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Herbicide options for control of yellow and knotroot foxtail for possible use in turfgrass

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dicamba; imazaquin; imazethapyr; iodosulfuron; knotroot foxtail; metribuzin; nicosulfuron; Pinoxaden; rimsulfuron; *Setaria parviflora* (Poir.) Kerguélen; *Setaria pumila* (Poir.) Roem. & Schult.; sethoxydim; sulfentrazone; thiencarbazone; yellow foxtail

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Abstract

Yellow and knotroot foxtail are two common weed species infesting turfgrass and pastures in the southeastern region of the United States. Yellow and knotroot foxtail share morphological similarities and are frequently misidentified by weed managers, thus leading to confusion in herbicide selection. Greenhouse research was conducted to evaluate the response of yellow and knotroot foxtail to several turfgrass herbicides: pinoxaden (35 and 70 g ai ha^{-1}), sethoxydim (316 and 520 g ai ha^{-1}), thiencarbazone + dicamba + iodosulfuron (230 g ai ha^{-1}), nicosulfuron + rimsulfuron (562.8 g ai ha^{-1}), metribuzin (395 g ha^{-1}), sulfentrazone (330 g ai ha^{-1}), sulfentrazone + imazethapyr (504 g ai ha^{-1}), and imazaquin (550 g ai ha^{-1}). All treatments controlled yellow foxtail >87% with more than 90% reduction of the biomass. By comparison, only sulfentrazone alone controlled knotroot foxtail 90% and completely reduced aboveground biomass. Sethoxydim (520 g ai ha^{-1}), metribuzin, and imazaquin controlled knotroot foxtail >70% at 28 d after application. In a rate response evaluation, nonlinear regression showed that yellow foxtail was approximately 8 times more susceptible to pinoxaden and 2 times more susceptible to sethoxydim than knotroot foxtail based on log (WR_{50}) values, which were 50% reduction in fresh weight. Our research indicates that knotroot foxtail is more difficult to control across a range of herbicides, making differentiation of these two species important before herbicides are applied.

Introduction

In the southeastern region of the United States, yellow and knotroot foxtail are two common species infesting managed and unmanaged turfgrass, pastures, roadsides, and some cropping systems (Bryson and DeFelice 2009; Hitchcock 1971). Yellow and knotroot foxtail belong to the genus *Setaria*, which contains other major weeds, such giant foxtail (*Setaria faberi* Herrm.) and green foxtail [*Setaria viridis* (L.) P. Beauv.], forming the foxtail species group (Dekker 2003). Yellow and knotroot foxtail originated from Asia and North America, respectively (Dekker 2003; Rominger 1962). Nevertheless, they share morphological similarities and are frequently misidentified by weed managers, thus leading to confusion in herbicide selection (Darmency and Dekker 2011).

Yellow and knotroot foxtail are annual and perennial weeds, respectively, with few options for effective chemical control in warm-season turfgrass. Pinoxaden, labeled in the United States for use on bermudagrass [*Cynodon dactylon* (L.) Pers.], controls yellow foxtail postemergence 95% at 0.001 kg ha^{-1} but is not labeled for control of knotroot foxtail (Anonymous 2018; Peppers et al. 2020). Chlorsulfuron applied at 0.07 and 0.14 kg ha^{-1} gave season-long control of yellow foxtail when applied at the early growth stage in Kentucky bluegrass (*Poa pratensis* L.), but it is not labeled for turfgrass (Maloy 1985). Little research has been done to gain an understanding of the chemical control of knotroot foxtail. In pasture conditions, hexazinone at 1.26 kg ha^{-1} alone or mixed with nicosulfuron or metsulfuron controlled knotroot foxtail by more than 80% at 4 and 6 wk after application (Burns 2006). Nicosulfuron + metsulfuron applied at 0.04 kg ha^{-1} controlled knotroot foxtail 70% in bermudagrass forage at the actively growing stage (Russell 2021). Other herbicides could potentially control yellow and knotroot foxtail but are not currently labeled. For instance, thiencarbazone + dicamba + iodosulfuron is labeled for controlling yellow foxtail and giant foxtail but not knotroot foxtail.

