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Winter Wheat Response to Weed Control and Residual Herbicides

Timothy L. Grey and Larry J. Newsom

Additional information is available at the end of the chapter

Abstract

Italian ryegrass has become one of the most common and troublesome weeds of wheat production in the Southern United States. There are multiple reports in this region of Italian ryegrass herbicide resistance to acetyl-CoA carboxylase (ACCase), acetolactate synthase (ALS), and glyphosate herbicides. One commonality for Italian ryegrass resistance in this area is that most of these mechanisms of action for these herbicides are all postemergence (POST) applied. In order to have profitable soft red winter wheat production, applications of preemergence (PRE) herbicides with residual control of Italian ryegrass and other winter weed species would benefit growers. There are a very limited number of herbicides that can be applied at the time of wheat planting, primarily only when pyroxasulfone is registered for this timing. Research was conducted to establish weed control information when herbicides were applied to soft red winter wheat PRE, at wheat emergence (AE), or POST at Feekes stages 1.0–1.9, depending on herbicide label recommendations. Injury from any pyroxasulfone PRE treatments up to 120 g a.i. ha⁻¹ was transient and did not affect wheat yield for any experiment. Italian ryegrass control was variable depending on location and year. Susceptible and diclofop-resistant Italian ryegrass control was 86% or greater with pyroxasulfone at 60 g a.i. ha⁻¹ and greater with applied PRE. Italian ryegrass control was variable ranging from 27 to 49% with pendimethalin ME-applied PRE, diclofop at Feekes sage 1.0, and pinoxaden applied at Feekes stage 1.9.

Keywords: crop tolerance, Italian ryegrass, wild radish, diclofop, 2,4-diclorophenoxy acetic acid, pyroxasulfone, pendimethalin ME, metribuzin, thifensulfuron, tribenuron, MCPA, pinoxaden, mesosulfuron

1. Introduction

Information about wheat production in the United States has been recorded since 1867 with respect to hectares planted (black dots on **Figure 1A**) and yield (bars on **Figure 1B**). While production in hectares first increased until 1950, it then decreased as yield in kg per hectare increased.
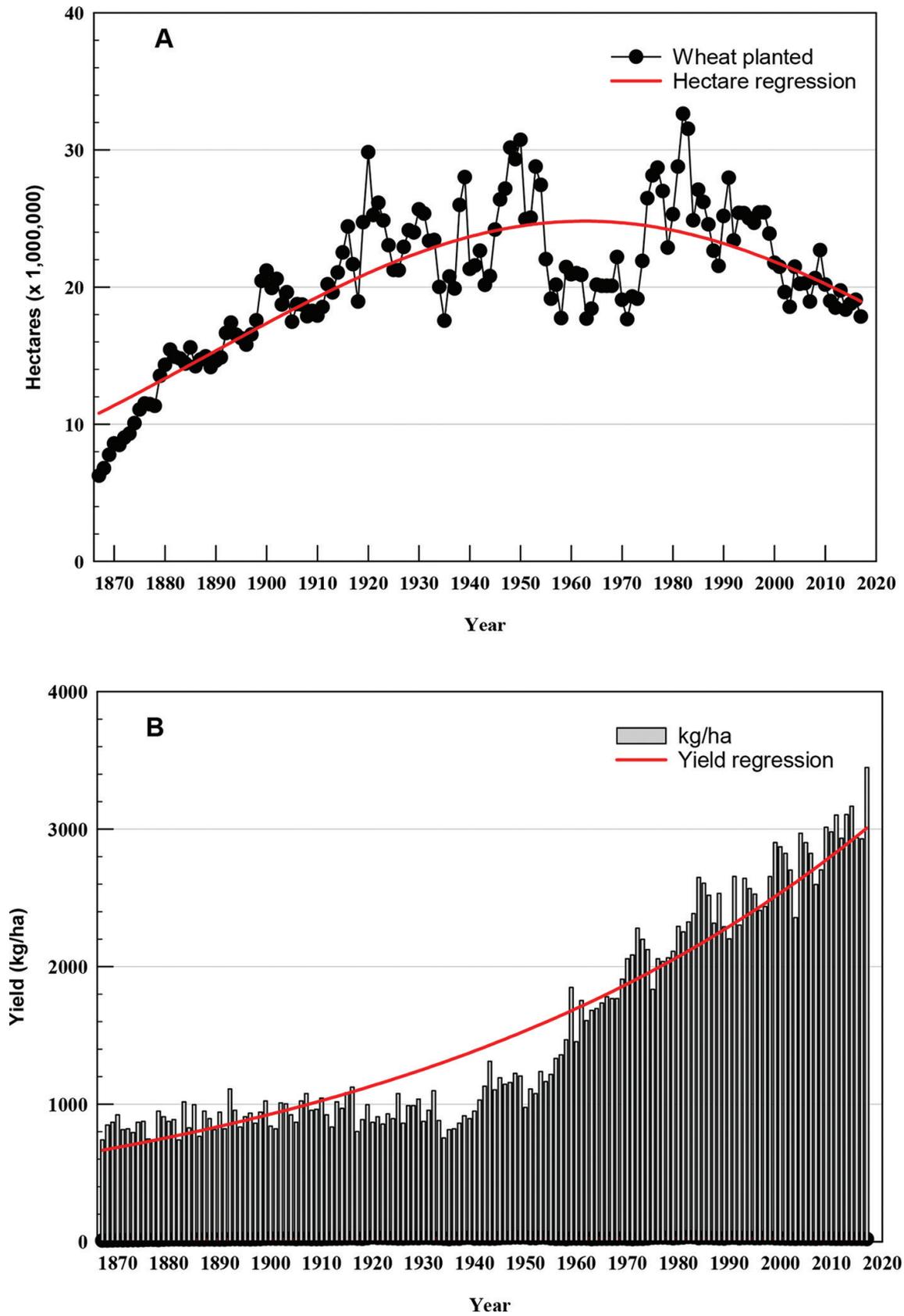
Figure 1. Hectares of wheat planted (A) and grain yield (B) in the United States (National Agricultural Statistics Service, USDA. Hectare and kg/ha data available at https://www.nass.usda.gov).

