Kentucky bluegrass and tall fescue growth when seeded after herbicide application

by

Daniele McFadden

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Approved by:

Co-Major Professor
Steve Keeley

Approved by:

Co-Major Professor
Jack Fry

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Abstract

Weed control before seeding is often required for successful turfgrass establishment since weed interference prior to turfgrass tillering causes a reduction of cover and density. However, herbicides differ widely in the delay required after herbicide application before seeding can occur. In these experiments, postemergence herbicides used for control of broadleaf weeds, annual grasses, and nutsedge were the focus. One preemergence herbicide, dithiopyr (Dimension), was also included for comparison. In Chapter 1, herbicide effects on emergence and growth of Kentucky bluegrass (*Poa pratensis*) and tall fescue (*Schedonorus arundinaceus*) were evaluated in the field when seeding was done between 0 and 14 days after application. Seeding Kentucky bluegrass or tall fescue into plots treated with 2,4-D + MCPP + dicamba (Trimec Classic, for broadleaf weeds) or quinclorac (Drive, for control of annual grasses) had little or no effect on emergence or growth, whereas seeding into plots treated with halosulfuron-methyl (Sedgehammer, for nutsedge control) or dithiopyr inhibited growth of both species. Dithiopyr exhibited less inhibition of tall fescue when seeding was done 7 or 14 DAT compared to 0 or 3 DAT, which may have been attributed to frequent irrigation prior to seeding. To evaluate the influence of irrigation, a greenhouse experiment (Chapter 2) was done using the same herbicides to evaluate emergence and growth of tall fescue seeded after application. Overall, irrigation had no influence on the impact of herbicides on shoot or root growth in the greenhouse. Growth of tall fescue seeded into soil treated with 2,4-D + MCPP + dicamba 3 to 14 DAT was similar to that in nontreated soil; however, tall fescue root volume and dry weight was inhibited when seeded before 7 DAT of quinclorac. No tall fescue emergence occurred in soil treated with dithiopyr. Finally, the introduction of new combination products focused on

broadleaf weed control, raises concerns regarding the delay in seeding required after application. Therefore, another field experiment (Chapter 3) was conducted to determine the influence of combination products used for postemergence control of broadleaf weeds on emergence and growth of tall fescue seeded between 0 and 14 days after application. Seeding between 0 to 14 days after an application of carfentrazone-ethyl + MCPP + 2,4-D + dicamba (Speedzone), fluroxypyr + halauxifen-methyl + 2,4-D (GameOn), or triclopyr + pyraflufen-ethyl + 2,4-D + dicamba (4-Speed XT) had little or no effect on tall fescue emergence and growth under the conditions evaluated in these experiments, whereas tall fescue seeded into soil treated with penoxsulam + sulfentrazone + 2,4-D + dicamba (Avenue South) was consistently lower in cover, canopy height, and NDVI ratings compared to nontreated turf. In summary, under conditions evaluated in these experiments, some herbicide labels appear to suggest a greater period of time after application than is needed prior to seeding Kentucky bluegrass and/or tall fescue. Other labels are written properly or may need modifications to address concerns that could arise from seeding too soon after application.

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Dedication

To my grandma, Donna Hatter, for instilling in me the value of hard work and a good looking yard.

Chapter 1 - Emergence and Growth of Kentucky Bluegrass and Tall Fescue Seedlings after Herbicide Application

This chapter has been prepared using style guidelines for submission to *Crop, Forage, and Turfgrass Management*

Introduction

Mid-August through early September is the optimum time to seed cool-season turfgrasses in the Midwest (Beard, 1975). Turfgrass seeded during this optimal time will increase the chance for successful establishment of a dense stand that withstands the stress of winter (Reicher et al., 2000). Removal of annual and perennial grassy and broadleaf weeds is commonly required when lawns are renovated, and is usually done using postemergence herbicides. Effective weed control before seeding decreases competition and increase turfgrass establishment rate (Patton et al., 2009). However, the use of postemergence herbicides often requires that seeding be avoided for a specified period after application, and labels typically include information on how long seeding should be delayed. For example, the label for Glyphomate 41 [glyphosate (N-(phosphonomethyl)glycine)], a nonselective herbicide that controls broadleaf and grassy weeds, indicates that the product can be applied prior to or at turfgrass planting. Conversely, the label for the postemergence broadleaf herbicide Trimec Classic [2,4-D (2,4-Dichlorophenoxyacetic acid) + MCPP ((R)-2-(4-chloro-o-tolyloxy)propionic acid) + dicamba (3,6-dichloro-2-methoxybenzoic acid)], requires that seeding be delayed until four weeks after application.

Herbicides, by design, are phytotoxic and selectivity depends on several factors such as environment, dose, weed lifecycle stage, timing, and method of application (Khaliq and Matloob, 2012). There is minimal information on nontarget effects of herbicides, and effects on seedling emergence have been understudied despite the common practice of seeding native plants immediately after herbicide application (Wagner and Nelson, 2014). Sensitivity levels to a particular herbicide can vary by cultivar (White and Boutin, 2007). Furthermore, dicotyledon and monocotyledon plant species could react differently. Monocot seedlings lack morphological features such as leaf sheaths that enclose the meristem and protect mature monocot plants from detrimental effects (Cobb and Reade, 2010). These monocot seeds also have a lower biomass and higher relative exposure compared to mature monocots (Wagner and Nelson, 2014). Previous research with many herbicides has resulted in differing toxicity levels to crops, weeds, and nontarget plants depending on formulation (Nalewaja and Matysiak, 1992; Riechers et al., 1995; Sharma and Singh, 2001). The additional ingredients contained in herbicides may result in increased efficacy when compared to the active ingredient alone (White and Boutin 2007). However, these inert ingredients, along with surfactants and adjuvants which affect droplet size, retention, and uptake efficiency, can all influence seedling emergence.

There are limited herbicides that can be applied at the time of seeding to prevent the onset of weed encroachment, including the preemergence herbicide siduron [N-(2-methylcyclohexyl)-N'-phenylu- rea] (Bevard and Watschke, 1999). Most preemergence herbicides cannot be used at the time of planting or after seeding turfgrasses as they often injure newly seeded and immature cool-season turfgrasses, causing sward establishment to fail (Landschoot et al., 1993; Dunn and Diesburg 2004). Other herbicides that are labeled for use at seeding time are Tenacity [mesotrione (2-[4-(methylsulfonyl)-2-nitrobenzoyl]-1,3-cyclohexanedione)], which has pre- and postemergence activity on broadleaf and grassy weeds, and Pylex [topramezone (3-(4,5-dihydro-isoxazol-3-yl)-4-methanesulfonyl-2-methyl-phenyl](5-hydroxy-1-methyl- 1H-pyrazol-4-yl)methanone], which is a postemergence grass herbicide. One postemergence broadleaf product labeled for use one day prior to turfgrass seeding is SquareOne [carfentrazone-ethyl (2-chloro-3-[2-chloro-4-fluoro-5-[4-(difluoromethyl)-4,5-diydro-3-methyl-5-oxo-1H-1,2,4-trizol-1-yl)phenyl]propanoate) + quinclorac (3,7-dichloro-8-quinolinecarboxylic acid)].

Application of postemergence broadleaf herbicides, Imprelis 2SL [aminocyclopyrachlor (6-Amino-5-chloro-2-cyclopropylpyrimidine-4-carboxylic acid)] or 2,4-D + dicamba + MCPP, at different rates at 0, 2, 4, or 6 weeks before seeding perennial ryegrass (*Lolium perenne* L.) and tall fescue (*Schedonorus arundinaceus* (Schreb.) Dumort.), resulted in similar establishment to the nontreated control and suggested no delay is required after application (Workman et al., 2012). Much of the research related to herbicides and turf establishment has evaluated their effects on turfgrass growth and quality when applied after turfgrass seedling emergence (McCalla et al., 2004; McElroy et al., 2005; Willis et al., 2006; Patton et al., 2009). Research conducted on herbicide influence on emergence of cool-season turfgrasses seeded at different intervals after herbicide application is limited. Therefore, the objective of this research was to determine the influence of selective postemergence grass, broadleaf, and sedge herbicides on emergence and growth to Kentucky bluegrass (*Poa pratensis* L.) and tall fescue seeded between 0 and 14 days after application.

Materials and Methods

Research Site Information

Field experiments were initiated at the Rocky Ford Turfgrass Research Center in Manhattan, Kansas (long. 39.13° N, lat. 96.36° W) and replicated at the Ohio Agricultural Research and Development Center in Wooster, Ohio (long. 40.43° N, lat. 81.52° W) The soil in Manhattan was a Chase silty clay loam (fine, smectitic, mesic Aquertic Argiudoll) with 6.8 pH and 2.7% organic matter. Before study initiation in Manhattan, the site previously contained a mixture of Kentucky bluegrass and tall fescue. The trial area was scalped with a reel mower to 0.5 inches following sequential applications of glyphosate at a rate of 2.1 lb a.i. acre^{-1} on 1 Aug. 2019 and 22 Aug. 2019 to mimic conditions common of a lawn renovation.

Before study initiation in Wooster, the site previously contained a mixture of perennial ryegrass and tall fescue maintained at a 3-inch height of cut. The research site was scalped to 1 inch and clippings collected, then sprayed with glyphosate at a rate of 2.1 lb a.i. acre^{-1} on 7 Sept. 2019 and 21 Sept. 2019. The soil in Wooster was a Canfield silt loam (fine-loamy, mixed, active, mesic Aquic Fragiudalf) with pH 6.1 and 4.3% organic matter.

Herbicides and Seeding Intervals

Field experiments were initiated on 6 Sept. 2019 in Manhattan and 2 Oct. 2019 in Wooster. The experiments were arranged in a three-way factorial, randomized complete block design with four replications. Main factors included two turfgrass species (Kentucky bluegrass and tall fescue), four seeding intervals (0, 3, 7, and 14 days after herbicide application), and five herbicide treatments (noted below) for a total of 40 individual treatments.

In this study, herbicide treatments consisted of a nontreated control and four herbicides: 2,4-D + MCPP + dicamba (Trimec Classic®, PBI/Gordon Corporation, Kansas City, MO); quinclorac (Drive® 75, BASF Chemical Company, Research Triangle Park, NC); halosulfuron-methyl [3-chloro-5-(4,6-dimethoxypyrimidin-2-ylcarbamoylsulfamoyl)] (SedgeHammer®, Gowan Company, Yuma, AZ); and dithiopyr [2-(difluoromethyl)-4-(2-methylpropyl)-6-(trifluoromethyl)pyridine-3,5-dicarbothioate)] (Dimension™ 2EW, Dow AgroSciences LLC, Indianapolis, IN). Active ingredients and the respective percentages contained in each herbicide are shown in Table 1.1. The preemergence herbicide dithiopyr was included as a negative control, as growth should be inhibited when applied before label restrictions. Each herbicide was applied to the trial area at its highest label rate recommended for cool-season turfgrass.