The objectives of this research were to (1) evaluate the response of yellow foxtail and knotroot foxtail to several turfgrass herbicides and (2) evaluate the rate response of yellow and knotroot foxtail to increasing rates of pinoxaden and sethoxydim and estimate the application rate at which 50% (I_{50}) of both species are injured using a nonlinear regression model.

Material and Methods

Research was conducted in 2021 and 2022 in a greenhouse to evaluate yellow and knotroot foxtail response to selected turfgrass herbicides. Two different studies were conducted: (1) an initial herbicide evaluation and (2) a rate response evaluation of sethoxydim and pinoxaden. For both studies, seeds of yellow and knotroot foxtail were harvested from a local population in Montgomery, AL. Seeds were cleaned and stored at 4 C prior to the experiments. Seeds were planted in flats of potting medium and were then transplanted individually at the 2-leaf stage into 230-cm^3 pots filled with sandy loam soil (Marvyn sandy loam). Pots were irrigated three times a day with overhead irrigation with approximately 5 mm of water. Fertilizer was applied (28-8-16 Miracle-Gro® Water-Soluble All-Purpose Plant Food, Scotts Miracle-Gro Products, Marysville, OH, USA) once a week to promote growth as needed, until the plants were healthy and established. After herbicide application, pots were not watered for approximately 24 hr to allow adequate leaf absorption. Herbicide applications were made at 3- to 4-leaf stages in all the experiments. All herbicide treatments were applied with a CO_2-pressurized sprayer calibrated to deliver 280 L ha^{-1} with a handheld four-nozzle boom (TP8002 flat fan nozzles with 25-cm spacing, TeeJet® Technologies, Wheaton, IL, USA). A nonionic surfactant (Induce®, Helena® Agri-Enterprises, Collierville, TN, USA) was included in all treatments at 0.25% v/v. Treatments were compared with a nontreated control.

Initial Greenhouse Evaluations

Two experiments were conducted at the Auburn University Weed Science Greenhouse in Auburn, AL (32.35°N, 85.29°W) in 32/28 C (±1 C d/n) conditions with an average relative humidity of 70%. Herbicides included pinoxaden (35 and 70 g ai ha^{-1}) (Manuscript®, Syngenta Crop Protection, Greensboro, NC, USA), sethoxydim (316 and 520 g ai ha^{-1}) (Segment®, BASF, Research Triangle Park, NC, USA), thiencarbazone + dicamba + iodosulfuron (230 g ai ha^{-1}) (Celsius® WG, Bayer Crop Science, Pikeville, NC, USA), nicosulfuron + rimsulfuron (562.8 g ai ha^{-1}) (Dupont™ Steadfast®, Corteva Agriscience, Wilmington, DE, USA), metribuzin (395 g ai ha^{-1}) (Sencor®, Bayer Crop Science), sulfentrazone (330 g ai ha^{-1}) (Dismiss® CA, FMC, Philadelphia, PA, USA), sulfentrazone + imazethapyr (504 g ai ha^{-1}) (Dismiss® South, FMC), and imazaquin (550 g ai ha^{-1}) (Scepter® T&O, AMVAC Chemical, Newport Beach, CA, USA). Herbicides were selected based on the current herbicide label with yellow foxtail listed for control but not knotroot foxtail or with both species not listed on the label but with the potential for the herbicide to control grass species in turfgrass.

Rate Response Evaluation

Owing to the various responses of the acetyl-CoA carboxylase (ACCase)-inhibiting herbicides pinoxaden and sethoxydim, rate response screen studies for these herbicides were conducted in the greenhouse with the same environmental conditions as the previous evaluations. Pinoxaden and sethoxydim were applied at nine different rates to generate a dose–response curve. Pinoxaden rates were 0, 2.21, 4.42, 8.8, 17.7, 35.4, 70.8, 141.4, 282.9, and 565.8 g ai ha^{-1}. Sethoxydim rates were 0, 19.8, 39.5, 79.0, 158.0, 316.1, 632.2, 1,264.0, 2,529.0, and 5,057.2 g ai ha^{-1}.