Improved genetics, fertility, disease, insect, and weed control options contributed to increased yield. As **Figure 1A** indicates, hectares planted decreased from 1950 to 1955, then stayed relatively constant until 1980, and then began to decline in 2000 and have continued this downward trend into the twenty-first century. However, wheat yield doubled from approximately 1000 to 2000 kg/ha from 1950 to 1980 (**Figure 1B**). Then, from 1980 to 2010, yield increased from 2000 to 3000 kg/ha as the overall number of hectares planted again declined to the 1950s level. The mid-1950s increase is significant as it occurred with the introduction of herbicides. Multiple weed species have become an issue in wheat all across this production region. However, Italian ryegrass [*Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot] is one of the most common and troublesome weeds in wheat. As a winter forage, Italian ryegrass is planted and then becomes a problematic weed in small grains due to escapes [1–3]. While herbicides can be used to control this weed, there are also herbicide-resistant issues. There are multiple reports of Italian ryegrass herbicide resistance to acetyl CoA carboxylase (ACCase), acetolactate synthase (ALS), and glyphosate herbicides [1, 4]. A commonality for Italian ryegrass resistance is that most of these herbicides mechanisms of action that have resistance issues are generally all postemergence (POST) applied to the weed. In order to have profitable wheat production, applications of preemergence (PRE) herbicides with residual control of Italian ryegrass and other winter weed species would benefit growers. Currently, there are limited herbicides that can be applied at the time of wheat planting.

2. Importance

Soft red winter wheat is an autumn-seeded crop in the Mid-South and Southeastern United States where it is double-cropped with cotton (*Gossypium hirsutum* L.), peanut (*Arachis hypogaea* L.), or soybean (*Glycine max* (L.) Merr.). Italian ryegrass is a vigorous erect winter annual native to temperate Europe where it was grown as a forage with reports of its presence in France, Switzerland, and England from 1818 to 1831 [3]. This use led to its migration to the Western Hemisphere with reports by Henderson on its quality [5]. Because of easy establishment, it was adapted for forage production. However, volunteer Italian ryegrass seed can become a weedy plant in small grains such as wheat [2, 3]. It can grow to over 1 m in height protruding above the wheat canopy, producing multiple tillers and seed heads from a single plant (**Figure 2**). It has long, clasping auricles, and awned seeds (**Figure 2**). Over time, it has become a major weed species for this region due to its aggressive growth and seed production. It has consistently ranked as being one of the most common and troublesome weeds in small grains and wheat for over 20 years [6–10]. Stone et al. [11] reported that Italian ryegrass interference with wheat was the result of its greater root density relative to the crop, which creates excess competition for moisture and nutrients. With respect to aboveground development, Ball [12] determined that leaf production rate was greater for Italian ryegrass as compared to wheat. Liebl and Worsham [13] noted that wheat grain yields were reduced by 4% for every ten Italian ryegrass plants per m^2 and that declining yields could be primarily attributed to reductions in crop tillering. According to Appleby et al. [14], Italian ryegrass infestations of 29–118 plants per m^2 reduced wheat yields between 7 and 50%. Italian ryegrass has similar growth stages to soft red winter wheat (**Figure 3**) and thus competes for resources in terms of space, sunlight, nutrients, and moisture.

Figure 2. Italian ryegrass [*Lolium multiflorum* L. ssp. multiflorum (Lam.) Husnot] in soft red winter wheat field, spikelet, and single seed, respectively (photos by Sidney Cromer).

Figure 3. Italian ryegrass [*Lolium multiflorum* L. ssp. multiflorum (Lam.) Husnot] in seedling, tillering, and reproductive phases, respectively [photos by Timothy Grey (center) and Sidney Cromer (left and right)].

Wild radish (*Raphanus raphanistrum* L.) is another common and troublesome winter annual weed in soft red winter wheat production regions of the Southeastern United States [6]. Cruciferous species compete vigorously with wheat, and data indicate that significant yield losses can occur if these weeds are not controlled soon after crop emergence [15]. Seeds of cruciferous species are high in erucic acid and glucosinolates that can pose quality problems in harvested wheat [16]. Once wild radish is established in wheat, it can be controlled with POST-applied herbicides, but these herbicides are not always used for economic, management, or even herbicide-resistant reasons [17–19]. Other winter weeds in soft red winter wheat production include henbit (*Lamium amplexicaule* L.), swine cress [*Coronopus didymus* (L.) Sm.], and cutleaf evening primrose (*Oenothera laciniata* Hill.) [6].

3. Background information on wheat herbicides

As the records for the US wheat production indicated in **Figure 1**, yield and hectares increased from the 1870s to the 1950s due to improved agronomic practices. Herbicides were introduced in small grain production in the 1940s for broadleaf weed control [20] and marked the beginning for the trend of reduced hectares producing greater yields. These two facts are born out in regression of the data over this era, with a negative regression for hectares planted beginning in the 1960s. In contrast, yield in kg per ha has maintained a positive slope, with slight declines in production during the 1930's Dust Bowl. With the introduction of improved farming techniques, pesticides, fertility, and improved cultivars, wheat production after World War II began to increase significantly as herbicides were incorporated into production practices.

3.1. Herbicides

Herbicides are used for PRE and POST control of grass and broadleaf weed species in wheat. However, control with POST herbicide applications is often the most commonly used as noted by **Figure 4**. Herbicide-applied POST can have less than desired weed control. Reduced efficacy has been associated with variables such as delayed application, suboptimum rates, not including a suitable adjuvant, including in tank mixture with other herbicides that are antagonistic, or during environmentally induced plant stress. The second factor that contributes to control failure is herbicide-resistant weeds. Herbicides that inhibit ACCase include the aryloxyphenoxy-propionates and cyclohexanediones. Within the United States, there has been a rapid increase in ACCase-resistant Italian ryegrass biotypes since 1990 [21]. For example, Italian ryegrass resistant to diclofop was first reported in 1987 in Oregon [22, 23]. It has subsequently been reported in the Southeastern United States [21] and throughout the world [22, 24–27]. The widespread development of herbicide resistance in Italian ryegrass will reduce control options in wheat. While wild radish herbicide resistance has been reported in multiple wheat production regions including Australia, Brazil, and South Africa [4], no reports have occurred in North America.

