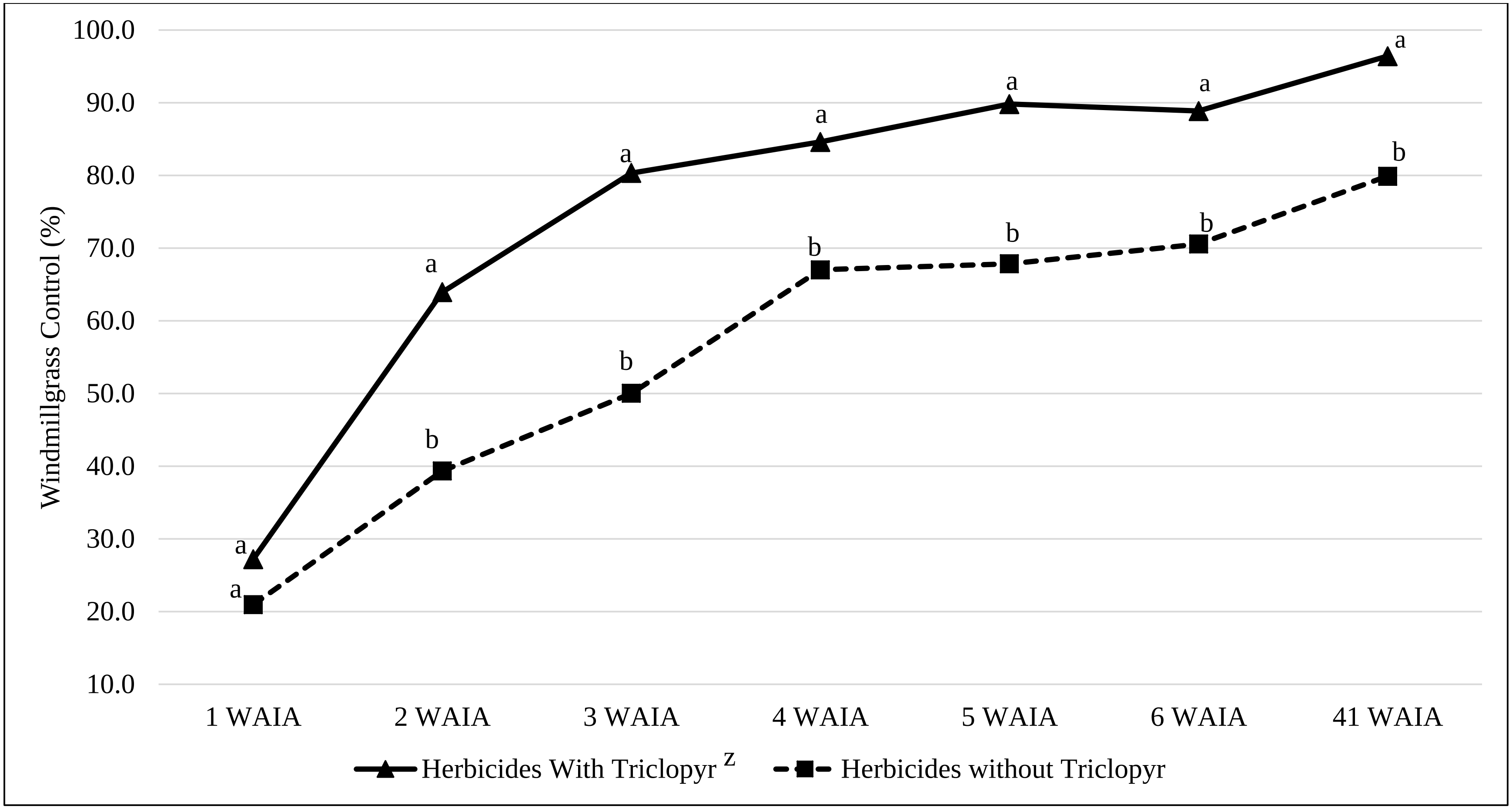

Figure 2.1 Percent windmillgrass control in Trial 1 comparing herbicides combinations with triclopyr to herbicides without triclopyr.