Statistical Analysis

All trials were arranged in a randomized complete block design with four replicates and were repeated once. Weed control was visibly evaluated against the relative control using a scale ranging from 0% (no phytotoxic effect) to 100% (total plant death) at 28 d after application (DAA). Plants were clipped at the soil surface, and fresh aboveground biomass was recorded at 28 DAA. Data were subjected to ANOVA and mean comparison at a significance level of $P < 0.05$ using RStudio with packages DPLYR, GGPLOT2, AGRICOLAE, and FSA (de Mendiburu 2020; Hadley et al. 2019; Ogle et al. 2022; RStudio Team 2020). Interactions of herbicide, herbicide rate, and run (repetition of the experiment in time) were analyzed, with visible plant injury and relative fresh weight as response variables. A significant interaction between runs was not detected based on herbicide evaluation by run interaction for greenhouse studies ($P \geq 0.05$); therefore data were pooled across runs. Nonlinear regressions were modeled with the DRC package in RStudio (Ritz et al. 2015; RStudio Team 2020). Prior to modeling, nine pinoxaden and sethoxydim rates were transformed to log rates to maintain equal spacing between treatments, including the nontreated set to 0.04 and 0.99. Both species were modeled with appropriate models that best expressed plant response with the lowest Akaike information criterion as described by Knezevic et al. (2007) and Seefeldt et al. (2017). Plant visible injury for pinoxaden, sethoxydim, and aboveground biomass for sethoxydim was fitted to a four-parameter Weibull equation (Equation 1):

$$f(x) = C + (D - C) \times \exp\{-\exp[b(\log x - \log e)]\} \quad [1]$$

where f is the percent visible injury relative to the nontreated control, x is the log-transformed rate, C is the lower limit, D is the upper limit, b is the relative slope, and e is the inflection point. This equation was used to calculate the I_{50} value, which is the rate causing 50% of injury. Aboveground biomass for pinoxaden was fitted to a four-parameter Weibull model (Equation 2):

$$f(x) = C + \frac{(D-C)}{1+\{\exp[b(\log x - \log e)]\}} \quad [2]$$

This equation was used to calculate the WR_{50}, which is the rate causing 50% biomass reduction relative to the nontreated. Aboveground biomass data were transformed into relative percentage of the nontreated control using the formula

$$\%\ \text{Relative} = \frac{\text{Mean nontreated} - \text{Mean treatment}}{\text{Mean nontreated}} \quad [3]$$

The relationship between the aboveground biomass and visual control was assessed using the Pearson correlation coefficient, where 0 is no correlation, 1 is total positive correlation, and −1 is total negative correlation, using the equation

$$\rho(x, y) = \frac{\text{cov}(x,y)}{\sigma_x \sigma_y} \quad [4]$$

where $\rho(x, y)$ is the Pearson correlation coefficient, $\text{cov}(x, y)$ is the covariance between relative aboveground biomass and visual control, σ_x is the variance of visual control, and σ_y is the variance of relative aboveground biomass (Kotu and Deshpande 2018).

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Table 1. Yellow and knotroot foxtail control and aboveground biomass relative to the nontreated in response to herbicide treatments at 28 d after application.[a,b,c]

		Yellow foxtail		Knotroot foxtail	
Treatment	Rate	Control	% ABRN	Control	% ABRN
	g ai ha^{-1}				
Pinoxaden (low)	35	100 a	100 a	10 bc	14 cd
Pinoxaden (high)	70	87 a	96 a	20 c	30 b–d
Sethoxydim (low)	316	100 a	100 a	40 a–c	47 a–d
Sethoxydim (high)	520	100 a	100 a	77 a	94 ab
Thiencarbazone + dicamba + iodosulfuron	230	99 a	100 a	70 ab	90 ab
Metribuzin	395	100 a	99 a	81 a	96 a
Nicosulfuron + rimsufuron	563	98 a	98 a	64 a–c	90 ab
Sulfentrazone	330	98 a	100 a	91 a	96 a
Sulfentrazone + imazethapyr	504	93 a	100 a	62 a–c	78 a–c
Imazaquin	550	99 a	100 a	72 a	92 a

[a]Values with the same letters in a column have no significant difference according to Tukey's HSD (P = 0.05).
[b]Abbreviation: ABRN, aboveground biomass relative to the nontreated.
[c]Nontreated controls were not included in the analysis due to all rates being zero for control.