At the Manhattan location seeding intervals consisted of 0 (6 Sept. 2019), 3 (9 Sept. 2019), 7 (13 Sept. 2019), and 14 (20 Sept. 2019) days after herbicide application. Plots measured

4 x 4 ft and rows were separated with a 1-ft nontreated border. Kentucky bluegrass and tall fescue were seeded at 3.86 lb PLS 1,000ft^{-2} and 10.22 lb PLS 1,000ft^{-2}, respectively. The Kentucky bluegrass seed blend included 24.8% Gladstone, 24.7% Shamrock, 24.7% Wildhorse and 24.6% Blue Coat. Cultivars in the tall fescue seed blend included 36.8% Copious, 31.1% Technique, and 30.9% Leonardo. All treatments were applied using a CO_2-pressurized, hand-held spray boom sprayer equipped with four TeeJet8003 flat-fan nozzles on 9.8-inch spacing calibrated to deliver 43 gal acre^{-1}.

At the Wooster location, seeding intervals consisted of 0 (2 Oct. 2019), 3 (5 Oct. 2019), 7 (9 Oct. 2019), and 14 (16 Oct. 2019) days after herbicide application. The seeding rates and blends used were the same as the Manhattan study. Herbicides were applied using a single nozzle TeeJet 8008EVS CO_2-pressurized backpack sprayer with a spray volume of 44 gal acre^{-1}.

Irrigation was withheld until 24 hours after herbicide application. Prior to seeding plots within each respective interval, a three-tine rotary cultivator was used to disturb the surface of the soil (Fig. 1.1), and a starter fertilizer [14-20-04 (N-P-K)] was applied to deliver 1 lb P 1,000ft^{-2}. Both the granular fertilizer and seed were spread independently using a shaker bottle in multiple directions. Plots were not mown throughout the duration of the study at either location.

Measurements and Statistical Analysis

Kentucky bluegrass and tall fescue percent cover were visually rated weekly using a scale of 0 to 100% coverage (0% = no visible coverage; 100% = full coverage of plot). Canopy height (inches) was measured weekly by visually estimating height in three random areas of each plot; means were recorded. Handheld NDVI (FieldScout CM 1000 NDVI Meter, Spectrum Technologies, Aurora, IL) measurements were recorded at 21, 28, and 42 days after seeding. All data for each of the ratings were subjected to ANOVA in SAS (9.4) using the GLIMMIX procedure and means were separated according to Fisher's Protected LSD ($P \leq 0.05$). Because the studies were conducted at different timings in two separate locations, data for each study were analyzed separately as there were treatment by experiment interactions. Therefore, data for the Manhattan and Wooster experiments are presented separately. Emergence and growth were highest in this study six weeks after trial initiation, and that is the focus for data and discussion herein.

Herbicide Effects on Kentucky Bluegrass and Tall Fescue

Kentucky bluegrass

Seeding interval x herbicide interaction was not significant for measured variables except canopy height in Manhattan, KS (Table 1.2). Main effect of herbicides on visual cover and NDVI will be presented. Dithiopyr-treated plots exhibited little emergence of Kentucky bluegrass and data are included in tables for reference; however, discussion will focus on comparison of postemergence herbicides to nontreated plots.

Seeding was done at an optimum time in Manhattan, and environmental conditions promoted good establishment (Fig. 1.2). Six weeks after seeding, Kentucky bluegrass cover and NDVI in the nontreated control, 2,4-D + MCPP + dicamba-treated, and quinclorac-treated plots were not significantly different (Table 1.3). However, seeding into halosulfuron-methyl-treated plots reduced coverage and NDVI compared to the nontreated control. Canopy height of Kentucky bluegrass was not affected by postemergence herbicides, regardless of seeding interval (Table 1.4). In addition, Kentucky bluegrass seeding interval within postemergence herbicides or the nontreated control did not influence canopy height.

Seeding interval x herbicide interaction was significant for Kentucky bluegrass for all variables measured in Wooster, OH (Table 1.2). Seeding in Wooster was initiated later than in

Manhattan, which resulted in less coverage and growth six weeks after seeding due in large part to lower temperatures (Fig. 1.3).

Visual coverage of Kentucky bluegrass seeded 7 DAT in Wooster in halosulfuron-methyl-treated plots was lower than that in the nontreated control (Table 1.5). No differences were observed among other postemergence herbicides in coverage compared to the nontreated control regardless of seeding interval. The Seeding Interval main effect indicated halosulfuron-methyl was the only postemergence herbicide which did not impact visual coverage when seeding was done at 14 DAT, which was likely because coverage was also inhibited when seeding was performed closer to herbicide application.

NDVI measurements showed no significant difference in live green vegetation in Wooster compared to the nontreated control when Kentucky bluegrass was seeded in 2,4-D + MCPP + dicamba-treated plots, regardless of seeding interval (Table 1.6). However, seeding into quinclorac-treated plots at 0 DAT or halosulfuron-methyl-treated plots at 0, 3, or 7 DAT reduced NDVI. Halosulfuron-methyl also reduced canopy height compared to nontreated plots when seeded at 0 DAT (Table 1.4).

Tall fescue

Tall fescue seedling emergence and growth were generally less affected by postemergence herbicides than was Kentucky bluegrass. The herbicide x seeding interval significance observed for tall fescue at both locations was commonly due to the inclusion of dithiopyr, which reduced tall fescue emergence significantly (Table 1.2). Among postemergence herbicides in Manhattan, only seeding into halosulfuron-methyl-treated plots at 0 DAT reduced tall fescue coverage (Table 1.7) and NDVI (Table 1.8). Canopy height of tall fescue seeded into halosulfuron-methyl-treated plots at 0 or 3 DAT was reduced (Table 1.9). However, in Wooster, halosulfuron-methyl reduced tall fescue coverage after seeding at 0 or 3 DAT and 2,4-D + MCPP + dicamba reduced tall fescue coverage after seeding at 0 DAT (Table 1.7). 2,4-D + MCPP + dicamba reduced canopy height across all seeding intervals (Table 1.3).

Turf Responses Compared to Label Guidelines

Application of 2,4-D + MCPP + dicamba generally had little influence on growth of Kentucky bluegrass or tall fescue, with the exception of tall fescue canopy height and visual coverage when seeded at 0 DAT in Wooster. The Trimec Classic label indicates that grass seed can be sown 3 to 4 weeks after application (PBI-Gordon Corporation, 2017), but it seems this length of time could be reduced. Application of 2,4-D + MCPP + dicamba at 0, 2, 4, or 6 weeks before tall fescue seeding resulted in no visual cover reduction compared to the nontreated areas in Griffin, GA, Knoxville, TN, and Lubbock, TX (Workman et al. 2012).

Quinclorac did not influence growth of Kentucky bluegrass or tall fescue in Manhattan. However, NDVI of Kentucky bluegrass that was seeded at 0 DAT in Wooster was reduced compared to the nontreated areas. The product label indicates that use of Drive 75 DF before or after seeding or over-seeding a turf area will not significantly interfere with the turfgrass seed germination and growth of grass types identified as tolerant or moderately tolerant (BASF Professional and Specialty Solutions, 2014). Quinclorac at 0.84 kg ha^{-1} applied at seeding delayed the cover of Kentucky bluegrass up to 16 weeks in West Lafayette, IN but did not cause visible injury (Reicher et al., 1999). Willis et al. (2006) found that an application of quinclorac made on the same day of turfgrass seeding, along with 4 and 8 weeks after planting, appeared to be sufficiently safe for use during tall fescue seedling establishment and controlled weeds equal to or better than siduron.

Halosulfuron-methyl, commonly used for control of yellow nutsedge, was the only postemergence herbicide that consistently affected coverage and NDVI in Manhattan and Wooster. The SedgeHammer label indicates to allow 4 weeks between application and seeding or sodding of turfgrass (Gowan Company, 2019), and research herein supports waiting over 14 DAT before seeding Kentucky bluegrass or tall fescue. Tall fescue emerging in halosulfuron-methyl-treated plots exhibited minor chlorosis; however, turf had fully recovered by the end of the experiment. Sulfosulfuron (4,6-dimethoxypyrimidin-2-yl)-3-(2-ethylsulfonylimidazo[1,2-a]pyridin-3-yl), in the same sulfonylurea family as halosulfuron-methyl, applied 1 week before seeding reduced Kentucky bluegrass coverage up to 70% compared to nontreated areas (Lycan and Hart, 2005).

Throughout the field studies, both turfgrass species were highly sensitive when seeded into dithiopyr-treated plots. This was expected, as dithiopyr was included as a "treated" control at both locations. The Dimension 2EW label indicates reseeding or overseeding of treated areas within 3 months after application may inhibit establishment of desirable turf (Corteva Agriscience, 2015). However, Kentucky bluegrass exhibited greater sensitivity to dithiopyr than tall fescue. Kentucky bluegrass reached a maximum of 4% coverage in Manhattan (Table 1.3) and 0% cover in Wooster (Table 1.5) at six weeks after seeding. In Manhattan, tall fescue seeded on the same day as dithiopyr application reached only 6% coverage after six weeks, whereas that seeded at 7 and 14 DAT had a mean visual coverage of 50% and 76%, respectively (Table 1.7). The amount of growth in plots seeded at 7 and 14 DAT was likely due to a loss of herbicide residual in the soil before seeding. After seeding at 0 DAT, all plots in the experiment area received irrigation three times daily, including those to be seeded at 3, 7, or 14 DAT, which may have encouraged dithiopyr degradation. Warm soil temperatures could have also enhanced dithiopyr degradation at a level that could have been greater than if it were applied during cool, spring conditions. Tall fescue cover did not exceed 4% in dithiopyr-treated plots in Wooster, which was likely attributed to the later seeding date in Wooster than Manhattan. More research is needed to evaluate the effects of irrigation on tall fescue emergence in dithiopyr-treated plots, as suggested by results in Manhattan.

Trial initiation timing was a major factor in differences in locations. In Kansas, plots were seeded on 6 Sept. 2019 and the average daily high and low air temperatures throughout the study period were 72°F and 51°F, respectively (Figure 1.2). In Ohio, plots were seeded on 2 Oct. 2019 and the average daily high air temperature was 57°F, while nighttime low air temperatures averaged 35°F throughout the seven-week rating period (Figure 1.3). The late trial initiation in Wooster caused less Kentucky bluegrass and tall fescue emergence, less coverage and NDVI, and shorter canopy heights compared to data collected in the Manhattan field trial. This was to be expected as temperatures below the ideal range limit growth (Huang et al., 2014).

Overall, this study demonstrated that seeding between 0 and 14 days after an application of 2,4-D + MCPP + dicamba or quinclorac has little or no effect on Kentucky bluegrass or tall fescue growth under the conditions evaluated in these experiments. However, herbicide manufacturers must consider making changes on labels before turf managers can consider these strategies. Halosulfuron-methyl reduced Kentucky bluegrass and tall fescue growth when seeded within 14 DAT, which matches warnings on the herbicide label. This research demonstrates that turfgrass managers who unknowingly seed into areas treated with the postemergence herbicides evaluated herein within 0 to 14 DAT will likely observe successful establishment of Kentucky bluegrass or tall fescue.

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Table 1.1 Herbicide active ingredients and highest label rates recommended for cool-season turfgrass for products used in herbicide x species x seeding interval field study.