Means followed by the same letter on WAIA are not significantly different ($P \leq 0.05$) according Fisher's Protected LSD.

[z] triclopyr alone and non-treated removed from data.

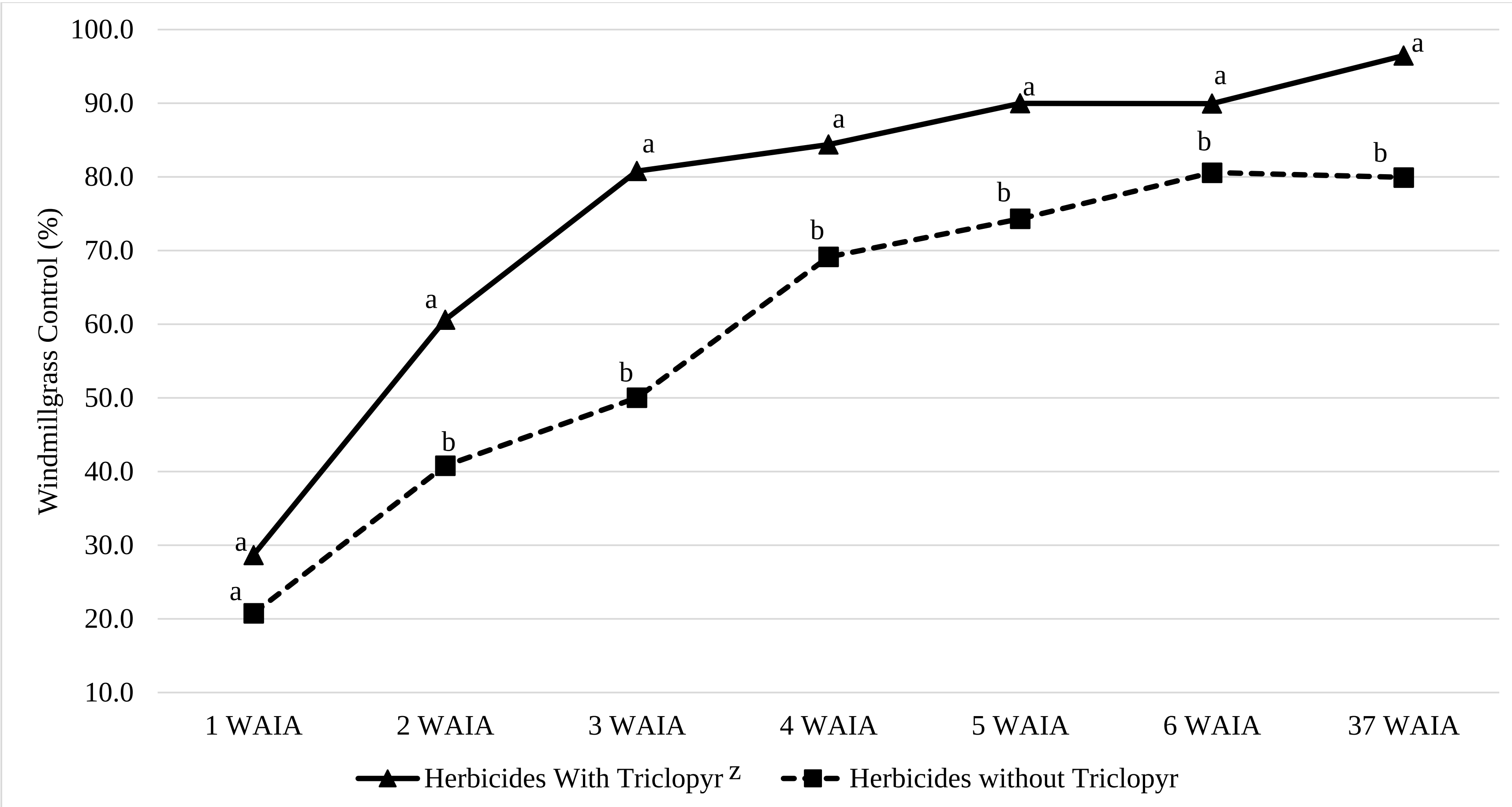

Figure 2.2 Percent windmillgrass control in Trial 2 comparing herbicide combinations with triclopyr to herbicides without triclopyr.