3.2. Synthetic auxin herbicides

The first herbicide to be introduced for chemical weed control in any crop was 2,4-(dichlorophenoxy)acetic acid (2,4-D). Reports of the plant growth regulatory effects were first noted by Marth and Mitchell [25] in the journal *Botanical Gazette*. They reported via a personal communication that 2,4-D could potentially be used for weed control. Marth and Mitchell [28] reported on the delivery of 2,4-D specifically via POST aqueous spray solutions at 500 and 1000 ppm, with efficacy on several broadleaf weed species including dandelion (*Taraxacum officinale* F.H. Wigg.) and plantain (*Plantago lanceolata* L.) that were controlled in Kentucky bluegrass (*Poa pratensis* L.). Klingman [29] experimented with wheat and noted 2,4-D tolerance when applied with postemergence to the crop. After decades of further research on wheat evaluating rate and timing of applications, 2,4-D became a standard herbicide used for broadleaf weed control and is still currently used as a POST treatment. Other auxin herbicides which used POST in wheat for broadleaf weed control include (4-chloro-2-methylphenoxy) acetic acid (MCPA) and 3,6-dichloro-2-methoxybenzoic acid (dicamba). These herbicides have

had consistent use patterns for the past 25 years in winter wheat with 2,4-D averaging over 1,000,000 kg applied in the United States annually (**Figure 4**). Dicamba and MCPA have averaged between 200,000 and 400,000 kg annually since 2006 (**Figure 4**) in winter wheat [30].
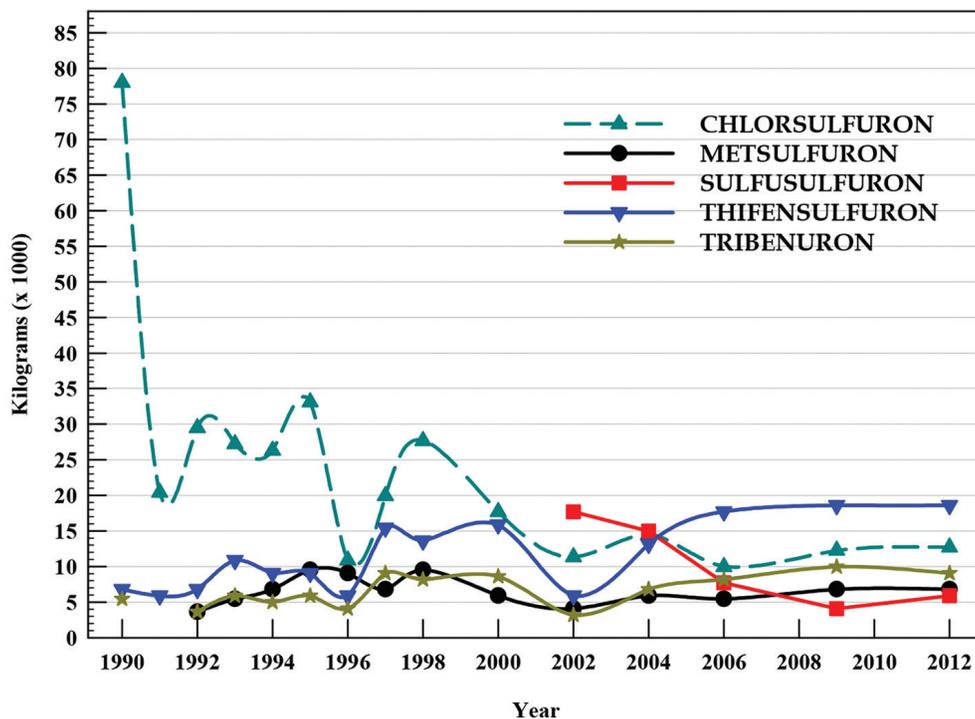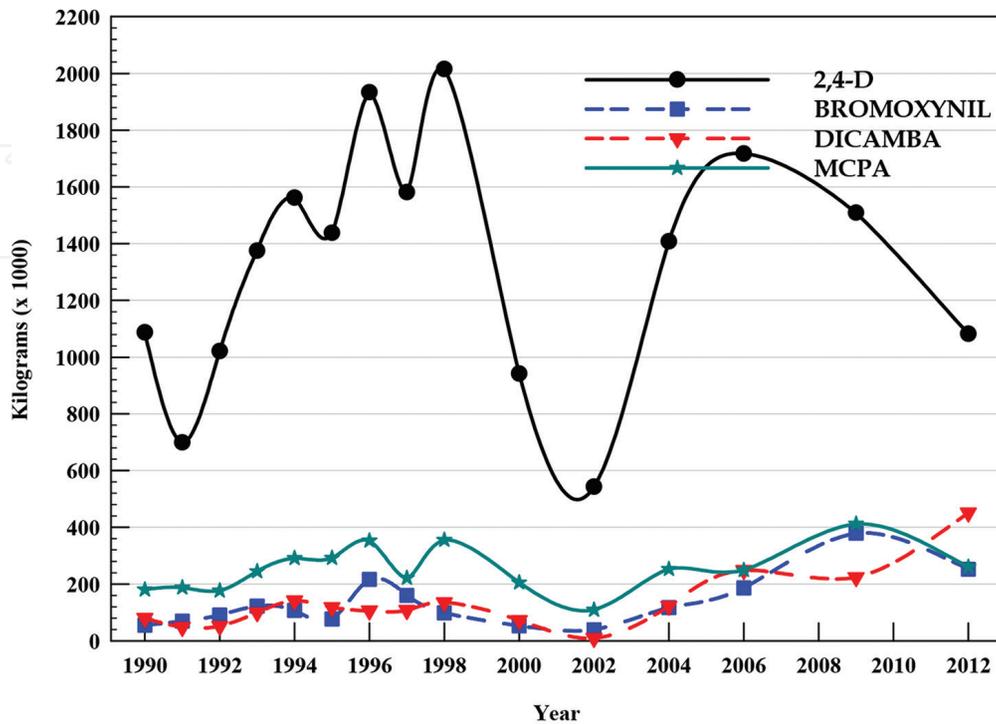
Figure 4. Herbicide use in winter wheat from 1990 to 2012 in the United States for multiple mechanisms of action. Data available at http://www.nass.usda.gov/Statistics_by_Subject/Environmental/index.asp.