Table 2. Correlation between relative aboveground biomass to the nontreated and percent control in initial herbicide evaluation (Study 1) and in response to increasing rates of sethoxydim and pinoxaden (Study 2) at 28 d after application.[a]

Study	Yellow foxtail	Knotroot foxtail
Study1	0.83	0.75
Study 2–pinoxaden	0.72	0.61
Study 2–sethoxydim	0.68	0.60

[a]Each value represents the Pearson correlation.

Results and Discussion

In the initial greenhouse evaluation, yellow and knotroot foxtail responded differently to the selected herbicides. All herbicides controlled yellow foxtail effectively with more than 85% control at 28 DAA (Table 1). Aboveground biomass data followed the same pattern. All the herbicides reduced yellow foxtail aboveground biomass by more than 95% compared to the nontreated at 28 DAA. Knotroot foxtail was more difficult to control in general than yellow foxtail. Sulfentrazone controlled knotroot foxtail >90%, which was the best treatment. Metribuzin controlled knotroot foxtail 81%, imazaquin 71%, sethoxydim (high rate) 76%, and thiencarbazone + dicamba + iodosulfuron 70%. All the other treatments controlled knotroot foxtail <65%. Relative plant fresh-weight data followed the same pattern with visually estimated control data. The Pearson correlation between visual control and relative plant fresh-weight data at 28 DAA was 0.83 and 0.75 for yellow and knotroot foxtail, respectively (Table 2). Sulfentrazone, metribuzin, sethoxydim (high rate), thiencarbazone + dicamba + iodosulfuron, and imazaquin reduced the aboveground biomass by >90%. Nicosulfuron + rimsulfuron reduced knotroot foxtail biomass by 89%. However, pinoxaden (low and high rates) and sethoxydim (low rate) were less effective on knotroot foxtail, with <50% biomass reduction.

Results from the rate response evaluation indicate that yellow foxtail is more susceptible to pinoxaden and sethoxydim that knotroot foxtail (Figures 1 and 2). The lack of a fitted test was not significant for log-logistic and Weibull models with four parameters, demonstrating a proper choice for estimating I_{50} and WR_{50} (Ritz et al. 2015). Pinoxaden provided >80% yellow foxtail control but <15% control of knotroot foxtail at 35.4 g ha^{-1}. The I_{50} value for yellow foxtail control was 6.7 g ha^{-1}, whereas for knotroot foxtail, it was 263 g ha^{-1}. Nevertheless, knotroot foxtail susceptibility to pinoxaden was quite different from yellow foxtail. The I_{50} value for knotroot foxtail visible injury was 263 g ha^{-1}. Relative biomass data showed a similar trend with visual control, with Pearson correlation 0.72 and 0.61 for yellow and knotroot foxtail, respectively. Pinoxaden reduced yellow foxtail biomass >95% and knotroot foxtail <20% at 8.8 g ha^{-1}. The WR_{50} value for yellow foxtail biomass was 1.73 g ha^{-1} and for knotroot foxtail was 39.7 g ha^{-1}. Equation parameters and 95% CIs for the visible injury and relative biomass data are displayed in Table 3 and Table 4, respectively.