Means followed by the same letter on WAIA are not significantly different ($P \leq 0.05$) according Fisher's Protected LSD.

[z] triclopyr alone and non-treated removed from data.

Table 2.1 ANOVA for percent Windmillgrass (*Chloris verticillata* Nutt.) control at various WAIA with application and herbicide for in Trial 1 at Rocky Ford Turfgrass Research Center Manhattan, KS.

	P-Value Associated with *F*						
	Windmillgrass Control						
	WAIA						
	1[a]	2	3[b]	4	5	6	41
Application (A)[c]	NS[d]	NS	NS	0.0007	<.0001	<.0001	<.0001
Herbicide (H)	0.0031	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
A x H	NS	NS	NS	<.0001	<.0001	<.0001	<.0001

Abbreviations: ANOVA, Analysis of Variance**;** WAIA, Weeks after initial application; NS, not significant

[a] Application made on August 16, 2018.

[b] Sequential application made on September 9, 2018.

[c] Application is single versus sequential applications.

[d] Significance of WAIA reaction terms when data were subjected to ANOVA (P=0.05).

Table 2.2 ANOVA for percent Windmillgrass (*Chloris verticillata* Nutt.) control at various WAIA with application and herbicide in Trial 2 at Rocky Ford Turfgrass Research Center Manhattan, KS.

	P-Value Associated with *F*						
	Windmillgrass Control						
	WAIA						
	1[a]	2	3[b]	4	5	6	37
Application (A)[c]	NS[c]	NS	NS	0.0015	<.0001	<.0001	<.0001
Herbicide (H)	0.0093	0.0003	<.0001	<.0001	<.0001	<.0001	<.0001
A x H	NS	NS	NS	NS	0.0008	0.0020	<.0001

Abbreviations: ANOVA, Analysis of Variance; WAIA, Weeks after initial application; NS, not significant

[a] Application made on September 11, 2018.

[b] Sequential application made on October 2, 2018.

[c] Application is single versus sequential applications.

[d] Significance of WAIA reaction terms when data were subjected to ANOVA (P=0.05).

Table 2.3 Interaction between herbicide and application of Windmillgrass (*Chloris verticillata* Nutt.) Percent control in Trial 1 at Rocky Ford Turfgrass Research Center Manhattan, KS.

	Windmillgrass Control (%)			
Herbicide[a]	4 WAIA[b]	5 WAIA	6 WAIA	41 WAIA
non-treated	0 f[c]	0 g	7.1 e	2.5 d
fenoxaprop	38.9 Ade[d]	34.3 Aef	27.2 Bcd	42.5 Bc
fenoxaprop 2x[e]	60.7 Abcd	75.2 Abc	93.8 Aa	90.6 Aab
fenoxaprop + triclopyr	56.5 Acd	46.4 Bde	45.2 Bc	82.4 Bb
fenoxaprop + triclopyr 2x	72.5 Aabc	100 Aa	100 Aa	100 Aa
triclopyr	55.8 Acd	62.1 Bcd	69.5 Bb	88.6 Aab
triclopyr 2x	73.7 Aabc	100 Aa	100 Aa	100 Aa
topramezone	90.6 Aab	86.9 Aab	85.6 Aab	93.8 Aab
topramezone 2x	96.2 Aa	100 Aa	100 Aa	100 Aa
topramezone + triclopyr	100 Aa	100 Aa	100 Aa	100 Aa
topramezone + triclopyr 2x	97.2 Aa	100 Aa	100 Aa	100 Aa
mesotrione	15.7 Bef	10.7 Bfg	16.9 Bd	52.5 Bc
mesotrione 2x	100 Aa	100 Aa	100 Aa	100 Aa
mesotrione + triclopyr	89.8 Aab	92.5 Aab	88 Bab	96.1 Aab
mesotrione + triclopyr 2x	91.7 Aa	100 Aa	100 Aa	100 Aa

[a] Herbicides ranked no specific order.