3.3. Photosystem II herbicides

Photosystem II (PS II) herbicides used in winter wheat include metribuzin and bromoxynil and are utilized in the Southeastern United States [16]. Metribuzin can be POST applied to winter wheat for control of annual grasses and dicot weeds including Italian ryegrass and wild radish [16] just as the coleoptile is emerging from soil. While metribuzin can control Italian ryegrass effectively, careful management, including cultivar selection and timely application, is required to achieve acceptable crop tolerance and weed control. Many agronomically desirable, high-yielding wheat cultivars are sensitive to metribuzin and cannot be planted if metribuzin is to be applied and some cultivars are extremely sensitive [31–33]. Bromoxynil in wheat will control wild radish but is ineffective on Italian ryegrass. Bromoxynil use in soft red winter wheat has averaged over 200,000 kg in the United States since 2006 (**Figure 4**).

3.4. Acetolactate synthase (ALS) herbicides

Sulfonylurea (SU) herbicides were first synthesized by E.I. DuPont Corp. in the mid-1950s and screened for pesticide properties, but first attempts revealed no significant biological activity [34]. It was not until the 1970s that the analogs of SUs began to be synthesized and their herbicidal activity evaluated. Prior to this there was no precedence for high potency and extremely low use rates in the g ha^{-1} range for weed control. One example described by Bhardwaj [34] was that university researchers would move the decimal two places as they could not believe that herbicides could be effectively applied at g ha^{-1}, rather than kg ha^{-1}. The result was that weeds would not grow in treated test plots after 2 years, despite half-lives of 6–8 weeks. Thus, the potency of the SUs was recognized, and their use in plant production systems, including wheat, was quickly established. The key components to SUs are two moieties (R1 and R2) on either side of a sulfonylurea bridge. Generally, the moieties are composed of an aryl group, a pyrimidine ring, or a triazine ring [35, 36]. Variation in herbicidal activity occurs by substitutions made to branches on these rings. Chlorsulfuron was the first SU herbicide released by E.I. DuPont for weed control in small grains [37]. LaRossa and Schloss [38] reported that sulfometuron methyl was a potent acetolactate synthase (ALS) isozyme II inhibitor by testing of *Salmonella typhimurium*. Since then, all SUs have been identified as ALS inhibitors [39]. There are currently several SUs used in wheat weed control including chlorsulfuron, metsulfuron, sulfosulfuron, mesosulfuron, thifensulfuron, and tribenuron. Use rates vary but fall primarily within a range of 4–280 g ha^{-1}. These use patterns are reflected in the masses of herbicides used when comparing the auxin and PS II inhibitors combined to average over 2,450,000 kg in 2012, versus the ALS herbicides at 53,000 kg (**Figure 4**): a 46 times greater application mass. This comparison reflects the potency and reduces environmental impact aspect of the ALS herbicides. Another POST ALS wheat herbicide is the triazolopyrimidine pyroxsulam that is specifically preferred in the Southeastern United States because it controls Italian ryegrass and wild radish. However, there are multiple reports of ALS resistance in Italian ryegrass that make these herbicides less viable options and essentially render those useless [40].

3.5. Soil residual herbicides

New herbicide chemistries and new formulations of older compounds are available for weed control in soft red winter wheat. These include options for grass and broadleaf weed species. Pendimethalin [N-(1-ethylpropyl)-3,4-dimethyl-2,6-dintrobenzenamine] formulated as a micro-encapsulated (ME) aqueous capsule suspension contains 38.7% (0.47 kg L^{-1}) active ingredient and can be applied after wheat has the first true leaf. This will provide residual weed control to later emerging weeds, but does not overcome the issue of weeds emerging right after wheat planting.

Pyroxasulfone (3-[5-(difluoromethoxy)-1methyl-3-(trifluoromethyl)pyrazol-4-ylmethylsulfo-nyl-4,5-dihydro-5,5-dimethy-1,2-oxazole) is an isoxazoline PRE soil residual herbicide registered for soft red winter wheat since 2014 in the United States [41]. It has been researched and registered in multiple wheat production regions of the world including Australia [42], Japan, Canada, Saudi Arabia, South Africa, and the United States [43]. Pyroxasulfone inhibits the biosynthesis of very-long-chain fatty acids (VLCFAs) leading to the buildup of fatty acid precursors, specifically inhibiting many elongation steps catalyzed by VLCFA elongases, as a Group 15 (WSSA)/Group K$_3$ (HRAC) herbicide [39, 44]. Nakatani et al. [43] noted that the herbicide benthiocarb (S-[(4-chlorophenyl)methyl]diethylcarbamothioate) was used as the basis for research development of pyroxasulfone by developing a novel chemical structure by using various substitutions. This resulted in a compound with low water solubility (3.49 mg L^{-1}), no pKa, and hydrolytically stable at all pH values at 25 C, allowing less susceptibility to decomposition and thus providing extended soil residual activity [39, 43]. Dissipation rates (DT$_{50}$) for pyroxasulfone have ranged from 8 to 71 days in the top 8 cm of Tennessee soils [45] and 54 to 94 days in the top 7.5 cm of Colorado soils [46]. Pyroxasulfone's soil residual activity and utility have allowed it to be registered for multiple uses including corn (field, sweet, and pop) (Zea mays L.), soybean, cotton, fallow land, and non-crop areas [47–49]. Winter wheat tolerance has been well documented with only minor injury in the form of stunting with no negative effects on yield [50–52]. With PRE soil activity on broadleaf and grass species including ALS- [52], ACCase- [41], and glyphosate- [1] resistant Italian ryegrass biotypes, pyroxasulfone use in wheat will afford growers an early season weed control option that was previously unavailable.