Sethoxydim data followed the same trend as pinoxaden. Sethoxydim controlled yellow foxtail >95% at 316 g ha^{-1}, but knotroot foxtail was controlled <40% at the same rate. The I_{50} value estimated was 102.4 and 2,148.6 g ha^{-1} for yellow and knotroot foxtail, respectively. Sethoxydim reduced yellow foxtail biomass >90% at a rate of 79.02 g ha^{-1}, and the WR_{50} value estimated for yellow foxtail biomass reduction was 29.45 g ha^{-1}. Sethoxydim provided significant reduction of aboveground biomass, but none of the sethoxydim rates injured knotroot foxtail >95%. It reduced knotroot foxtail biomass by >70% at a rate of 316.0 g ha^{-1}, and the WR_{50} value estimated for knotroot foxtail biomass reduction was 219.14 g ha^{-1}. We detected a significant slope (I_{50}) difference between yellow and knotroot foxtail for both sethoxydim and pinoxaden. This estimation indicated that there was not equal susceptibility between yellow and knotroot foxtail for pinoxaden and sethoxydim. Furthermore, considering the relative biomass, those results indicate that yellow foxtail is more susceptible to pinoxaden and sethoxydim than knotroot foxtail.

This study found that yellow foxtail responded differently than knotroot foxtail to the selected herbicides, and knotroot foxtail was more difficult to control. A published report showed that nicosulfuron + metsulfuron, two herbicides inhibiting acetolactate synthase, was one of the best treatments for knotroot foxtail suppression but did not provide complete control in a bermudagrass hayfield (Bryson and DeFelice 2009). This study found that nicosulfuron + rimsulfuron reduces knotroot foxtail biomass >80% but provides 60% control. Pinoxaden provides excellent control of yellow foxtail at the recommended label rate. Peppers

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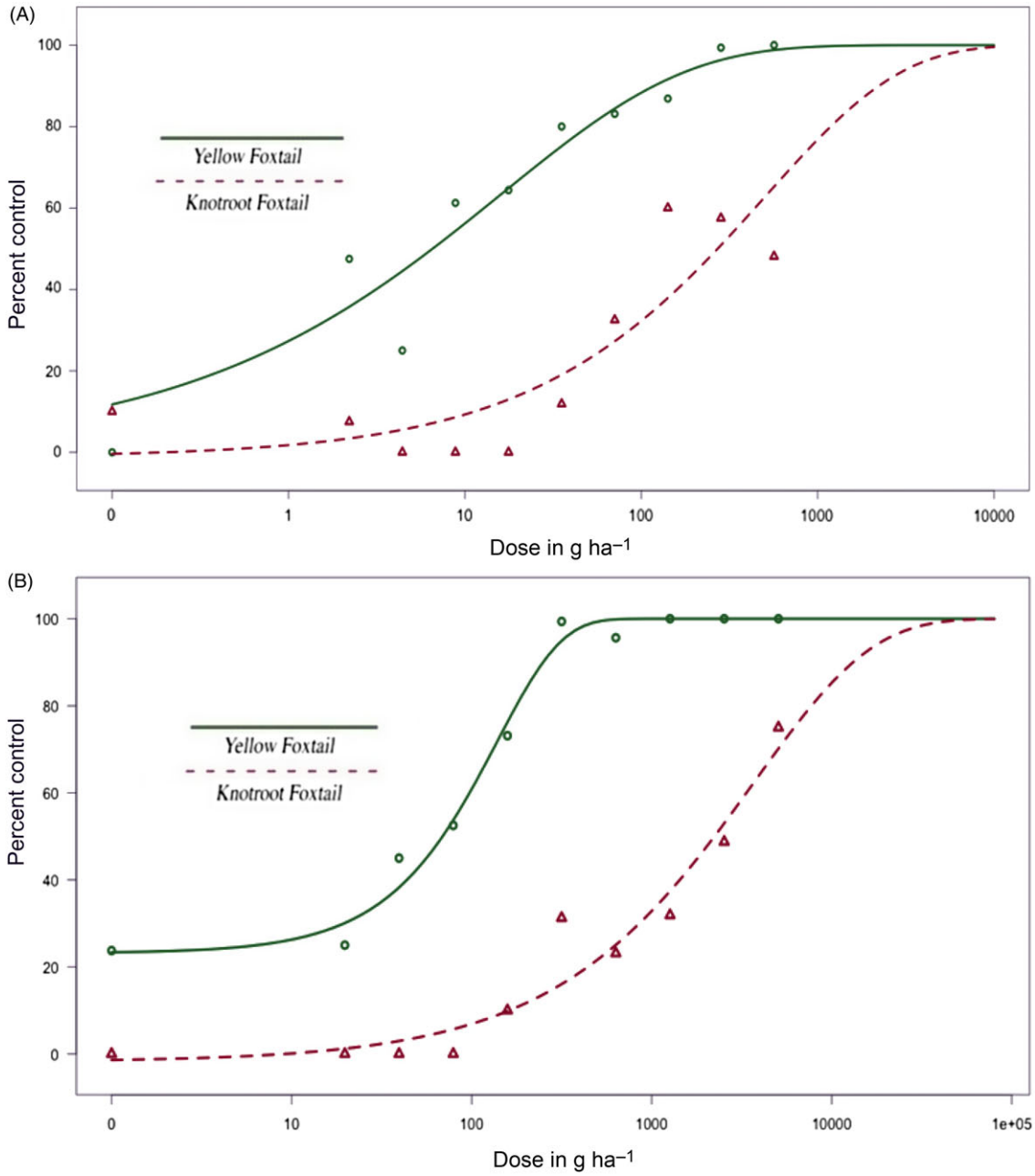