[b] WAIA= Weeks after Initial Application.

[c] Treatment means followed by the same capital letter are not significantly different among the same herbicide between single and sequential of the same treatment application at the same WAIA according to Fisher's protected LSD (α= 0.05)

[d] Treatment means followed by the same lower case letter are not significantly different within each herbicide at the same WAIA according to Fisher's protected LSD (α= 0.05).

[e] 2x = two applications or had a sequential application.

Table 2.4 Interaction between herbicide and application of Windmillgrass (*Chloris verticillata* Nutt.) Percent control in Trial 2 at Rocky Ford Turfgrass Research Center Manhattan, KS.

	Windmillgrass Control (%)		
Herbicide[a]	5 WAIA[b]	6 WAIA	37 WAIA
non-treated	2.1 e[c]	2.1 e	4 e
fenoxaprop	47.2 Acd[d]	42.2 Bd	41.5 Bc
fenoxaprop 2x[e]	77.2 Aab	95 Aa	89.8 Aba
fenoxaprop + triclopyr	45 Bcd	49.8 Bd	82.9 Bb
fenoxaprop + triclopyr 2x	100 Aa	100 Aa	100 Aa
triclopyr	64.2 Abc	72.6 Abc	85.8 Aab
triclopyr 2x	100 Aa	100 Aa	100 Aa
topramezone	90.3 Aa	87.5 Aab	94.5 Bab
topramezone 2x	100 Aa	100 Aa	100 Aa
topramezone + triclopyr	100 Aa	100 Aa	100 Aa
topramezone + triclopyr 2x	100 Aa	100 Aa	100 Aa
mesotrione	31.3 Bd	58.8 Bcd	54 Bc
mesotrione 2x	100 Aa	100 Aa	100 Aa
mesotrione + triclopyr	95 Aa	90 Aba	95.8 Aab
mesotrione + triclopyr 2x	100 Aa	100 Aa	100 Aa

[a] Herbicides ranked no specific order.

[b] WAIA= Weeks after Initial Application.

[c] Treatment means followed by the same capital case letter are not significantly different among the same herbicide between single and sequential of the same treatment application at the same WAIA according to Fisher's protected LSD (α= 0.05)

[d] Treatment means followed by the same lower case letter are not significantly different within each herbicide at the same WAIA according to Fisher's protected LSD (α= 0.05).

[e] 2x = two applications or had a sequential application.

Table 2.5 Main effect of herbicide of Windmillgrass (*Chloris verticillata* Nutt.) Percent control in Trial 1 at Rocky Ford Turfgrass Research Center Manhattan, KS.

	Percent Control of Windmillgrass		
Herbicide[a]	1 WAIA[b]	2 WAIA	3 WAIA
non-treated	0 c[c]	0 c	0 d
fenoxaprop	20.7 bc	37.5 b	35.4 c
fenoxaprop 2x[d]	-[e]	-	-
fenoxaprop + triclopyr	27.6 ab	54.7 ab	47.4 c
fenoxaprop + triclopyr 2x	-	-	-
triclopyr	25.7 b	39.2 b	55.7 bc
triclopyr 2x	-	-	-
topramezone	15.3 bc	28.7 b	83.8 ab
topramezone 2x	-	-	-
topramezone + triclopyr	24.7 b	77.8 a	100 a
topramezone + triclopyr 2x	-	-	-
mesotrione	24.7 b	35 b	22.8 cd
mesotrione 2x	-	-	-
mesotrione + triclopyr	47.2 a	73.2 a	86.3 ab
mesotrione + triclopyr 2x	-	-	-

[a] Herbicides ranked no specific order.

[b] WAIA= Weeks after Initial Application.