4. Research

While auxins, PS IIs, and SUs are effective in wheat production, they have traditionally been POST applied for weeds that have already emerged. By applying after the crops emergence, the potential for weed infestation increases leading to a greater production costs, resulting in yield loss and potential quality issues. By utilizing herbicides either as PRE or soon after emergence, weed control could be enhanced in soft red winter wheat. Pyroxasulfone is labeled for delayed PRE or early POST application. The registrations for application of pyroxasulfone differ by company. One company defines that applications of pyroxasulfone must be delayed PRE as to when wheat has 80% germinated seed with a 1.2 cm long shoot, as well as having an early POST from spike to the fourth tiller timing [44]. Other companies have regional and state requirements that wheat must be planted 2.5–3 cm deep for PRE application (Pacific

north western region of the United States) [45] but can also have POST applications for specific states [46]. Therefore, this chapter will emphasize pyroxasulfone, pendimethalin ME, and other herbicides for PRE and POST weed control and wheat response.

4.1. Field studies

Field studies were conducted to evaluate herbicides used for soft red winter wheat production focusing on residual and contact active ingredients, as well as timing when applied either PRE or POST with respect to crop emergence. All studies were conducted as described in **Table 1** for soil nomenclature, soil texture, soil pH, organic matter content, wheat cultivar, and dates associated with seeding, herbicide application timings, and harvest. Experiments were conducted from autumn to spring in 2009–2010 (**Table 2**), 2010–2011 (**Tables 2** and **3**), 2011–2012 (**Tables 2** and **3**), 2012–2013 (**Tables 4** and **5**), and 2013–2014 (**Table 4**). Experiments were conducted on the University of Georgia property at the Bledsoe Research Farm near Williamson, at the Southwest Georgia Branch Experiment Station located near Plains, or at the Ponder and Lang Research Farms near Tifton. Treated plots included eight rows of wheat on 19 cm spacing (1.8 m wide), in plots 7.6 or 9.1 m long, with wheat seeding rates of 90 kg ha^{-1}. A randomized complete block design with four replications was used for all experiments. Herbicides were applied with a CO_2-pressurized sprayer calibrated to deliver 187 L ha^{-1} at 210 kPa for all experiments. PRE applications were made prior to wheat emergence; at emergence (AE) applications were made at Feekes 0.9 [53] when the coleoptile was soil emerged. POST applications were applied between Feekes 1.0 and 1.9. Fertilizer and liming requirements were based on the University of Georgia Extension recommendations for wheat. Insects and plant diseases were monitored and sprayed when necessary. Wheat stand counts were made multiple times during the season on 1 m of length of row. Wheat injury and natural infestations of weeds were evaluated for each location at multiple times during the growing season. Wheat injury and weed control were visually estimated on a scale of 0 (no injury) to 100% (death). Data for experiments that were identical were combined for analysis. Weed control, wheat stand counts, wheat injury, and wheat yield were subjected to mixed model analysis of variance (ANOVA) in SAS 9.2 [54]. Complete treatment description for all 15 experiments is listed in **Table 1**.

	Griffin		Plains		Tifton		Plains		Tifton
	2009–2010	2010–2011	2009–2010	2010–2011	2009–2010	2010–2011	2010–2011	2011–2012	2010–2011
Soil nomen-clature	Clayey, kaolinitic, thermic, Typic Hapludult		Clayey, kaolinitic, thermic, Typic Kandiudults		Fine-loamy, kaolinitic, thermic, Plinthic Kandiudult		Clayey, kaolinitic, thermic, Typic Kandiudults		Fine-loamy, kaolinitic, thermic, Plinthic Kandiudult
Soil texture	Cecil sandy clay loam		Faceville sandy loam		Tifton loamy sand		Faceville sandy loam		Tifton loamy sand
Soil pH	6.3	6.2	6.0	6.2	5.9	6.1	6.2	5.9	6.2
Organic matter (%)	1.5	1.0	1.0	0.5	1.1	0.5	1.0	1.3	0.5
Wheat cultivar	AGS 2031	AGS 2026	AGS 2000	AGS 2020	Gore	AGS 2031	Gore	CL 7	AGS 2020

	Griffin		Plains		Tifton		Plains		Tifton
	2009–2010	2010–2011	2009–2010	2010–2011	2009–2010	2010–2011	2010–2011	2011–2012	2010–2011
Seeding date	5 Nov 2009	2 Nov 2010	18 Nov 2009	19 Nov 2010	5 Nov 2009	2 Nov 2010	19 Nov 2010	22 Nov 2011	23 Nov 2010
Number of treatments	12	12	12	12	12	12	14	14	14
PRE application(s)	7 Nov 2009	8 Nov 2010	18 Nov 2009	19 Nov 2010	6 Nov 2009	8 Nov 2010	8 Nov 2010	9 Nov 2011	12 Nov 2010
	——	——	——	——	——	——	19 Nov 2010	22 Nov 2011	23 Nov 2010
POST application(s)	14 Jan 2010	17 Jan 2011	13 Jan 2010	24 Jan 2011	12 Jan 2010	17 Jan 2010	26 Nov 2010	1 Dec 2011	3 Dec 2010
	——	——	——	——	——	——	24 Jan 2011	14 Dec 2011	10 Jan 2011
Harvest date	4 June 2010	NY[a]	27 May 2010	6 June 2011	28 May 2010	2 June 2010	12 May 2011	1 May 2012	6 June 2011

	Griffin		Plains	Tifton	Griffin	Plains
	2012–2013	2013–2014	2012–2013	2012–2013	2012–2013	2012–2013
Soil name	Clayey, kaolinitic, thermic, Typic Hapludult		Clayey, kaolinitic, thermic, Typic Kandiudults	Fine-loamy, kaolinitic, thermic Plinthic Kandiudult	Clayey, kaolinitic, thermic, Typic Hapludult	Clayey, kaolinitic, thermic, Typic Kandiudults
Soil texture	Cecil sandy clay loam		Faceville sandy loam	Tifton loamy sand	Cecil sandy clay loam	Faceville sandy loam
Soil pH	6.0	6.3	6.5	5.9	6.0	6.5
Organic matter	1.0	1.5	2.0	1.1	1.0	2.0
Wheat cultivar	SS 8641	SS8461	AGS 3035	AGS 2020	SS 8641	AGS 3035
Seeding date	1 Nov 2012	31 Oct 2013	20 Nov 2012	14 Nov 2012	1 Nov 2012	20 Nov 2012
Number of treatments	15	15	15	15	10	10
PRE application	2 Nov 2012	4 Nov 2013	20 Nov 2012	14 Nov 2012	2 Nov 2012	20 Nov 2012
POST application(s)	13 Nov 2012	9 Nov 2013	3 Dec 2012	26 Nov 2012	13 Nov 2012	3 Dec 2012
	6 Dec 2012	20 Nov 2013	14 Dec 2012	18 Dec 2012	6 Dec 2012	14 Dec 2012
	——	——	——	——	15 Jan 2013	11 Jan 2013
Harvest date	NY[a]	NY	28 May 2013	29 May 2013	NY	28 May 2013

[a] No yield (NY) taken as natural infestations of ryegrass populations made harvest impossible.