Herbicide	Active Ingredients (a.i.)	% a.i.	Pounds a.i. $acre^{-1}$
Trimec Classic	2,4-D, dimethylamine salt	25.93	1.19
	MCPP, dimethylamine salt	6.93	0.32
	Dicamba, dimethylamine salt	2.76	0.13
Drive 75 DF	Quinclorac acid	75.00	0.75
SedgeHammer	Halosulfuron-methyl	75.00	0.06
Dimension 2EW	Dithiopyr	24.00	0.50

Table 1.2 ANOVA for Kentucky bluegrass and tall fescue cover, canopy height, and NDVI data six weeks after trial initiation as affected by seeding interval after herbicide application in Manhattan, KS and Wooster, OH.

	Manhattan, KS			Wooster, OH		
Source	Cover	Canopy height	NDVI	Cover	Canopy height	NDVI
Kentucky bluegrass						
Seeding Interval (S)	ns	ns	***	***	***	***
Herbicide (H)	***	***	***	***	***	***
S x H	ns	*	ns	***	*	**
Tall fescue						
S	***	***	*	***	***	***
H	***	***	***	***	***	***
S x H	***	*	***	***	ns	**

*,**,*** significant at $P < 0.05$, 0.001, and 0.0001, respectively.

ns = not significant

Table 1.3 Main effects of herbicide treatment on Kentucky bluegrass cover and NDVI in Manhattan, KS and tall fescue canopy height in Wooster, OH six weeks after herbicide application.

	Manhattan, KS		Wooster, OH
	Kentucky bluegrass		Tall fescue
Treatment[a]	Cover(%)[b]	NDVI[c]	Canopy height (inches)[d]
Non-treated	88a[e]	0.70a	2.2a
2,4-D + MCPP + dicamba	83a	0.67a	1.7b
Quinclorac	81a	0.66a	2.2a
Halosulfuron-methyl	73b	0.61b	1.9ab
Dithiopyr	4c	0.30c	0.6c

[a] Herbicides were applied on 6 Sept. 2019 (Manhattan, KS) and 2 Oct. 2019 (Wooster, OH).
[b] Coverage was rated visually on a 0 to 100% scale on which 0 = no coverage, and 100 = complete coverage.
[c] NDVI (normalized difference vegetation index) of Kentucky bluegrass in Manhattan, KS. Measurements range from -1 to 1, with higher values indicating greater plant health.
[d] Canopy height (inches) of tall fescue in Wooster, OH was measured randomly in three areas of each plot and means recorded.
[e] Means followed by the same letter in a column are not statistically different according to Fisher's LSD ($P \leq 0.05$). Means are averages over seeding intervals, n = 16.

Table 1.4 Canopy height of Kentucky bluegrass six weeks after herbicide application in Manhattan, KS and Wooster, OH.

	Canopy height (inches)							
	Manhattan, KS				Wooster, OH			
	Days after treatment (DAT)[a]							
Treatment[b]	0	3	7	14	0	3	7	14
Non-treated	0.9Aa[c]	0.9Aa	0.9Aa	1.0Aa	1.2Aa	1.1Ab	1.0Aab	0.4Ba
2,4-D + MCPP + dicamba	0.9Aa	0.9Aa	1.0Aa	0.9Aab	1.3Aa	1.3Aab	1.1Aa	0.1Ba
Quinclorac	1.0Aa	0.9Aa	1.0Aa	0.8Aab	1.3ABa	1.9Aa	1.1ABa	0.6Ba
Halosulfuron-methyl	0.8Aa	0.8Aa	0.8Aa	0.8Aab	0.9Ab	0.8Ab	0.7Ab	0.2Ba
Dithiopyr	0.0Bb	0.7Aa	0.4ABb	0.7Ab	0.0Ac	0.0Ac	0.0Ac	0.0Aa

[a] DAT, days after herbicide treatment that Kentucky bluegrass was seeded.
[b] Herbicides were applied on 6 Sept. 2019 (Manhattan, KS) and 2 Oct. 2019 (Wooster, OH).
[c] Means followed by the same capital letter in a row are not statistically different within each herbicide by location. Means followed by the same lower case letter in a column are not significantly different within each seeding interval according to Fisher's LSD ($P \leq 0.05$). Means are averages over seeding intervals and herbicides, n = 16.

Table 1.5 Effect of herbicide treatment seeding interval interaction on Kentucky bluegrass visual cover in Wooster, OH six weeks after herbicide application.

	Cover (%)[a]			
	Days after treatment (DAT)[b]			
Treatment[c]	0	3	7	14
Non-treated	48ABab[d]	54Aa	33Bab	3Ca
2,4-D + MCPP + dicamba	68Aa	31Ba	38Ba	4Ca
Quinclorac	49Aab	45Aa	28ABb	6Ba
Halosulfuron-methyl	33Ab	33Aa	21Ac	3Aa
Dithiopyr	0Ac	0Ab	0Ad	0Aa

[a] Coverage was rated visually on a 0 to 100% scale on which 0 = no coverage, and 100 = complete coverage.
[b] DAT, days after herbicide treatment that Kentucky bluegrass was seeded.
[c] Herbicides were applied on 2 Oct. 2019.
[d] Means followed by the same capital letter in a row are not statistically different within each herbicide. Means followed by the same lower case letter in a column are not significantly different within each seeding interval according to Fisher's LSD ($P \leq 0.05$). Means are averages over seeding intervals and herbicides, n = 16.

Table 1.6 Effect of herbicide treatment by seeding interval interaction on Kentucky bluegrass NDVI in Wooster, OH six weeks after herbicide application.

	NDVI[a]			
	Days after treatment (DAT)[b]			
Treatment[c]	0	3	7	14
Non-treated	0.48Aa[d]	0.45ABa	0.40Ba	0.33Ca
2,4-D + MCPP + dicamba	0.48Aa	0.40Bab	0.39Ba	0.33Ca
Quinclorac	0.41Ab	0.40Aab	0.38ABab	0.33Ba
Halosulfuron-methyl	0.40Ab	0.39ABb	0.35BCbc	0.32Ca
Dithiopyr	0.32Ac	0.28Ac	0.32Ac	0.32Aa

[a] NDVI measurements range from -1 to 1, with higher values indicating greater plant health.
[b] DAT, days after herbicide treatment that Kentucky bluegrass was seeded.
[c] Herbicides were applied on 2 Oct. 2019.
[d] Means followed by the same capital letter in a row are not statistically different within each herbicide. Means followed by the same lower case letter in a column are not significantly different within each seeding interval according to Fisher's LSD ($P \leq 0.05$). Means are averages over seeding intervals and herbicides, n = 16.

Table 1.7 Effect of herbicide treatment by seeding interval interaction on tall fescue visual cover in Manhattan, KS and Wooster, OH six weeks after herbicide application.

	Cover (%)[a]							
	Manhattan, KS				Wooster, OH			
	Days after treatment (DAT)[b]							
Treatment[c]	0	3	7	14	0	3	7	14
Non-treated	100Aa[d]	99ABa	96Ba	98ABa	90Aa	60Ba	50Ba	20Ca
2,4-D + MCPP + dicamba	100Aa	100Aa	96Ba	98ABa	69Abc	59ABab	36BCa	14Ca
Quinclorac	100Aa	99Aa	99Aa	99Aa	81Aab	69Aa	46Ba	18Ca
Halosulfuron-methyl	94Bb	99Aa	96ABa	95Ba	58Ac	46Bb	39Ba	16Ca
Dithiopyr	6Bc	19Bb	50Ab	76Ab	0Bd	4Ac	3ABb	1Bb

[a] Coverage was rated visually on a 0 to 100% scale on which 0 = no coverage, and 100 = complete coverage.
[b] DAT, days after herbicide treatment that tall fescue was seeded.
[c] Herbicides were applied on 6 Sept. 2019 (Manhattan, KS) and 2 Oct. 2019 (Wooster, OH).
[d] Means followed by the same capital letter in a row are not statistically different within each herbicide by location. Means followed by the same lower case letter in a column are not significantly different within each seeding interval according to Fisher's LSD ($P \leq 0.05$). Means are averages over seeding intervals and herbicides, n = 16.

Table 1.8 Effect of herbicide treatment by seeding interval interaction on tall fescue NDVI in Manhattan, KS and Wooster, OH six weeks after herbicide application.

	NDVI[a]							
	Manhattan, KS				Wooster, OH			
	Days after treatment (DAT)[b]							
Treatment[c]	0	3	7	14	0	3	7	14
Non-treated	0.84ABa[d]	0.85Aa	0.82ABa	0.80Ba	0.54Aa	0.45Bb	0.44Ba	0.35Ca
2,4-D + MCPP + dicamba	0.85ABa	0.87Aa	0.81BCa	0.80Ca	0.49Aa	0.44ABb	0.44ABa	0.32Ba
Quinclorac	0.83ABa	0.85Aa	0.79Ba	0.80ABa	0.53ABa	0.54Aa	0.46Ba	0.33Ca
Halosulfuron-methyl	0.74Bb	0.82Aa	0.79ABa	0.77ABa	0.45Aa	0.42ABb	0.40Bab	0.33Ca
Dithiopyr	0.32Bc	0.51ABb	0.59ABb	0.68Ab	0.31Ab	0.31Ac	0.34Ab	0.32Aa

[a] NDVI measurements range from -1 to 1, with higher values indicating greater plant health.
[b] DAT, days after herbicide treatment that tall fescue was seeded.
[c] Herbicides were applied on 6 Sept. 2019 (Manhattan, KS) and 2 Oct. 2019 (Wooster, OH).
[d] Means followed by the same capital letter in a row are not statistically different within each herbicide by location. Means followed by the same lower case letter in a column are not significantly different within each seeding interval according to Fisher's LSD ($P \leq 0.05$). Means are averages over seeding intervals and herbicides, n = 16.

Table 1.9 Canopy height of tall fescue six weeks after herbicide application in Manhattan, KS.

	Canopy height (inches)			
	Days after treatment (DAT)[a]			
Treatment[b]	0	3	7	14
Non-treated	2.8Aa[c]	3.0Aa	2.5Aab	1.8Bab
2,4-D + MCPP + dicamba	2.8Aa	2.9Aa	2.5Aab	1.8Bab
Quinclorac	2.8Aa	2.8Aa	2.8Aa	2.0Aa
Halosulfuron-methyl	1.7Bb	1.7Bb	2.0Abc	1.7Bab
Dithiopyr	1.2Ab	1.6Ab	1.6Ac	1.6Ab

[a] DAT, days after herbicide treatment that Kentucky bluegrass was seeded.
[b] Herbicides were applied on 6 Sept. 2019.
[c] Means followed by the same capital letter in a row are not statistically different within each herbicide. Means followed by the same lower case letter in a column are not significantly different within each seeding interval according to Fisher's LSD ($P \leq 0.05$). Means are averages over seeding intervals and herbicides, n = 16.

Figure 1.1 Three-tine rotary cultivator used to disturb the soil surface (left), and appearance of the plot prior to seeding and after cultivation (right).

Figure 1.2 Daily maximum and minimum air and soil temperatures throughout study in Manhattan, KS. Weather data collected from Kansas Mesonet Manhattan weather station. Downward arrows indicate seeding dates after herbicide application (DAT).