[c] Treatment means followed by the same letter are not significantly different between each herbicide within each WAIA according to Fisher's protected LSD ($P \leq 0.05$).

[d] 2x = two applications or had a sequential application.

[e] Sequential applications had not yet been applied.

Table 2.6 Main effects of herbicide Windmillgrass (*Chloris verticillata* Nutt.) Percent control in Trial 2 at Rocky Ford Turfgrass Research Center Manhattan, KS.

	Windmillgrass Control (%)			
Herbicide[a]	1 WAIA[b]	2 WAIA	3 WAIA	4 WAIA
non-treated	0 c[c]	0 d	0 d	0 e
fenoxaprop	22.8 bc	33.5 bc	40 c	40 d
fenoxaprop 2x[d]	-[e]	-	-	61.5 bcd
fenoxaprop + triclopyr	30.4 ab	52.3 ab	55.3 bc	56.4 cd
fenoxaprop + triclopyr 2x	-	-	-	71.7 abc
triclopyr	28.1 ab	43.4 bc	55.2 bc	58.2 cd
triclopyr 2x	-	-	-	71.2 abc
topramezone	16 bc	50.7 ab	72.6 ab	75.4 abc
topramezone 2x	-	-	-	100 a
topramezone + triclopyr	27.9 ab	77.7 a	100 a	100 a
topramezone + triclopyr 2x	-	-	-	97.5 a
mesotrione	14.3 bc	19.7 cd	33 F	37.9 d
mesotrione 2x	-	-	-	100 a
mesotrione + triclopyr	48.8 a	61.2 ab	90 a	90.8 ab
mesotrione + triclopyr 2x	-	-	-	90 ab

[a] Herbicides ranked no specific order.

[b] WAIA= Weeks after Initial Application.

[c] Treatment means followed by the same letter are not significantly different between each herbicide within each WAIA according to Fisher's protected LSD ($P \leq 0.05$).

[d] 2x = two applications or had a sequential application.

[e] Sequential applications had not yet been applied.

Chapter 3 - Windmillgrass (*Chloris verticillata*) Rate Response to Glyphosate with a Fall Application

Abstract

Windmillgrass (*Chloris verticillata* Nutt.) is a problematic perennial grass weed commonly found in the Midwest of the United States. Non-selective herbicides, such as glyphosate provides a great control option for undesired species. Two separate field research trials were initiated in Manhattan, KS at Rocky Ford Turfgrass Research Center, to identify if non-selective herbicide applications will be effective in the fall at the heading stage and to determine the effect of windmillgrass response to various rates of a non-selective herbicide and what is the lowest rate that can be applied in order to achieve complete windmillgrass control. Application was on 26 September 2018 for both trials. Research trials were arranged in a randomized complete block design with four replications. Evaluated factors were eight different glyphosate rates. The eight different glyphosate rates ranged from 0.03125× up to a 4× rate as well as a non-treated where no herbicide was applied. Treatments were applied to 1.22 × 1.22 m plots containing 50 to 65% windmillgrass cover using a CO_2 pressurized boom sprayer calibrated to deliver 402 L ha^{-1}. Data were based off visual ratings converted to percent windmillgrass control for each individual plot. ANOVA was performed in SAS and means were separated according to Fisher's protected LSD at 0.05 significance level. It was determined that 1.66 kg ae ha^{-1} of glyphosate will completely control windmillgrass as early as 2 WAA and will stay completely controlled over-winter until the spring.