Table 1. Location information by table for soft red winter wheat herbicide trials and weed control evaluations in Georgia.

Herbicide	Timing	Rate (g a.i. ha⁻¹)ᵇ	Injury (%)		Italian ryegrass (%)		Yield (kg ha⁻¹)
			15 DAP	**90 DAP**	**30 DAP**	**175 DAP**	
Nontreated control			0 c	0 e	0 e	0 e	3730 a
Pyroxasulfone	PRE	40	0 c	4 cde	72 abc	75 bc	4110 a
Pyroxasulfone	PRE	60	3 c	8 bcd	83 abc	90 ab	4230 a
Pyroxasulfone	PRE	80	9 b	14 b	91 ab	92 ab	4180 a
Pyroxasulfone	PRE	160	20 a	23 a	93 a	97 a	4000 a
Pendimethalin ME	PRE	1064	3 c	5 cd	66 c	54 cd	4050 a
Pinoxaden	POST	119	–	–	11 bc	75 abc	57 cd	3930 a
Pendimethalin ME + pinoxaden	POST	1064 + 119	–	–	8 bcd	84 abc	51 cd	4000 a
Pyroxasulfone + pinoxaden	POST	40 + 119	–	–	5 cd	70 bc	96 a	4110 a
Diclofop	POST	559	–	–	6 cd	27 d	50 d	3970 a
Pyroxsulam	POST	18	–	–	6 b	92 ab	86 ab	3987 a
Mesosulfuron	POST	15	–	–	9 bcd	94 a	79 ab	3970 a

ᵃSite-year locations: Griffin, Plains, and Tifton, Georgia

ᵇAbbreviations: a.i., active ingredient; DAP, days after planting; ME, microencapsulated; PRE, preemergence; POST, postemergence applied 65–70 DAP at Feekes scale 1.5–1.9

Table 2. Herbicide, rates, and timing of applications for evaluating weed control and soft red winter wheat growth response in Georgia, 2010–2011 and 2011–2012: data represents six site-year locationsᵃ.

Herbicide	Timing	Rate (g a.i. ha⁻¹)ᵇ	Injury (%)		Italian ryegrass (%)		Henbitᶜ	Yield (kg ha⁻¹)
			14 DAP	**28 DAP**	**30 DAP**	**175 DAP**	**30 DAP**	
Nontreated control			0 b	0 d	0 d	0 h	0 b	4370 a
Pyroxasulfone	12 DPRE	40	0 b	1 cd	88 a	55 def	95 a	4570 a
Pyroxasulfone	12 DPRE	60	0 b	2 cd	98 a	35 fg	97 a	4810 a
Pyroxasulfone	12 DPRE	80	4 b	5 bc	97 a	74 abcd	98 a	4600 a
Pyroxasulfone	12 DPRE	100	5 b	5 bc	98 a	66 bcd	97 a	4670 a
Pyroxasulfone	12 DPRE	120	11 a	7 ab	98 a	65 bcd	99 a	4760 a
Pyroxasulfone	PRE	40	3 b	2 cd	88 a	63 bcd	91 a	4620 a
Pyroxasulfone	PRE	60	3 b	1 cd	96 a	84 abc	91 a	4660 a
Pyroxasulfone	PRE	80	2 b	3 bcd	96 a	91 a	98 a	4860 a
Pyroxasulfone	PRE	100	10 a	9 a	98 a	92 a	98 a	4650 a
Pyroxasulfone	PRE	120	14 a	10 a	99 a	87 ab	91 a	4590 a
Saflufenacil	PRE	60	1 b	2 cd	97 a	54 def	98 a	4740 a

Herbicide	Timing	Rate (g a.i. ha⁻¹)[b]	Injury (%)		Italian ryegrass (%)				Henbit[c]		Yield (kg ha⁻¹)	
			14 DAP	28 DAP	30 DAP		175 DAP		30 DAP			
Pendimethalin ME	AE	1064	0 b	1 cd	48	c	27	g	91	a	4650	a
Pinoxaden	POST	119	0 b	3 bcd	68	b	40	efg	0	b	4450	a

[a]Site-year locations: Griffin, Plains, and Tifton, Georgia

[b]Abbreviations: a.i., active ingredient; DAP, days after planting; ME, microencapsulated; 12 DPRE, 12 days before planting; PRE, preemergence; AE, at wheat emergence; POST, postemergence applied 65–70 DAP at Feekes scale 1.5–1.9

[c]Henbit at Plains location 2010–2011 and 2011–2012

Table 3. Herbicide, rates, and timing of applications for evaluating weed control and soft red winter wheat growth response in Georgia, 2010–2011 and 2011–2012: data represents three site-year locations[a].