Figure 1. Percent visible injury to the nontreated control of yellow and knotroot foxtail 28 d after application with increasing rates of pinoxaden (A) and sethoxydim (B). The regression parameter is determined by the Weibull model with four parameters: $f(x) = C + (D - C) \times \exp\{-\exp[b(\log x - \log e)]\}$. Each bullet represents the average control for each treatment.

et al. (2020) found a similar result, with an I_{50} of 3.4 g ha^{-1}. However, pinoxaden should not be considered for controlling knotroot foxtail even at the maximum recommended label rate. Sethoxydim (high rate) effectively controlled yellow foxtail and reduced knotroot foxtail biomass >60% at the maximum labeled rate. Differential herbicide responses in closely related species may be due to differential absorption, translocation, or metabolism or to inherent differences in the toxicity of the herbicides (Thompson 1972). Differential response in ACCase herbicides is observed in grass species. McCarty et al. (1990) discovered that there was a difference in centipedegrass [*Eremochloa ophiuroides* (Munro) Hack.] and goosegrass [*Eleusine indica* (L.) Gaertn.] in sethoxydim metabolism. McCarty et al. also found that centipedegrass had <1% sethoxydim in its tissue, whereas goosegrass had 81% to 98% detected in its tissues 6 hr after application. In crop species, tolerance to sethoxydim is associated with metabolism detoxification in wheat (*Triticum aestivum* L.) and modification at the membrane level in annual ryegrass (*Lolium rigidum* Gaudin) (Dotray 1993; Hausler et al. 1991; Shimabukuro et al. 1979). Differential response of acetolactate synthase–inhibiting herbicide in foxtail species is not uncommon. Satchivi et al. (2017) found a differential response in green and yellow foxtail to pyrosulam, with yellow foxtail being more sensitive than green foxtail. Such differential control is associated with a difference in the metabolism of acetolactate synthase sensitivity, as the sequence of acetolactate synthase genes from both green and yellow foxtail