Introduction

Non-selective herbicides such as glyphosate provides a great control option for undesired plants. Minimal research has been conducted with glyphosate for controlling windmillgrass in a turfgrass system. However, Hennigh et al. (2005) conducted research on using glyphosate in the greenhouse as well as in a row crop corn field. Their greenhouse experiment aimed to determine the efficacy of glyphosate as well as acetyl-CoA carboxylase (ACCase^{-}) inhibitor herbicides on both prairie cupgrass (*Eriochloa contract*) and windmillgrass (*Chloris verticillata*) at different growth stages. At seedling stage plants were 6 to 10 cm tall, this stage occurs in the spring after breaking winter dormancy, as well as after a seed germinates and becomes a new plant. At the tillering stage plants had 5 to 10 tillers per plant, this stage usually occurs in late spring to early summer. The last stage was when the first seedhead was emerging at the heading stage, windmillgrass produces the seedhead in the summer time and will stay on the plant until either the wind breaks it off, or is mowed. The rates for glyphosate were 541; 841; and 1121g ha^{-1}. The ACCase^{-} inhibitors were sethoxydim, clethodim, and quizalofop applied at 350, 210, and 70 g ha^{-1} respectively. For windmillgrass and prairie cupgrass glyphosate at 1211 g ha^{-1} achieved complete control of both species. However, windmillgrass at the heading and seedling stage was less vulnerable to glyphosate than prairie cupgrass at those growth stages (Hennigh et al. 2005).

The efficacy of ACCase^{-} inhibitors herbicides on windmillgrass and prairie cupgrass was much greater than highest rate of glyphosate applied at those same growth stages. At both the tillering and heading stage all of the herbicide treatments, neither glyphosate or acetyl-CoA carboxylase was phytotoxic to both prairie cupgrass or windmillgrass.

Hennigh et al. (2005) also performed field experiments in 2001 and 2002 evaluating herbicide efficacy on controlling both windmillgrass and prairie cupgrass in a no-till corn field.

These experiments also used both preemergence herbicides and postemergent herbicides. Preemergence herbicides are applied to a site before weed seeds germinate and prevent weeds from properly emerging or developing (Patton & Weisenberger, 2019). The preemergence herbicides were acetohlor + atrazine; alachlor + atrazine; dimethenamid + atrazine; flufenacet + atrazine; s-metolachlor + atrazine; pendimethalin + atrazine; isoxaflutole + atrazine; and atrazine. The postemergent treatments were glyphosate; rimsulfuron + nicosulfuron + atrazine; primisulfuron + prosulfuron + atrazine; and mesotrione + atrazine. Glyphosate was used both for single and sequential applications treatments. The sequential applications were applied two weeks after the initial application.

Effective windmillgrass control was achieved throughout all herbicidal treatments (Hennigh et al. 2005). However, sequential applications of glyphosate showed complete control of both prairie cupgrass and windmillgrass in both years of the experiment. Both preemergence and postemergent herbicides achieved ≥90% control of windmillgrass in both years by six weeks after treatment. Sequential applications of glyphosate exhibited the greatest control in both years. Overall, preemergence herbicides provided a better control of windmillgrass than they did for prairie cupgrass. This research shows that application timing on both prairie cupgrass and windmillgrass greatly affect the control of both grasses. When herbicides are applied at the early seedling stage of both grasses, the control is much greater than when applied during the tillering and heading stages. The best control of prairie cupgrass and windmillgrass was achieved with sequential applications of glyphosate at 1211 g ha^{-1}.

Similar to windmillgrass, bermudagrass (*Cynodon* spp.) is also a perennial warm-season grass weed. A single autumn application of glyphosate prior to bermudagrass dormancy when applied in the transitional zone reduced bermudagrass cover the following spring (Hoyle et al. 2018).

Hoyle et al. (2018) conducted a field experiments to determine if multiple applications of glyphosate are needed in the summer for bermudagrass control. However, these applications do result in 3 to 4 months of aesthetically unpleasing turfgrass. The research examined a fall application of glyphosate plus the addition of fluazifop and mesotrione to glyphosate based on extension recommendations and previous research to improve the control of bermudagrass (Hoyle et a. 2018). The experiment was conducted in the fall in Manhattan, KS at two different locations that contained either hybrid or common mature bermudagrass. Seven herbicide treatments containing mixtures of glyphosate, fluazifop and mesotrione were evaluated as well as a non-treated application. All of the treatments containing glyphosate reduced the cover of bermudagrass at each location the following spring. The addition of fluazifop or mesotrione to glyphosate did not help control bermudagrass in the fall. Overall, the results showed that a single application of glyphosate to bermudagrass in the fall prior to dormancy reduces the cover of bermudagrass the following spring as effectively as the other alternatives that were studied (Hoyle et a. 2018).