Herbicide	Timing	Rate (g a.i. ha⁻¹)[b]	Injury (%)		Italian ryegrass (%)						Henbit[c]		Yield (kg ha⁻¹)	
			30 DAP		75 DAP		175 DAP				30 DAP			
Nontreated control			0	b	0	f	0	h			0	f	5120	b
Pyroxasulfone	PRE	60	0	b	95	a	93	a			75	e	5680	ab
Pyroxasulfone	PRE	80	1	b	95	a	95	a			69	e	5762	ab
Pyroxasulfone + saflufenacil	PRE	60+119	0	b	95	a	92	ab			95	ab	6080	a
Pyroxasulfone + saflufenacil	PRE	80+119	3	b	97	a	96	a			90	abcd	6310	a
Pyroxasulfone	AE	60	0	a	74	bcd	54	efg			75	e	6070	a
Pyroxasulfone	AE	80	0	b	78	bc	72	cde			81	bcde	6320	a
Metribuzin	AE	476	18	a	85	abc	73	cde			97	a	5670	ab
Pyroxasulfone + pendimethalin ME	AE	60+1064	0	b	74	cde	69	ed			98	a	6160	a
Pyroxasulfone + pendimethalin ME	AE	80+1064	0		76	bcd	67	edf			98	a	6440	a
Metribuzin + pendimethalin ME	AE	476+1064	17	a	87	ab	75	bcd			98	a	5350	b
Pyroxasulfone	POST	60	0	b	60	de	50	fg			76	de	6260	a
Pyroxasulfone	POST	80	0	b	70	cde	62	ed			78	cde	6020	a
Diclofop	POST	840	6	b	58	e	42	g			0	f	5750	ab
Pyroxsulam	POST	18	0	b	62	de	49	fg			92	abc	6330	a

[a]Site-year locations: Tifton and Griffin, Georgia.

[b]Abbreviations: a.i., active ingredient; DAP, days after planting; ME, microencapsulated; 12 DPRE, 12 days before planting; PRE, preemergence; AE, at wheat emergence; POST, postemergence applied 65–70 DAP at Feekes scale 1.5–1.9.

[c]Henbit at Griffin location 2012–2013 and 2013–2014.

Table 4. Herbicide, rates, and timing of applications for evaluating weed control and soft red winter wheat growth response in Georgia, 2012–2013 and 2013–2014: data represents four site-year locations[a].

Herbicide	Timing	Rate (g a.i. ha⁻¹)	Injury (%)		Italian ryegrass (%)				Yield (kg ha⁻¹)	
			30 DAP		75 DAP		175 DAP			
Nontreated control			0	b	0	d	0	e	6750	bcd
Pyroxasulfone Thifensulfuron + Tribenuron + MCPA	PRE[b] POST	45 17.5+4.3+420	0	b	88	ab	74	ab	7180	abc
Pyroxasulfone Thifensulfuron + Tribenuron + MCPA	PRE POST	60 17.5+4.3+420	0	b	95	a	94	a	6500	cd
Pyroxasulfone Thifensulfuron + Tribenuron + MCPA	PRE POST	120 17.5+4.3+420	0	b	97	a	95	a	6660	cd
Pyroxasulfone Thifensulfuron + Tribenuron + MCPA	AE POST	45 17.5+4.3+420	0	b	40	c	16	de	7410	a
Pyroxasulfone Thifensulfuron + Tribenuron + MCPA	AE POST	60 17.5+4.3+420	0	a	53	c	26	d	7150	abc
Pyroxasulfone Thifensulfuron + Tribenuron + MCPA	AE POST	120 17.5+4.3+420	0	b	74	b	54	bc	7130	abc
Pinoxaden Thifensulfuron + Tribenuron + MCPA	EPOST POST	60 17.5+4.3+420	6	a	77	b	54	bc	7290	ab
Pyroxasulfone Thifensulfuron + Tribenuron + MCPA	EPOST POST	60 17.5+4.3+420	0	b	42	c	34	cd	7370	a
Pyroxasulfone Thifensulfuron + Tribenuron + MCPA	EPOST POST	120 17.5+4.3+420	0	b	47	c	38	cd	7200	abc

[a]Site year locations: Plains and Griffin, Georgia.
[b]Abbreviations: a.i., active ingredient; DAP, days after planting; PRE, preemergence; AE, at wheat emergence; POST, postemergence applied 65–70 DAP at Feekes scale 1.5–1.9.

Table 5. Herbicide, rates, and timing of applications for evaluating weed control and soft red winter wheat growth response in Georgia, 2012–2013: data represents two site-year locations[a].

5. Crop response and weed control

Treatments were applied at times typically occurring in Georgia soft red winter wheat production (**Table 1**) and are thus representative of producer practices and label recommendations for the PRE herbicides evaluated. For AE and POST herbicide treatments, applications that included surfactants when needed were made based on label recommendations.

An important factor for any PRE-applied herbicide in soft red winter wheat is stand establishment. Crop injury or stand reduction can lead to weed infestations, promote disease proliferation, and thus reduce yield and quality. Three herbicides were PRE applied over the course of

these experiments: pyroxasulfone (40 to 160 g ha^{-1}), pendimethalin microencapsulated (ME) (1064 g ha^{-1}), and saflufenacil (60 g ha^{-1}). There was no stand reduction in any of the experiments for any PRE herbicide treatment where the average wheat stand was 21 (**Table 2**), 21 (**Table 3**), 22 (**Table 4**), and 24 (**Table 5**) plants per meter of row (data not shown). Even when pyroxasulfone was applied 12 days PRE (12 DPRE), no reduction in stands occurred (**Table 3**) (data not shown). These data indicate the crop safety which these herbicides, pyroxasulfone, pendimethalin ME, and saflufenacil PRE, have toward soft red winter wheat in this region. The AE and POST for these herbicide applications did not affect wheat stand.

Soft red winter wheat injury ranged from 0 to 20% across PRE treatment timings for all studies when evaluated at 14, 15, or 30 DAP (**Tables 2–5**). Pyroxasulfone PRE at 160 or 120 g/ha injured wheat 20 and 11% (**Tables 2** and **3**), respectively. This injury was in the form of stunting. Some stunting from pyroxasulfone was still visible at 90 DAP for the 80 and 160 g ha^{-1} rates (**Table 2**). However, this injury was transient by the end of the season and not observed. Metribuzin applied alone or in combination with pendimethalin ME at emergence resulted in significant injury, 18%, at 30 DAP (**Table 4**). The soils for the present studies were a sandy loam, loamy sand, or sandy clay loam with less than 2.0% organic matter. Hulting et al. [52] noted 3% or less wheat injury from pyroxasulfone rates up to 100 g ha^{-1} on a silt loam soil. Previous research indicated decreased pyroxasulfone injury with legumes grown in soils with greater clay contents [19]. Canadian dry bean research indicated that pyroxasulfone injury at 210 g/ha was 11% or less [55]. These data indicate that at rates up to 160 g ha^{-1} wheat had tolerance in sandy loam, loamy sand, and sandy clay loam soils of the Southeastern United States. When pyroxasulfone was POST applied at Feekes scale 1.0–1.9 (**Tables 2**, **4**, and **5**), no injury was ever observed. Pyroxasulfone has limited POST activity but can be applied after wheat emergence per label recommendation [47–49]. This will provide growers an opportunity to incorporate a residual herbicide to promote weed control. When pinoxaden, diclofop, or mesosulfuron was POST applied, wheat injury did occur but was consistently less than 9% (**Tables 2–4**).