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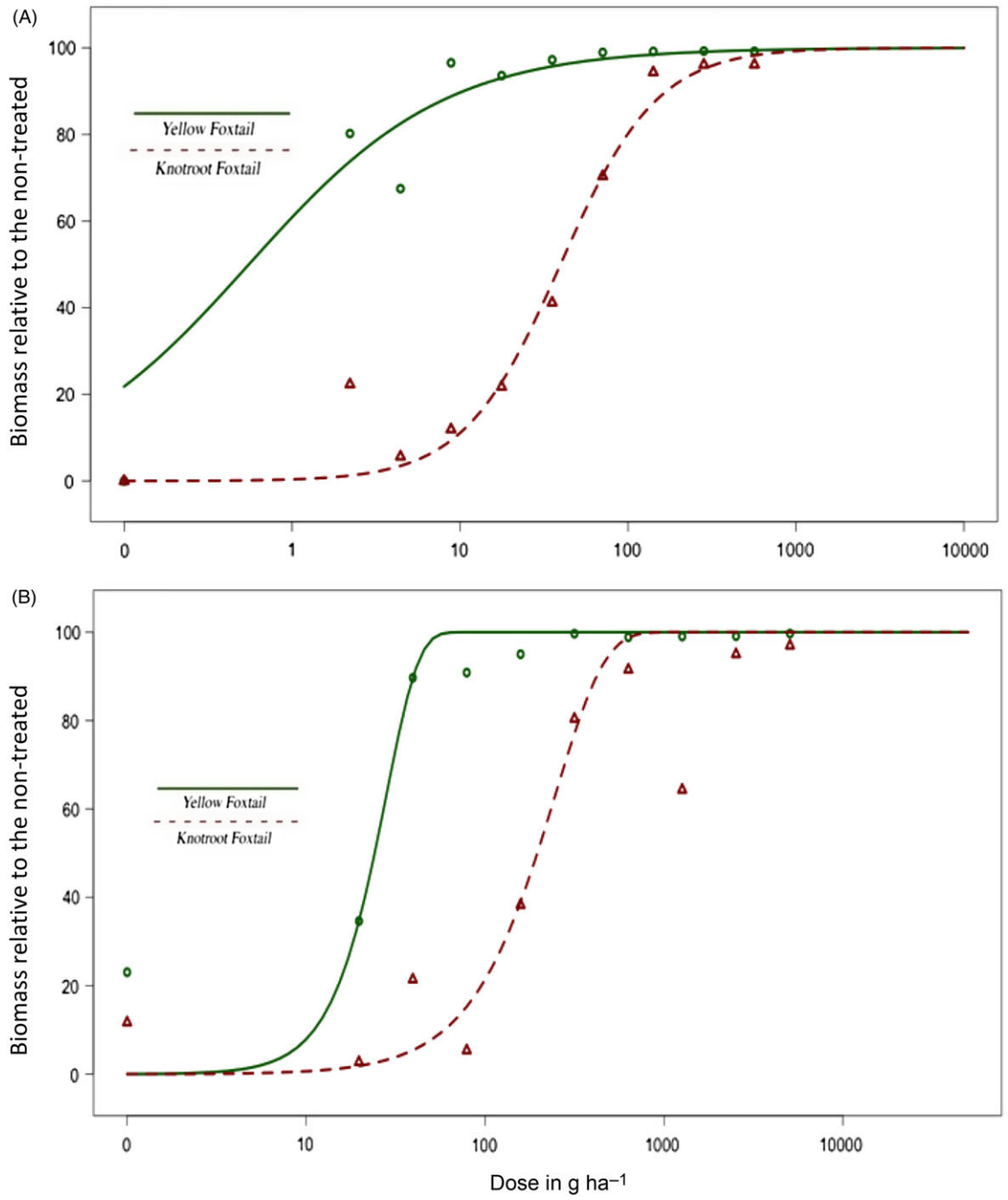

Figure 2. Biomass relative to the nontreated (ABGR) for yellow and knotroot foxtail at 28 d after application with increasing rates of pinoxaden (A) and sethoxydim (B). For pinoxaden, the regression parameter was determined by log-logistic with four parameters: $f(x) = C + [(D - C)/(1 + \{\exp [b(\log x - \log e)]\})]$. For sethoxydim, the regression parameter was determined by the Weibull model with four parameters: $f(x) = C + (D - C) \times \exp\{-\exp[b(\log x - \log e)]\}$. Each bullet represents the average ABGR for each treatment.

revealed amino acid differences (Satchivi et al. 2017). However, these changes are not associated with known resistance-inducing mutations (Satchivi et al. 2017). Wang et al. (1995) have explored the variation of the detoxification mechanism of multiple herbicides in foxtail species resistant to atrazine. This study found that giant, green, yellow, and knotroot foxtail have differences in glutathione *s*-transferase activity for plant detoxification, and this enzyme activity was similar to that found in susceptible populations (Wang et al. 1995). Oliver and Schreiber (1971) found this differential metabolism rate, with yellow foxtail more susceptible to atrazine and propazine than green and giant foxtail. Thompson (1972) confirmed that yellow and giant foxtail metabolized atrazine and propazine slowly, whereas green foxtail metabolized faster. While those two closely related species have various metabolism rates for different herbicide families, it is important to comprehend those differences at genetic and ecologic levels. The foxtail species group exhibits considerable variability within and among species with genetic diversity and phenotypic plasticity (Dekker 2003). Though yellow and knotroot foxtail originated from two continents (Dekker 2003), more investigation is needed to understand the relationship between local adaption and inherent herbicide susceptibility in those species.