With the addition of these active ingredients being deemed wasteful on bermudagrass we chose not to look into adding these herbicides to glyphosate. Therefore, the objectives of this research were to determine (1) if non-selective herbicide applications will be effective in the fall at the heading stage and (2) windmillgrass response to various rates of glyphosate.

Materials and Methods

Research Site Information

Two separate field experiments were both initiated on 26 September 2018 (trial 1) and (trial 2), respectively, at the Rocky Ford Turfgrass Center (RF) in Manhattan, KS. The soil was a Chase silty clay loam (fine, smectitic, mesic Aquertic Argiudolls) with 6.8 pH and 2.7% organic matter. Both trials were conducted on Tall fescue (*Schedonorus arundinaceus*) at RF. Plots were maintained at 7.6 cm with a rotary mower, mowing occurred once per week or as needed and clippings blown away from the study area. During each study, no supplemental irrigation was applied. Prior to each trial initiation oxadiazon[1] at 2.93 kg ha^{-1} was applied with a broadcast spreader[2] to prevent new windmillgrass populations.

Herbicides and Application Timings

Field experiments were arranged in a randomized complete block design with four replications. Treatments included; eight different glyphosate[3] rates ranging from 0.03125× up to a 4× rate. Plots were 1.22 × 1.22 m Treatments applied included glyphosate, at 0.104, 0.208, 0.416, 0.833, 1.66, 3.33, 6.66, and 13.33 kg ae ha^{-1}. A non-treated control where no glyphosate was applied.

All treatments were applied to 1.22 × 1.22 m plots using a CO_2 pressurized hand-held spray boom equipped with four 8003 flat-fan nozzles[4] on 25 cm spacing calibrated to deliver 402 L ha^{-1}.

Data Collection and Analysis

Visual windmillgrass grass percent cover was collected weekly 4 weeks after application (WAA) for each trial due to windmillgrass entering dormancy. Ratings were also collected on June 1, 2019 at spring green up for both trials. Weed control was visually rated on a scale of 0 to

100% where 0= no windmillgrass and 100= complete cover of windmillgrass. Visual ratings were converted using Equation 3.1 below is based off of (Karcher & Richardson, 2013).

[3.1] % Windmillgrass Control = [(visual windmillgrass percent cover at initial rating date – visual windmillgrass percent cover at rating date / visual windmillgrass percent cover at initial rating date) × 100]

Mean separations for % windmillgrass control comparisons were accomplished using Fisher's Protected LSD ($P \leq 0.05$).

Results and Discussion

Certain treatments were effective at 100% windmillgrass control as soon as 2 WAA and maintained 100% windmillgrass control the following spring at green up with both trials.

An interaction between locations and herbicide was not present for windmillgrass control; therefore, data were pooled for both trials. Therefore, both trials will be presented together.

As soon as 1 WAA there were significant differences in windmillgrass control with different rates (Table 3.1). The 6.66 kg ae ha^{-1} of glyphosate treatment had the highest percent of control at 83.5%. Both 6.66 and 13.33 kg ae ha^{-1} were significantly better than all the other glyphosate treatments.

At 2 WAA complete windmillgrass control was achieved at and above 1.66 kg ae ha^{-1} of glyphosate (Table 3.1). All treatments that achieved complete control were significantly different than those treatments that didn't achieve complete control. Glyphosate at 0.933 kg ae ha^{-1} of provided 71.2% windmillgrass control which was statistically better than all treatments less than 0.933 kg ae ha^{-1} of glyphosate.

At 3 WAA the same trend continued that complete control was achieved at and above 1.66 kg ae ha^{-1}of glyphosate (Table 3.1). However, 0.933 kg ae ha^{-1}of glyphosate showed that it was statistically the same as those treatments that had complete control. Glyphosate at 0.933 kg ae ha^{-1} showed 93.9% windmillgrass control which was also statically the same as 0.416 kg ae ha^{-1} of glyphosate which had 83.2% windmillgrass control.