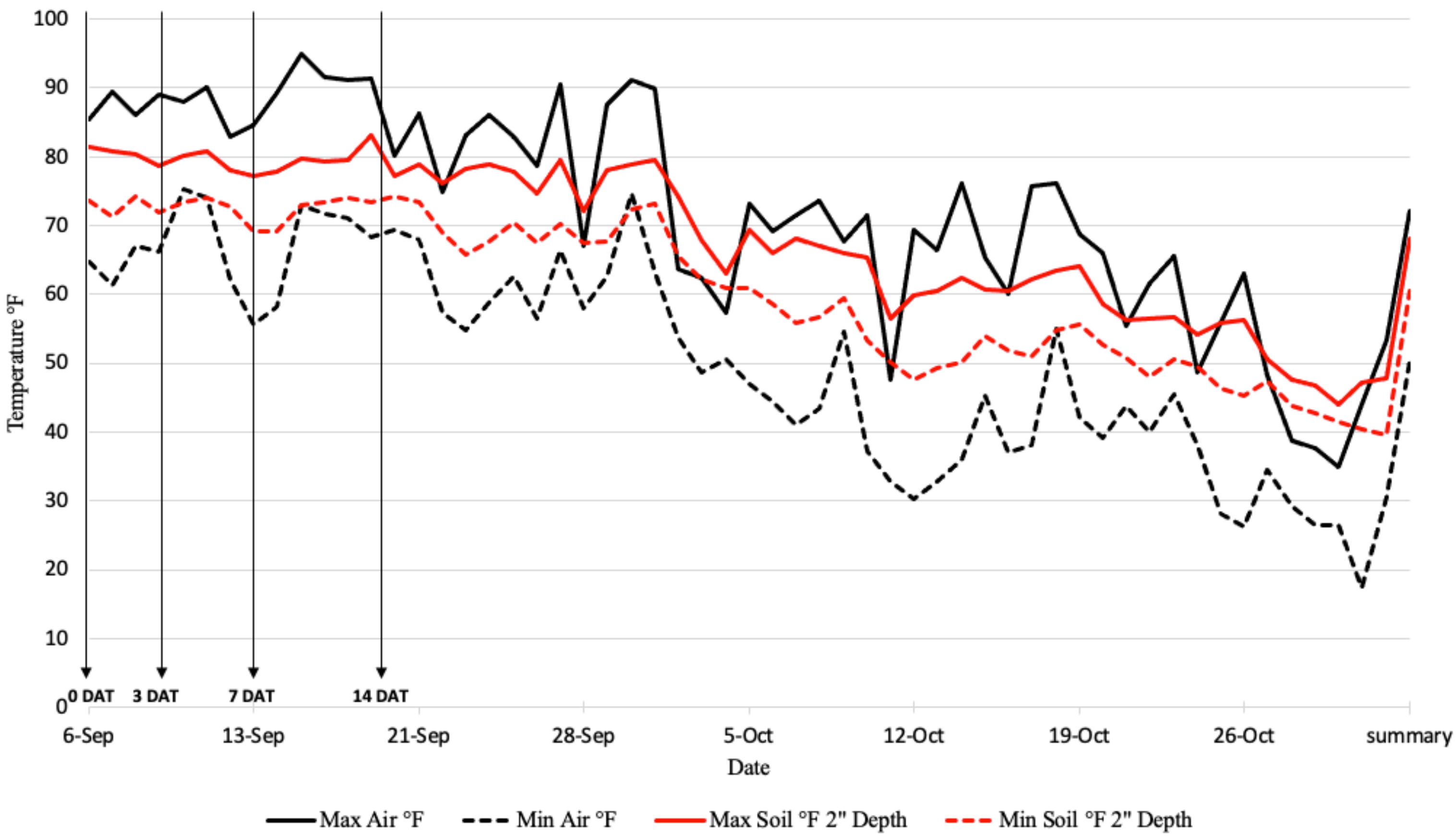
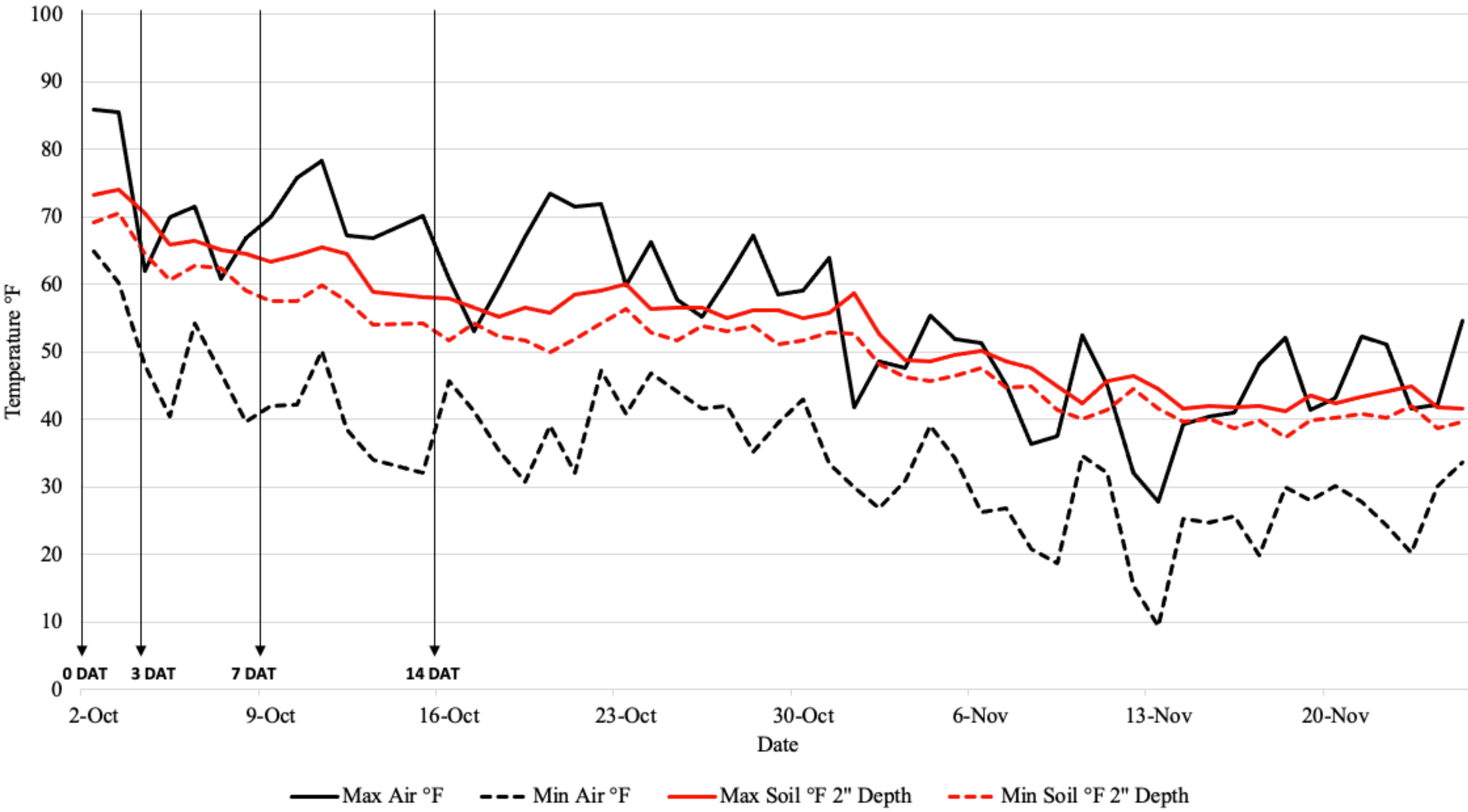


Figure 1.3 Daily maximum and minimum air and soil temperatures throughout study in Wooster, OH. Weather data collected from CFAES Weather System. Downward arrows indicate seeding dates after herbicide application (DAT).



Chapter 2 - Influence of Herbicides and Irrigation on Tall Fescue Shoot and Root Growth

This chapter has been prepared using style guidelines for submission to *Crop, Forage, and Turfgrass Management*.

Introduction

When turfgrass stands are under renovation, a common problem is removing weeds prior to seeding because seedling turf does not emerge and compete well with weeds that are present (McCalla et al., 2004). Reduction of turfgrass density and cover prior to tillering is caused by weed interference; however, many products used for postemergence weed control such as 2,4-D [(2,4-dichlorophenoxy) acetic acid], dicamba [3,6-dichloro-2-methoxybenzoic acid], triclopyr [3,5,6-trichloro-2-pyridinyloxyacetic acid], MCPP [2-(2-methyl-4-chlorophenoxy) propionic acid], or MSMA [monosodium methylarsenate] are only recommended for application after turfgrass seedlings have emerged and tillered (Willis et al., 2006; Askew and Hipkins, 2005). Most herbicide labels recommend waiting for a defined period of time prior to seeding. If seeding is done prior to the date prescribed on the herbicide label, seed germination and seedling growth may be inhibited (Johnston et al., 2016; McElroy and Breeden, 2007; Kaminski et al., 2004). Additionally, formulation and rate, or the inclusion of surfactants and other ingredients, result in differing effects and toxicity levels on weeds and nontarget plants (White and Boutin, 2007; Sharma and Singh, 2001).

Following an herbicide application, turfgrass managers may need to reseed out of necessity due to client needs or areas void of turf. Factors such as herbicide application rate and timing, environmental conditions, and cultural practices, including irrigation, all play a role on how turfgrass seed germination and establishment will be affected. Irrigation is one of the most critical cultural practices used for quality turf (Huang, 2008; McCarty, 2005). The amount of irrigation or rainfall that occurs after herbicide application and prior to seeding could influence the level of herbicide residual on the soil surface and its influence on seed germination and seedling growth.

Herbicides are also susceptible to run off and leaching (Frederick et al., 1996). Previous studies found that irrigation or rainfall events did not affect soil mobility of certain pesticides applied to turfgrass, and irrigation practices after treatment may not be an important factor in determining soil mobility (Niemczyk and Krueger, 1987; Cisar and Snyder, 1996; Gardner and Branham, 2001). However, Starrett et al. (2000) concluded that the movement of 2,4-D, dicamba, and MCPP is impacted by the frequency of irrigation. Since soil structure influences infiltration rates of water, soil structure impacts herbicide sorption rates (Krutz et al., 2005). In addition, herbicide and soil interaction is characterized by the K_{oc} (organic matter partitioning coefficient), which is related to the ratio of the herbicides mass adsorbed in soil to the mass of organic carbon (Jester et al., 2021; Gouy et al., 1999). So, an increase in K_{oc} will decrease the mobility of herbicides in soils containing increased amounts of organic carbon, and also reduce the level of plant absorbance.

In Chapter 1, tall fescue (*Schedonorus arundinaceus* (Schreb.) Dumort.) emergence and growth was less inhibited when seeding was done at 7 or 14 days after application of the preemergence herbicide dithiopyr [2-(difluoromethyl)-4-(2-methylpropyl)-6-(trifluoromethyl)pyridine-3,5-dicarbothioate)] (Dimension), compared to seeding the same day as application. Tall fescue emergence in plots seeded at 7 or 14 days after dithiopyr application could have been increased if frequent irrigation, which began at 0 DAT, enhanced herbicide breakdown prior to seeding at 7 or 14 DAT. Ongoing high levels of soil moisture can elevate microbial degradation of herbicides and reduce their influence on seedling emergence (Mueller et al., 1999). Therefore, the objective of this greenhouse study was to evaluate the influence of irrigation for its potential to lessen the effects of pre- and postemergence herbicides on emergence and growth of tall fescue seeded after application.