Wheat yield varied by location and by year (**Tables 2–5**). There were no differences for yield when pyroxasulfone was PRE applied (**Table 2**) or 12DPRE and PRE (**Table 3**) as compared to AE or POST applications of diclofop, pyroxsulam, mesosulfuron, or pinoxaden. For these experiments, yield exceeded 4000 kg ha^{-1} for all pyroxasulfone treatments and was always greater than the nontreated control. There was no rate response for wheat yield for pyroxasulfone rates of 40, 60, 80, 100, or 120 g ha^{-1} (**Tables 2** and **3**). There were no differences in wheat yield as compared to the nontreated control when pyroxasulfone was applied alone or in combination with saflufenacil PRE, AE, or POST (**Table 4**). Wheat yields in this set of experiments (four totals) were consistent with early season injury, in that metribuzin alone or in combination with pendimethalin ME-applied AE had significant injury 30 DAP, and this translated into reduced yields of 5670 and 5350 kg ha^{-1}, respectively. Previous research indicated that metribuzin reduced yield demonstrating the risks growers take when using this herbicide for weed control [16, 31, 33].

Early-season Italian ryegrass control for pyroxasulfone application at 40 to 160 g ha^{-1} 12DPRE or PRE was 72 to 99% when evaluated at 30 DAP (**Tables 2–4**). However, by 175 DAP Italian ryegrass control began to decline to 83% and less for the 40 and 60 g ha^{-1} rates of pyroxasulfone. Pyroxasulfone at 80 g ha^{-1} or greater provided 87% or greater season-long control (**Tables 2–4**). Previous research has noted similar Italian ryegrass response to pyroxasulfone at 50–150 g/ha

with control ranging from 63 to 100% [52]. Bond et al. [1] noted a significant difference of 37 versus 99% control of glyphosate-resistant Italian ryegrass for pyroxasulfone at 50 versus 160 g ha^{-1}, respectively. These data indicate that for season-long Italian ryegrass control, pyroxasulfone at 100 g/ha will be required in the Southeastern US soft red winter wheat production. As a PRE herbicide, soil dissipation of pyroxasulfone will occur over time [45, 46], thus requiring the appropriate rate to be utilized for season-long weed control. Applying pyroxasulfone 12DPRE prior to wheat planting resulted in 74% and less Italian ryegrass control. This could be potentially contributed to soil disruption in the planting process via the tractor wheels and planter disk blades.

Although no attempt was made to quantify the level of herbicide resistance in these Italian ryegrass populations, ACCase resistance is suspected in the Griffin GA population (unpublished data). Diclofop and pinoxaden are ACCase herbicides that failed to control Italian ryegrass effectively (**Tables 2–4**) when POST applied. Similarly, the ALS herbicide pyroxsulam exhibited variable Italian ryegrass control at 86 and 49% at 175 DAP (**Tables 2** and **4**, respectively) indicating potential ALS-susceptible and potential ALS-resistant populations. This was established even further when the ALS herbicides thifensulfuron plus tribenuron were used as sequential POST applications following AE or POST pinoxaden applications in that Italian ryegrass control was 54% at 175 DAP (**Table 5**). Multiple herbicide-resistant Italian ryegrasses to ALS and ACCase herbicides have been confirmed in Georgia [4]. Previously, growers relied on AE or POST herbicide combinations for weed control, but the addition of pyroxasulfone for PRE application in soft red winter wheat will provide much greater potential for successful crop production. However, pyroxasulfone must be applied prior to Italian ryegrass establishment, as noted by AE and POST applications in **Tables 4** and **5**. Italian ryegrass control declined significantly to 72% and less for any rate of pyroxasulfone AE or POST alone or when used with other POST-applied herbicides at 175 DAP.

Pyroxasulfone PRE controlled henbit 91% and greater (**Table 3**) or provided suppression (**Table 4**). Combinations with other herbicides improved control of this winter annual species (**Table 4**). These data indicate that henbit can be controlled with currently registered herbicides for wheat production. There is limited information about pyroxasulfone winter weed species control in wheat, other than Italian ryegrass, in the literature.

The complexity and difficulty of managing winter weed species in soft red winter wheat have increased with the discovery of herbicide-resistant weeds, specifically ACCase- and ALS-resistant Italian ryegrass [4]. Additionally, glyphosate-resistant Italian ryegrass is now an issue in this same region [1]. Successful management of Italian ryegrass resistant to multiple mechanisms of action will require diligent control programs utilizing PRE residual herbicides prior to wheat emergence, during the cropping season, and after crop rotation, in order to extend the use of pyroxasulfone's mechanism of action, which is different from all other previous wheat herbicides.

6. Conclusion/recommendations

This research indicated that using the appropriate rates of pyroxasulfone PRE could provide season-long control of Italian ryegrass in wheat. However, variability in Italian ryegrass control was observed when low rates or improper timing of application were used, which

indicates the need for further development as growers incorporate this herbicide. Eight different soft red winter wheat cultivars were used in this research, and all exhibited tolerance to pyroxasulfone alone and with other herbicide combinations. Future research should be conducted with the currently evaluated herbicides for control of other weed species. Italian ryegrass control was attained and maintained with the appropriate herbicide applications, but variability can be an issue if proper rates and timings are not adhered to. This should be considered as an area for future research efforts in soft red winter wheat production using combinations of these herbicides. Growers should follow registration recommendations for the herbicides evaluated in this research, along with crop rotation and using different mechanisms of action herbicides to limit exposure and reduce potential for resistance to proliferate.

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