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Table 3. Best fit model for percent visible injury of yellow and knotroot foxtail in response to increasing rates of sethoxydim and pinoxaden at 28 d after application.[a]

Herbicide	Species	Equation	I_{50}	Estimated I_{50} (95% CI)
			g ai ha^{-1}	
Pinoxaden[b]	Yellow foxtail	$f(x) = 0.44 + (100.44) \times (1 - \exp\{-\exp[0.41(\log x - \log 16.05)]\})$	6.66	[0.43, 12.89]
	Knotroot foxtail	$f(x) = -1.2 + 98.8 \times (1 - \exp\{-\exp[0.56(\log x - \log 503.2)]\})$	263	[94.85, 431.14]
Sethoxydim	Yellow foxtail	$f(x) = 23.1 + (100 - 23.1) \times (1 - \exp\{-\exp[1.21(\log x - \log(138.48))]\})$	102.35	[62.10, 142.6]
	Knotroot foxtail	$f(x) = -1.82 + (100 + 1.82) \times (1 - \exp\{-\exp[0.66(\log x - \log 3720)]\})$	2,148.61	[1,270.65, 3,026.57]

[a]Abbreviation: I_{50}, herbicide rate giving 50% control.
[b]Regression parameter was determined by the Weibull model with four parameters for data defined by Equation 1.

Table 4. Best fit model for relative aboveground biomass to the nontreated of yellow and knotroot foxtail in response to increasing rates of sethoxydim and pinoxaden at 28 d after application.[a]

Herbicide	Species	Equation	WR_{50}	Estimated WR_{50} (95% CI)
			g ai ha^{-1}	
Pinoxaden[b]	Yellow foxtail	$f(x) = \frac{100}{1+[\exp-0.74(\log x-\log 0.55)]}$	1.73	[1.36, 1.91]
	Knotroot foxtail	$f(x) = \frac{100}{1+[\exp-6.14(\log x-\log 1.55)]}$	39.65	[30.45, 47.97]
Sethoxydim[c]	Yellow foxtail	$f(x) = 23.1 + 76.9 \times (1 - \exp\{-\exp[3.62(\log x - \log 32.59)]\})$	29.45	[18.64, 40.26]
	Knotroot foxtail	$f(x) = 9.1 + 89.9 \times (1 - \exp\{-\exp[2.25(\log x - \log 257.7)]\})$	219.14	[152.66, 285.63]

[a]Abbreviation: WR_{50}, herbicide rate giving 50% biomass reduction.
[b]Regression parameter was determined by log-logistic with four parameters.
[c]Regression parameter was determined by the Weibull model with four parameters for data defined by Equation 1.

Practical Implications

Yellow and knotroot foxtail share morphological similarities and present phenotypic plasticity within and among species, making their differentiation challenging. The options to control yellow and knotroot foxtail simultaneously are limited. The results of this study suggest that sulfentrazone, thiencarbazone + dicamba + iodosulfuron, sethoxydim (high rate), and metribuzin can be considered for controlling yellow and knotroot foxtail at the recommended label rates. Pinoxaden, sethoxydim (low rate), nicosulfuron + rimsulfuron, and imazaquin can control yellow foxtail but not knotroot foxtail at labeled rates. Because yellow and knotroot foxtail are not listed on all herbicide labels used in the study, the herbicides' use in certain situations is not recommended unless the herbicide label is updated. This study, conducted in a controlled environment, provides a basis for understanding potential herbicide control options for yellow and knotroot foxtail. Overall, our research indicates that knotroot foxtail is more difficult to control across a range of herbicides, making differentiation of these two species important before herbicides are applied.

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