Materials and Methods

Material Preparation

A greenhouse study was conducted in the Throckmorton Plant Science Center at Kansas State University, Manhattan, KS from January to March, 2020 (Experiment 1) and May to July, 2020 (Experiment 2) to determine the effects of irrigation on seedling growth after herbicide application. The greenhouse was climate controlled (Step50A, Wadsworth Control Systems, Arvada, CO) with a day and night setpoint of 80°F and 64°F, respectively. Supplemental lighting (T101M, Intermatic Inc., Spring Grove, IL) was used to mimic the same day length from the field study, with lights turning on at 6:30 am and turning off at 8:30 pm daily. One coffee filter (Brew Rite® 4739990) was placed at the bottom of each 4-inch square thermoplastic greenhouse container (4 inches dia. by 4 inches deep), then filled with a 1:1 ratio of unpasteurized field soil and sand to a height of 3.5 inches. Each pot was filled with approximately 20 ounces of media and then compressed to 0.5 inches from the top of the container. A total of 160 pots were used for each experimental run.

Experimental Design

The experiment was arranged in a completely randomized design with four replicates and a three-way factorial treatment structure to evaluate the effect of herbicide (factor a), seeding interval (factor b) and irrigation (factor c). Herbicide treatments were a nontreated and 2,4-D + MCPP + dicamba (Trimec Classic®, PBI/Gordon Corporation, Kansas City, MO) at 1.19lbs, 0.32lbs, and 0.13lbs a.i. acre^{-1}, respectively; quinclorac [3,7-dichloro-8-quinolinecarboxylic acid] (Drive® 75, BASF Chemical Company, Research Triangle Park, NC) at 0.75lbs a.i. acre^{-1}; halosulfuron-methyl [3-chloro-5-(4,6-dimethoxypyrimidin-2-ylcarbamoylsulfamoyl)] (SedgeHammer®, Gowan Company, Yuma, AZ) at 0.06lbs a.i. acre^{-1}; and dithiopyr

(Dimension™ 2EW, Dow AgroSciences LLC, Indianapolis, IN) at 0.50lbs a.i. $acre^{-1}$. Each herbicide was applied to the soil surface of the pots using a CO_2-pressurized hand-held spray boom equipped with four TeeJet8003 flat-fan nozzles on 9.8-inch spacing calibrated to deliver 43 gal $acre^{-1}$.

The four seeding intervals included 0, 3, 7 and 14 days after herbicide application. Cultivars in the tall fescue seed blend included 36.8% Copious, 31.1% Technique, and 30.9% Leonardo. Before seed was sown into each pot, a 0.45-inch in diameter dowel rod was used to prepare the top 0.5 inch of the seedbed by pressing 12 holes per square inch. A starter fertilizer with an analysis [14-20-04 (N-P-K)] was applied to deliver 1 lb P 1,000ft^{-2} to each pot.

Following herbicide application, treatments were placed on either an irrigated bench or non-irrigated bench. All non-irrigated treatments were initially placed on the non-irrigated bench and transferred to the irrigated bench after each respective seeding interval. Irrigation was applied using a mist system and ran three times daily for three minutes each applying a total of 0.072 inches of water daily, comparable to irrigation amounts in Chapter 1. Shower curtain liners (Zenna Home® Heavyweight Clear PEVA) were hung to block irrigation between benches. For both experimental runs, Tekken Broad Spectrum Fungicide (isofetamid [N-[1-(4-isopropoxy-2-methylphenyl)-2-methyl-1-oxopropan-2-yl]-3-methylthiophene-2-carboxamide;2-Thiophenecarboxamide, N-[1,1-dimethyl-2-[2-methyl-4-(1-methylethoxy)phenyl]-2-oxoethyl]-3-methyl-] + tebuconazole [1-(4-chlorophenyl)-4,4-dimethyl-3-(1H-1,2,4-triazol-1-ylmethyl)pentan-3-ol] was applied at 21 and 35 days after herbicide application at 3 fl. oz. of product per 1,000 ft^{-2}.

Measurements and Statistical Analysis

Tall fescue was harvested 42 days after each seeding interval. Because pots of tall fescue were mowed throughout the duration of the trial to maintain acceptable growth, all treatments were trimmed down to 2.75 inches above the soil surface before harvesting. Shoots were then collected by cutting at the soil surface and weighed using a Denver Instrument scale (Model MXX-612, Bohemia, NY). After shoot harvest, rootzone material from the pot was placed on a sifter and soil was washed from roots. Immediately after washing, roots were manually compressed to remove water then submerged in a graduated cylinder with a known amount of water. Root volume was determined by the amount of water displaced and then calculated and recorded in cubic inches. Shoots and roots were then placed in individual paper bags and dried for approximately 48 hours in an electric drying oven (Hamilton; Model 2185632, Two Rivers, WI) at 150°F. After the 48 hours, dried shoots and roots were weighed. Because the experiment was repeated, data for each experimental run was analyzed with experiment number as a factor to determine if data could be combined. All data for each of the harvest weights were subjected to ANOVA in SAS (9.4) using the GLIMMIX procedure and means were separated according to Fisher's Protected LSD ($P \leq 0.05$).

Results and Discussion

The Herbicide x Experiment interaction was significant for tall fescue shoot fresh and dry weights, but neither Herbicide x Seeding Interval nor Irrigation x Herbicide x Seeding Interval was impactful (Table 2.1). Halosulfuron-methyl- and dithiopyr-treated soil reduced tall fescue shoot fresh weights in experiment 1 compared to the nontreated soil (Table 2.2). Dithiopyr-treated soil was the only herbicide that reduced tall fescue shoot dry weights in experiment 1. All herbicides reduced fresh shoot weight compared to the nontreated soil in experiment 2. All herbicides reduced dry shoot weight compared to the nontreated soil in experiment 2, with a greater reduction in halosulfuron-methyl and dithiopyr-treated pots compared to those treated with 2,4-D + MCPP + dicamba or quinclorac.

Although the three way-interaction of Irrigation x Herbicide x Seeding Interval shows significance in Table 2.1 for root data, inspection of the interaction plots revealed little to no impact of irrigation. As such, discussion will focus on the Herbicide x Seeding Interval x Experiment interaction, which was significant for root volume and root dry weight. All herbicides reduced root volume compared to nontreated soil at 0 DAT in experiment 1 (Table 2.3). In experiment 1, when seeding was done at 3 and 7 DAT, tall fescue in halosulfuron-methyl-treated soil had lower root volume than that in nontreated soil. At 3, 7, and 14 DAT dithiopyr-treated soil caused tall fescue to have root volume that was significantly lower than turf in nontreated soil. In experiment 2, tall fescue seeded into quinclorac-treated soil at 0 DAT, along with halosulfuron-methyl- and dithiopyr-treated soil at 0, 3, 7, and 14 DAT, had reduced root volume compared to turf in nontreated soil (Table 2.3).

In experiment 1, all herbicides reduced root dry weight compared to the nontreated soil when seeded 0 DAT; however, no herbicide affected root dry weight compared to nontreated soil at 7 and 14 DAT (Table 2.4). In experiment 2, tall fescue seeded into quinclorac-treated soil at 7 DAT, along with halosulfuron-methyl and dithiopyr at 0, 3, 7, and 14 DAT, had reduced dry root weight compared to nontreated soil.

Tall fescue root volume and dry weights differed between experiments. There was a three- and eightfold increase in root volume and dry weight, respectively, in experiment 1 compared to experiment 2 for nontreated tall fescue seeded at 0 DAT. This may have been due to higher greenhouse temperatures causing a decline in plant health during experiment 2. Although the climate control system had a daytime setpoint of 80°F, outside air temperatures in the summer months likely increased the greenhouse temperature above the maximum setpoint. Tall fescue prefers cooler soil and air temperatures for shoot and root development (Fry and Huang, 2004). Fungicides were regularly applied during both experiments; however, greenhouse temperatures were harder to maintain in experiment 2, which likely affected root development.

Tall fescue seeded into soil treated with 2,4-D + MCPP + dicamba or quinclorac established a well-developed root system compared to soil treated with halosulfuron-methyl regardless of seeding interval after treatment (Fig. 2.1; Table 2.3). Tall fescue seeded into 2,4-D + MCPP + dicamba and quinclorac treatments had similar fresh and dry root weights compared to nontreated soil and exhibited the same safeness of seeding that we observed in the field.

Unlike in the field study outlined in Chapter 1, there was no emergence or growth of tall fescue after seeding into dithiopyr-treated soil. Results from a study conducted in Arizona demonstrated that at the time of overseeding perennial ryegrass into bermudagrass in October, only 12 to 16% of the dithiopyr applied in late August remained in the soil (Shaner and Umeda, 2011). In the same experiment, dithiopyr was shown to dissipate twice as rapidly as prodiamine (Shaner and Umeda, 2011). Soil composition, chemistry, and microbial activity are factors that affect herbicide persistence (Curran, 2016).

Herbicide breakdown in the field is also enhanced by photodegradation from sunlight (Katagi, 2004). The extent of photolysis from sunlight is dependent on the UV absorption properties of the pesticide, the turf canopy and surrounding soil medium, and the sunlight emission spectrum (Katagi, 2004). In addition, an increase in UV-B (315-280 nm) was potentially reached during the years 2010 to 2020 from peak exposure in the northern hemisphere caused by a decrease in atmospheric ozone (Talaas et al., 2000; Nangle et al., 2015).

In the greenhouse, little UV light reaches the soil surface, and this may have influenced the impact of herbicides, and particularly dithiopyr, and tall fescue growth.

The Trimec Classic label indicates that seed can be sown 3 to 4 weeks after application (PBI-Gordon Corporation, 2017). In experiment 1, root inhibition was observed when tall fescue was seeded at 0 DAT, but had similar dry weights compared to the nontreated at 3, 7, and 14 DAT and were comparable to the nontreated at all four seeding intervals for fresh and dry shoot weights. These results indicate that the reseeding interval on the product label could be shorter than 3 to 4 weeks after application. In Chapter 1, growth was not affected when tall fescue was seeded into an application of 2,4-D + MCPP + dicamba at 0 to 14 DAT.

The product label indicates that the use of Drive 75 DF before or after seeding or over-seeding a turf area will not significantly interfere with the turfgrass seed germination and growth of grass types identified as tolerant or moderately tolerant (BASF Professional and Specialty Solutions, 2014). Tall fescue is labeled as a tolerant species when quinclorac is applied prior to or at seeding. In experiment 1 there were no differences in fresh and dry shoot weights compared to nontreated soil; however, root volume and dry weight were inhibited with seeding at 0 DAT. In experiment 2, tall fescue root volume was lower than nontreated turf when seeded at 0, 3, and 7 DAT, and dry weight was lower than nontreated turf at all four seeding intervals. These results suggest that waiting at least 7 days after quinclorac application before seeding may be beneficial for tall fescue growth. In Chapter 1, quinclorac did not affect seedling growth and tall fescue seeded into quinclorac-treated plots was comparable to nontreated plots at 0 to 14 DAT; however, root development was not evaluated in Chapter 1.