Much like observed in 2 WAA and 3 WAA, 4 WAA complete control of windmillgrass was achieved with and above 1.66 kg ae ha^{-1} of glyphosate (Table 3.1). Also, similar to 2 WAA 0.933 kg ae ha^{-1} of glyphosate was statistically the same as those treatments that controlled windmillgrass completely at 97.9% windmillgrass control. At Spring green-up on June 1, 2018 which was 35 WAA there was statistical difference in those treatments that controlled windmillgrass completely, to those treatments that did not achieve complete windmillgrass control. Complete windmillgrass control was achieved at and above 1.66 kg ae ha^{-1} of glyphosate.

Conclusions

Much like Hennigh et al. (2005) discovered that 6 weeks after treatment glyphosate at 1.121 kg ae ha^{-1} resulted in 93% windmillgrass control. However, at corn harvest it resulted in 100% windmillgrass control. Although that rate wasn't used in our study, it does fit in between the 0.993 and 1.66 kg ae ha^{-1} of glyphosate where there were significant differences between complete control and not complete control at spring green up (Table 3.1).

Although 4 WAA we saw 97.9% windmillgrass control with 0.933 kg ae ha^{-1} of glyphosate, at spring green up this treatment only showed 60.2% windmillgrass control (Table 3.1). This shows that 0.933 kg ae ha^{-1} of glyphosate only injured windmillgrass and didn't control at all because grow back was achieved in the spring.

Overall it is determined that fall would be an adequate time to control windmillgrass. It was also determined that at just 1.66 kg ae $ha^{-1}$of glyphosate will completely control windmillgrass as early as 2 WAA and will stay completely controlled over-winter until the spring. Although 1.66 kg ae ha^{-1} showed complete control, all rates we researched above 1.66 kg ae ha^{-1} of glyphosate also completely controlled windmillgrass.

Results indicate complete windmillgrass control will be achieved at several different rates of glyphosate. Homeowners, lawn care professionals, and golf course superintendents should use 1.66 kg ae ha^{-1} of glyphosate to control windmillgrass.

Sources of Materials

[1] Oxadiazon 2G, Control Solutions Inc. Pasadena, TX 77507

[2] SiteOne Landscape Supply. Roswell, GA 30076

[3] GlyphoMate® 41, PBI Gordon. Shawnee, KS 66286

[4] TeeJet 8003 Spraying Systems Co. Glendale Heights, IL 60139

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Table 3.1 Windmillgrass (*Chloris verticillata* Nutt.) rate response to glyphosate with a fall application percent control at Rocky Ford Turfgrass Research Center Manhattan, KS.

		% Windmillgrass Control				
Rate of GlyphoMate®	kg ae ha^{-1}	1 WAA[a]	2 WAA	3 WAA	4 WAA	35 WAA
0	0	0.0 d[b]	0.0 d	6.0 e	7.7 d	0.0 d
0.03125	0.104	0.0 d	4.4 d	33.1 d	73.6 c	4.0 d
0.0625	0.208	3.9 d	25.1 c	55.7 c	77.3 c	1.7 d
0.125	0.416	4.1 d	30.7 c	83.2 b	89.2 d	16.0 c
0.25	0.933	23.9 c	71.2 b	93.9 ab	97.9 a	60.2 b
0.5	1.66	51.1 b	100.0 a	100.0 a	100.0 a	100.0 a
1[c]	3.33	57.5 b	100.0 a	100.0 a	100.0 a	100.0 a
2	6.66	83.5 a	100.0 a	100.0 a	100.0 a	100.0 a
4	13.33	79.1 a	100.0 a	100.0 a	100.0 a	100.0 a

[a] WAA= Weeks after Application.

[b] Treatment means followed by the same letter are not significantly different within each WAA according to Fisher's protected LSD ($P \leq 0.05$).

[c] This is the highest labeled rate for a single application