The SedgeHammer label indicates that 4 weeks should pass after application before seeding or sodding of turfgrass (Gowan Company, 2019), and research herein supports waiting more than 14 DAT before seeding tall fescue. Shoot and root inhibition were observed when seeded at 0, 3, 7, and 14 days after application. While the experiment only evaluated seeding within 2 weeks of application, it would be valuable to evaluate tall fescue emergence and growth if seeded between 2 and 4 weeks after application. In Chapter 1, tall fescue seeded into halosulfuron-methyl 0 or 3 DAT had reduced cover, NDVI, and canopy height and results from the field study support waiting over 14 DAT before seeding tall fescue.

The Dimension 2EW label indicates reseeding or overseeding of treated areas within 3 months after application may inhibit establishment of desirable turf (Corteva Agriscience, 2015). In this study, no tall fescue emergence occurred after seeding at 0, 3, 7, and 14 DAT, and demonstrates the influence of dithiopyr on turfgrass seedling emergence. In Chapter 1, as discussed earlier, tall fescue emergence and growth did occur in the field when seeding was done at 7 and 14 DAT of dithiopyr.

Overall, irrigation did not affect shoot or root growth in these greenhouse experiments. The results align with previous studies that concluded post-treatment irrigation practices might not be an important factor in affecting herbicide residue in soil (Niemczyk and Krueger, 1987; Cisar and Snyder, 1996; Gardner and Branham, 2001). Similar to our findings in Chapter 1, seeding tall fescue into soil treated with 2,4-D + MCPP + dicamba was generally found to be safe on shoot and root development, along with tall fescue seeded into quinclorac at least 3 DAT. These results conclude that seeding after the application of 2,4-D + MCPP + dicamba or quinclorac resulted in minimal injury. However, herbicide manufacturers could consider altering label reseeding intervals, using results reported herein as guidelines.

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Table 2.1 ANOVA results for tall fescue shoot and dry weight, and root volume and dry weight 42 days after seeding as affected by irrigation, herbicide application, and seeding interval.

Source	Fresh shoot weight	Dry shoot weight	Root volume	Root dry weight
Irrigation (I)	***	***	*	ns
Herbicide (H)	***	***	***	***
Seeding interval (S)	ns	ns	***	***
H*S	ns	ns	***	***
I*H*S	ns	ns	**	*
H*Experiment (E)	***	***	***	***
H*S*E	ns	ns	***	***
I*H*S*E	ns	ns	ns	ns

*,**,*** significant at $P < 0.05$, 0.001, and 0.0001, respectively.

ns = not significant

Table 2.2 Main effects of herbicide treatment on tall fescue fresh shoot and dry weight 42 days after herbicide application in experiment 1 and 2.

	Fresh weight (oz)[a]		Dry weight[b] (oz)	
Treatment[c]	Exp. 1	Exp. 2	Exp. 1	Exp. 2
Nontreated	0.13a[d]	0.17a	0.03a	0.04a
2,4-D + MCPP + dicamba	0.13a	0.14b	0.04a	0.03b
Quinclorac	0.14a	0.13b	0.03a	0.03b
Halosulfuron-methyl	0.11b	0.10c	0.04a	0.02c
Dithiopyr	0.00c	0.00d	0.00b	0.00d

[a] oz = ounces

[b] Dry weights recorded after 48-hour oven dry-down period at 150°F.

[c] Herbicides were applied on 20 Jan. 2020 (Exp. 1) and 18 May 2020 (Exp. 2).

[d] Means followed by the same letter in a column are not statistically different ($P \leq 0.05$) according to Fisher's LSD. Means are averages over seeding intervals, n = 16.

Table 2.3 Interaction of herbicide treatment by seeding interval on tall fescue root volume 42 days after herbicide application in experiment 1 and 2.

	Root volume (in^3)[a]							
	Days after treatment (DAT)[b]							
	Exp. 1				Exp. 2			
Treatment[e]	0	3	7	14	0	3	7	14
Nontreated	2.86A[d]	1.33CD	1.33CD	0.82EFGHI	0.88AB	0.93A	0.91AB	0.82ABCD
2,4 + MCPP+dica[e]	2.09B	1.11CDEF	1.31CDE	0.99DEFG	0.80ABCDE	0.80ABCDE	0.84ABC	0.76BCDE
Quinclorac	1.53C	1.24CDE	1.14CDEF	0.93DEFGH	0.68E	0.69DE	0.71CDE	0.88AB
Halosulf-methyl[f]	0.47HIJ	0.55GHI	0.72FGHI	0.34IJ	0.29G	0.32FG	0.32FG	0.46F
Dithiopyr	0.00J	0.00J	0.00J	0.00J	0.00H	0.00H	0.00H	0.00H

[a] in^3 = cubic inches
[b] DAT = days after treatment
[c] Herbicides were applied on 20 Jan. 2020 (Exp. 1) and 18 May 2020 (Exp. 2).
[d] Means followed by the same capital letter are not statistically different within rows or columns under each experiment according to Fisher's LSD ($P \leq 0.05$).
[e] 2,4-D + MCPP + dicamba
[f] Halosulfuron-methyl

Table 2.4 Interaction of herbicide treatment by seeding interval on tall fescue root dry weight 42 days after herbicide application in experiment 1 and 2.

	Dry weight (oz)[a,b]							
	Days after treatment (DAT)[c]							
	Exp. 1				Exp. 2			
Treatment[d]	0	3	7	14	0	3	7	14
Nontreated	0.63A[e]	0.21C	0.11CDEF	0.10DEF	0.08A	0.07AB	0.05CD	0.06BC
2,4 + MCPP+ dica[f]	0.40B	0.18CD	0.11CDEF	0.10DEF	0.05CD	0.05CD	0.04DE	0.04DE
Quinclorac	0.36B	0.15CDE	0.10DEF	0.10DEF	0.04DE	0.04CDE	0.03FE	0.04DE
Halosulf-methyl[g]	0.04F	0.06EF	0.03F	0.02F	0.01GH	0.02FG	0.01GH	0.02FG
Dithiopyr	0.00F	0.00F	0.00F	0.00F	0.00H	0.00H	0.00H	0.00H

[a] oz = ounces
[b] Dry weights recorded after 48-hour oven dry-down period at 150°F.
[c] DAT = days after treatment
[d] Herbicides were applied on 20 Jan. 2020 (Exp. 1) and 18 May 2020 (Exp. 2).
[e] Means followed by the same capital letter are not statistically different within rows or columns under each experiment according to Fisher's LSD ($P \leq 0.05$).
[f] 2,4-D + MCPP + dicamba
[g] Halosulfuron-methyl

Figure 2.1 Differences in rooting of tall fescue 42 days after seeding into 2,4-D + MCPP + dicamba (left) and halosulfuron-methyl (right) at 0 DAT in March 2020.

Chapter 3 - Emergence and Growth of Tall Fescue Seedlings after Postemergence Broadleaf Herbicide Application

This chapter has been prepared using style guidelines for submission to *Crop, Forage, and Turfgrass Management*.

Introduction

Effective weed control prior to seeding is essential for proper turfgrass establishment since competition from weeds can cause sward establishment to fail (Patton et al., 2009; Dunn and Diesburg 2004). Herbicides are a vital component to weed management in turfgrass; however, limited research exists on chemical weed control at seeding despite the common practice of reseeding immediately after herbicide application (McElroy and Martins, 2013; Wagner and Nelson, 2014).

Commonly used products for postemergence broadleaf weed control such as 2,4-D [(2,4-dichlorophenoxy) acetic acid], dicamba [3,6-dichloro-2-methoxybenzoic acid], triclopyr [3,5,6-trichloro-2-pyridinyloxyacetic acid], or MCPP [2-(2-methyl-4-chlorophenoxy) propionic acid] are only recommended for application after turfgrass seedlings have emerged and tillered (Willis et al., 2006; Askew and Hipkins, 2005). Most herbicide labels recommend waiting for a defined period of time prior to seeding. Applying herbicides before seeding can impact germination and growth of seedlings (Johnston et al., 2016; McElroy and Breeden, 2007; Kaminski et al., 2004).

In Chapter 1, shoot growth was not affected when tall fescue (*Schedonorus arundinaceus* (Schreb.) Dumort.) was seeded 0 to 14 days after application of 2,4-D + MCPP + dicamba (Trimec Classic). In Chapter 2, root inhibition was observed when tall fescue was seeded into 2,4-D + MCPP + dicamba-treated pots at 0 DAT, but neither root or shoot growth was affected when seeded into the same treatment at 3, 7, or 14 DAT. This suggests that delaying seeding more than 3 days after herbicide application may not be necessary. In Georgia, Tennessee, and Texas, application of the postemergence broadleaf herbicides aminocyclopyrachlor [(6-Amino-5-chloro-2-cyclopropylpyrimidine-4-carboxylic acid) Imprelis 2SL] or 2,4-D + dicamba + MCPP, at different rates at 0, 2, 4, or 6 weeks before seeding perennial ryegrass (*Lolium perenne* L.) and tall fescue resulted in similar establishment to nontreated turf and suggested no seeding delay was required after application (Workman et al., 2012). Another study by Li et al. (2015) found that combination products used for broadleaf weed control such as sulfentrazone [N-[2,4-dichloro-5-[4-(difluoromethyl)-4,5-dihydro-3-methyl-5-oxo-1H-1,2,4-triazol-1-yl]phenyl]methanesulfonamide] + quinclorac (3,7-dichloro-8-quinolinecarboxylic acid), carfentrazone-ethyl [(2-chloro-3-[2-chloro-4-fluoro-5-[4-(difluoromethyl)-4,5-diydro-3-methyl-5-oxo-1H-1,2,4-trizol-1-yl)phenyl]propanoate)] + quinclorac, and sulfentrazone + prodiamine [2,6-Dinitro-N,N-dipropyl-4-(trifluoromethyl)-1,3-benzenediamine] were safe to apply at the time of buffalograss [*Buchloe dactyloides* (Nutt.) Engelm.] seeding and effectively minimized weed pressure.

The introduction of new combination products raises concerns regarding the delay in seeding required after application. Herbicides with multiple active ingredients from different chemical families could increase efficacy, but hinder the establishment of newly seeded turf. In Chapter 1 and Chapter 2 we concluded that 2,4-D + MCPP + dicamba (Trimec Classic) was generally safe to seed into at 0 to 14 days after application. However, information is needed on other postemergence broadleaf combination herbicides (some of which contain herbicides that target grassy weeds). Therefore, the objective of this research was to determine the influence of combination products used for postemergence control of broadleaf weeds on emergence and growth of tall fescue seeded between 0 and 14 days after application.

Materials and Methods

Research Site Information

Field experiments were conducted at the Olathe Horticulture Research and Extension Center in Olathe, KS (long. 39.48 °N, 95.66 °W) and at the Rocky Ford Turfgrass Research Center in Manhattan, KS (long. 39.13° N, lat. 96.36° W). Soil type in Olathe was an Oska-Martin silty clay loam with 5.5 pH, and the soil type in Manhattan was a Chase silty loam (fine, smectitic, mesic Aquertic Argiudoll) with 6.8 pH. Prior to seeding at each location, sequential applications of a non-selective herbicide were applied to control existing vegetation (tall fescue in Manhattan and zoysiagrass in Olathe). Prior to trial initiation in Olathe, the study site was verticut in three directions with a power rake (Billy Goat Industries Inc., Lee's Summit, MO) with 2.0 inch knife spacing on a No. 4 setting. Plots were raked to remove the material that had been verticut before herbicide application. The Manhattan study site was scalped with a reel mower to 0.5 inches in two directions with clippings collected.

Herbicides and Seeding Intervals

Field experiments were initiated on 24 Aug. 2020 in Olathe and 2 Sept. 2020 in Manhattan. The experiments were arranged in a two-way factorial, randomized complete block design with four replicates. Treatments were five herbicides (noted below) and four seeding intervals (0, 3, 7, and 14 days after herbicide application) for a total of 20 individual treatments.

Herbicides consisted of a nontreated control and four herbicides: Carfentrazone-ethyl + MCPP + 2,4-D + dicamba (SpeedZone®, PBI/Gordon Corporation, Kansas City, MO); Fluroxypyr [(4-amino-3,5-dichloro-6-fluoro-2-pyridinyl)oxy 1-methylheptyl ester] + halauxifen-methyl [2-pyridinecarboxylic acid, 4-amino-3-chloro-6-(4-chloro-2-fluoro-3-methoxyphenyl)-, methyl ester] + 2,4-D Choline[ethanaminium, 2-hydroxy-N,N,N-trimethyl-,2-(2,4-

dichlorophenoxyacetic acid] (GameOn™, Corteva AgriScience, Indianapolis, IN); Triclopyr + pyraflufen-ethyl [ethyl 2-chloro-5-difluromethoxy-1-methyl-1H-pyrazol-3-yl)-4-fluorophenoxyacetate] + 2,4-D + dicamba (4-Speed® XT, Nufarm, Alsip, IL); Penoxsulam [2-(2,2-difluoroethoxy)-6-(trifluoromethyl-N-(5,8- dimethoxy[1,2,4] triazolo[1,5,-c]pyrimidin-2-yl)) benzenesulfonamide] + sulfentrazone + 2,4-D + dicamba (Avenue™ South, PBI/Gordon Corporation, Kansas City, MO). Active ingredients and the respective percentages contained in each herbicide are shown in Figure 3.1. Each herbicide was applied to the trial area at its highest label rate recommended for cool-season turfgrasses.

In Olathe, seeding intervals consisted of 0 (24 Aug. 2020), 3 (27 Aug. 2020), 7 (31 Aug. 2020), and 14 (7 Sept. 2020) days after herbicide application. At the Manhattan location seeding intervals consisted of 0 (2 Sept. 2020), 3 (5 Sept. 2020), 7 (9 Sept. 2020), and 14 (16 Sept. 2020) days after herbicide application. For both study sites, plots measured 4 x 4 ft and rows were separated with a 1-ft nontreated border. Tall fescue (Heat Wave™ Fescue, Grass Pad, Olathe, KS) was seeded at 10.28 lb PLS 1,000ft^{-2} and cultivars in the blend included 28.3% Rendition, 28.2% Covenant II, 26.8% Falcon IV, and 16% Renegade DT. All treatments were applied using a CO_2-pressurized, hand-held spray boom sprayer equipped with four TeeJet8003 flat-fan nozzles on 9.8-inch spacing calibrated to delivery 43 gal acre^{-1}. Irrigation was withheld until 24 hours after herbicide application. Prior to seeding plots within each respective interval, a three-tine rotary cultivator was used to disturb the surface of the soil, and a starter fertilizer [14-20-4 (N-P-K)] was applied to deliver 1 lb P 1,000ft^{-2}. Both the granular fertilizer and seed were spread independently using a shaker bottle in multiple directions. The study areas were not mown throughout the duration of the trial at either location.

Measurements and Statistical Analysis

Coverage of all plots was visually rated weekly using a scale of 0 to 100% cover (0% = no visible coverage; 100% = full coverage of plot). A handheld NDVI meter (FieldScout CM 1000 NDVI Meter, Spectrum Technologies, Aurora, IL) was used to record measurements at 21, 28, 42, and 56 days after seeding. Canopy height (inches) was measured 42 DAT (days after herbicide treatment) by visually estimating height in three random areas of each plot; means were recorded. Turf quality was visually rated on a 1 to 9 scale (1 = poorest quality, 9 = optimum color, density, and uniformity) at 42 and 56 DAT. All data for each of the ratings were subjected to ANOVA in SAS (9.4) using the GLIMMIX procedure and means were separated according to Fisher's Protected LSD ($P \leq 0.05$).

Results and Discussion

The herbicide treatment main effect was significant for tall fescue cover, NDVI, canopy height, and quality ratings, but Seeding Interval x Herbicide was not impactful (Table 3.1). Herbicide treatment x Location was significant for all but the 42 DAT quality rating, so quality data are averaged across locations. Coverage, NDVI and canopy height data are presented separately by location.

At the Manhattan site, tall fescue visual cover was reduced in penoxsulam + sulfentrazone + 2,4-D + dicamba-treated plots compared to the nontreated. No other herbicide treatment reduced cover compared to the nontreated; all had ≥ 94% visual cover (Table 3.2). At the Olathe site, no herbicide treatment affected tall fescue cover compared to nontreated tall fescue. Visual quality ratings were combined across locations and seeding intervals and resulted in no significant difference from any herbicide treatment compared to nontreated tall fescue (Table 3.3).

Canopy height was significantly lower in penoxsulam + sulfentrazone + 2,4-D + dicamba-treated plots at both study sites when compared to nontreated turf (Table 3.4). No other herbicide treatment reduced canopy height compared to nontreated tall fescue at either site.

NDVI measurements showed no significant difference in live green vegetation at either site for all herbicide treatments compared to nontreated tall fescue except for penoxsulam + sulfentrazone + 2,4-D + dicamba-treated plots (Table 3.5). However, all treatments had a mean NDVI value above 0.80.

Tall fescue seeded into soil treated with carfentrazone-ethyl + MCPP + 2,4-D + dicamba was not significantly different than the nontreated for all ratings at either study site. Carfentrazone-ethyl is a protox (PPO)-inhibitor and works by increasing the production of reactive oxygen species (ROS) in susceptible plants (Senseman, 2007). The SpeedZone label states that treated areas may be reseeded 1 week following application (PBI/Gordon Corporation, 2018). However, results from this study indicate that the reseeding interval could be shorter than the label recommendations.

Tall fescue treated with fluroxypyr + halauxifen-methyl + 2,4-D was comparable to nontreated turf for all ratings at both study sites. Fluroxypyr, a popular chemical in cool-season turf, is a synthetic auxin in the pyridine carboxylic acid family and is effective for postemergence broadleaf weed control (MacDonald et al., 1993; Neal, 1990). A new active ingredient halauxifen-methyl, in the arylpicolinate family, is also a synthetic auxin with minimal research conducted on the effects of seedling injury after application. Results herein suggest that seeding into soil treated with this herbicide 0 to 14 DAT did not affect cover, NDVI, canopy height or visual quality when compared to nontreated plots. However, the GameOn label indicates that reseeding is not recommended for at least three weeks after application (Corteva Agriscience, 2019). Therefore, based upon the results from these experiments, it's possible that the reseeding interval on the product label could be shorter than 3 weeks after application.

Triclopyr + pyraflufen-ethyl + 2,4-D + dicamba-treated tall fescue plots were not significantly different than nontreated turf at either location for cover, NDVI, canopy height, and visual quality. Triclopyr has little to no impact on grasses, as it targets and controls broadleaf plants by mimicking the hormone auxin (Tu et al., 2001). Pyraflufen-ethyl, a PPO inhibitor, included with synthetic auxin herbicides can provide fast necrosis of target weed foliage (Raudenbush and Keeley, 2014). The 4-Speed XT label states that reseeding should be delayed until 2 weeks after application (Nufarm Americas Inc., 2015). Our results herein conclude shoot growth and visual quality were not affected compared to nontreated tall fescue, indicating that the reseeding interval on the product label could be shorter than 2 weeks after application.

Penoxsulam + sulfentrazone + 2,4-D + dicamba-treated plots were consistently lower in cover, canopy height, and NDVI ratings compared to nontreated turf. Penoxsulam is an acetolactate synthase (ALS)-inhibiting herbicide with early postemergence activity on broadleaf weeds and is often combined with other herbicides for a broader spectrum of control with a single application (Loughner et al., 2006; Brosnan and Breeden, 2019). Sulfentrazone, a PPO-inhibitor, is in the same chemical class as carfentrazone-ethyl and is absorbed through the roots and shoots (Senseman, 2007). Sulfentrazone applied either at the time of seeding buffalograss and at emergence effectively minimized weed pressure while leaving buffalograss establishment unharmed (Li et al., 2015). The Avenue South label does not indicate a specific reseeding interval after the application of this product. However, the product label recommends to apply on turfgrass that is reasonably free of stress to avoid turf injury (PBI/Gordon Corporation, 2018). Our results indicate that a reseeding interval of 14 days or more after the application of this product may be necessary for optimal tall fescue seedling development and growth.

Overall, this study demonstrated that seeding between 0 to 14 days after an application of carfentrazone-ethyl + MCPP + 2,4-D + dicamba, fluroxypyr + halauxifen-methyl + 2,4-D, or triclopyr + pyraflufen-ethyl + 2,4-D + dicamba had little or no effect on tall fescue growth under the conditions evaluated in these experiments. It should be noted that rooting was not evaluated in this experiment, and some postemergence herbicides can inhibit rooting of seedlings after application (Chapter 2). Tall fescue rooting was inhibited in Chapter 2 with 2,4-D + MCPP + dicamba when seeding was done at 0 DAT but not at 3, 7 or 14 DAT. In general, herbicide manufacturers could consider altering label reseeding intervals, using results reported herein as guidelines.

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Figure 3.1 Herbicide active ingredients (a.i.) used in Olathe and Manhattan, KS field studies.

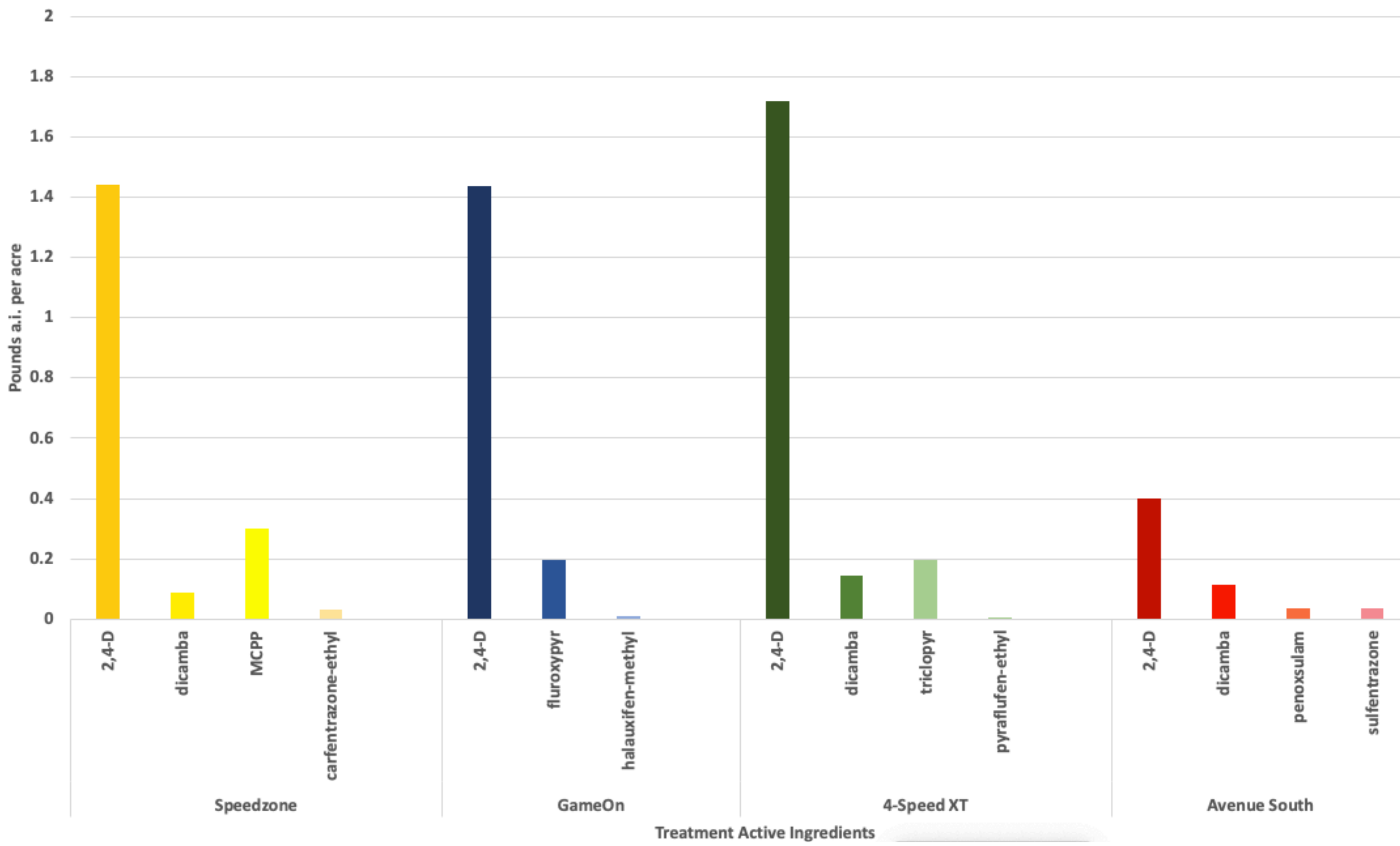

Table 3.1 ANOVA for tall fescue cover, canopy height, NDVI, and quality as affected by seeding interval, herbicide application, and location.

Source	Cover	Canopy height	NDVI	Quality
Seeding interval (S)	***	ns	ns	***
Herbicide (H)	***	***	***	***
S x H	ns	ns	ns	ns
Location (L)	***	***	***	***
S x L	ns	*	***	**
H x L	**	***	*	ns
S x H x L	ns	ns	ns	ns

*,**,*** significant at $P < 0.05$, 0.001, and 0.0001, respectively.

ns = not significant

Table 3.2 Effect of herbicides on tall fescue cover eight weeks after planting when seeded at 0 to 14 DAT.

	Cover (%)[a]	
Treatment[b]	Olathe	Manhattan
Nontreated	92a[c]	95a
Carfentrazone-ethyl + MCPP + 2,4-D + dicamba	92a	95a
Fluroxypyr + halauxifen-methyl + 2,4-D	93a	95a
Triclopyr + pyraflufen-ethyl + 2,4-D + dicamba	92a	94a
Penoxsulam + sulfentrazone + 2,4-D + dicamba	90a	88b

[a] Coverage was rated visually on a 0 to 100% scale on which 0 = no coverage, and 100 = complete coverage.
[b] Herbicides were applied on 24 Aug. 2020 (Olathe, KS) and 2 Sep. 2020 (Manhattan, KS). Tall fescue was seeded at 0, 3, 7, and 14 DAT.
[c] Means followed by the same capital letter in a column are not significantly different according to Fisher's LSD ($P \leq 0.05$). Means are averages over seeding intervals, n = 16.

Table 3.3 Main effect of herbicides on tall fescue turf quality six weeks after seeding 0 to 14 DAT in Olathe and Manhattan, KS (average of Olathe and Manhattan locations).

Treatment[a]	Quality[b]
Nontreated	5.6ab[c]
Carfentrazone-ethyl + MCPP + 2,4-D + dicamba	5.6ab
Fluroxypyr + halauxifen-methyl + 2,4-D	5.8a
Triclopyr + pyraflufen-ethyl + 2,4-D + dicamba	5.7ab
Penoxsulam + sulfentrazone + 2,4-D + dicamba	5.4b

[a] Herbicides were applied on 24 Aug. 2020 (Olathe, KS) and 2 Sep. 2020 (Manhattan, KS). Tall fescue was seeded at 0, 3, 7, and 14 DAT.

[b] Tall fescue was rated on a 1 to 9 scale (1 = dead, 9 = green, healthy, turgid plants).

[c] Means followed by the same capital letter are not significantly different according to Fisher's LSD ($P \leq 0.05$). Means are averages over locations and seeding intervals, n = 32.

Table 3.4 Main effect of herbicides on tall fescue seedling canopy height six weeks after seeding 0 to 14 DAT in Olathe and Manhattan, KS.

	Canopy height (inches)	
Treatment[a]	Olathe	Manhattan
Nontreated	3.3a[b]	5.0a
Carfentrazone-ethyl + MCPP + 2,4-D + dicamba	3.4a	5.1a
Fluroxypyr + halauxifen-methyl + 2,4-D	3.4a	5.2a
Triclopyr + pyraflufen-ethyl + 2,4-D + dicamba	3.2a	5.4a
Penoxsulam + sulfentrazone + 2,4-D + dicamba	2.6b	2.7b

[a] Herbicides were applied on 24 Aug. 2020 (Olathe, KS) and 2 Sep. 2020 (Manhattan, KS). Tall fescue was seeded at 0, 3, 7, and 14 DAT.

[b] Means followed by the same capital letter in a column are not significantly different according to Fisher's LSD ($P \leq 0.05$). Means are averages over seeding intervals, n = 16.

Table 3.5 Main effect of herbicides on tall fescue NDVI eight weeks after seeding 0 to 14 DAT in Olathe and Manhattan, KS.

	NDVI[a]	
Treatment[b]	Olathe	Manhattan
Nontreated	0.86a[c]	0.91a
Carfentrazone-ethyl + MCPP + 2,4-D + dicamba	0.86a	0.90a
Fluroxypyr + halauxifen-methyl + 2,4-D	0.87a	0.90a
Triclopyr + pyraflufen-ethyl + 2,4-D + dicamba	0.87a	0.89a
Penoxsulam + sulfentrazone + 2,4-D + dicamba	0.81b	0.81b

[a] NDVI measurements range from -1 to 1, with higher values indicating greater plant health.

[b] Herbicides were applied on 24 Aug. 2020 (Olathe, KS) and 2 Sep. 2020 (Manhattan, KS). Tall fescue was seeded at 0, 3, 7, and 14 DAT.

[c] Means followed by the same capital letter in a column are not significantly different according to Fisher's LSD ($P \leq 0.05$). Means are averages over seeding intervals, n = 16.

Figure 3.2 Daily maximum and minimum air and soil temperatures throughout study in Olathe, KS. Weather data collected from Kansas Mesonet Olathe weather station. Downward arrows indicate seeding dates after herbicide application (DAT).

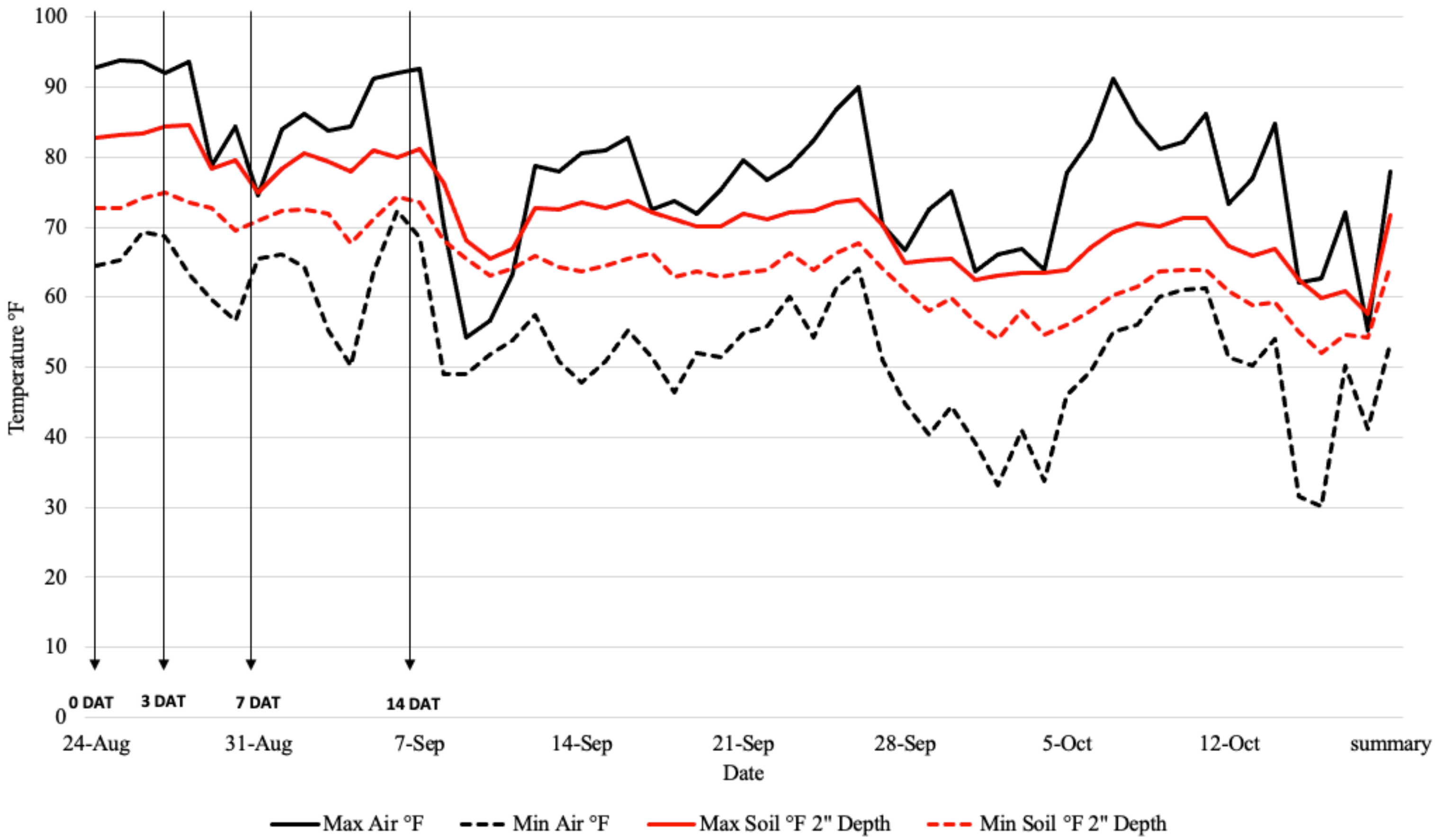

Figure 3.3 Daily maximum and minimum air and soil temperatures throughout study in Manhattan, KS. Weather data collected from Kansas Mesonet Manhattan weather station. Downward arrows indicate seeding dates after herbicide application (DAT).