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

http://dx.doi.org/10.5772/67305

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 stage 1.0, and pinoxaden applied at Feekes stage 1.9.

Keywords: crop tolerance, Italian ryegrass, wild radish, diclofop, 2,4-dichlorophenoxy 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 \( \text{Lolium perenne L. ssp. multiflorum (Lam.) Husnot} \) 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 \( \text{(Gossypium hirsutum L.)} \), peanut \( \text{(Arachis hypogaea L.)} \), or soybean \( \text{(Glycine max (L.) Merr.)} \). 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.
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].

**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)].
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 aryloxyphenoxypropionates 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, sulfuron, 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 pyroxasulam 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 \([N-(1-ethylpropyl)-3,4\text{-dimethyl-2,6-dintrobenzenamine}]\) 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-ylmethylsulfonyl]-4,5-dihydro-5,5-dimethyl-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) (\textit{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- \([52]\), ACCCase- \([41]\), 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 IIIs, 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.

|                | Griffen          | Plains          | Tifton          | Griffen          | Plains          | Tifton          |
|----------------|------------------|-----------------|-----------------|------------------|-----------------|-----------------|
| 2009–2010      | 2010–2011        | 2009–2010       | 2010–2011       | 2009–2010        | 2010–2011       | 2009–2010        |
| Soil nomenclature | Clayey, kaolinitic, thermic, Typic Hapludult | Clayey, kaolinitic, thermic, Typic Kandiudults | Fine-loamy, kaolinitic, thermic, Plinthic Kandiudults | Clayey, kaolinitic, thermic, Typic Kandiudults | Fine-loamy, kaolinitic, thermic, Plinthic Kandiudults |
| Soil texture    | Cecil sandy clay loam | Faceville sandy loam | Tifton loamy sand | Faceville sandy loam | Tifton loamy sand |
| Soil pH         | 6.3              | 6.0             | 5.9             | 6.2              | 5.9             | 6.2             |
| Organic matter (%) | 1.5              | 1.0             | 1.1             | 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 | Griffin | Plains | Tifton |
|----------------|---------|--------|--------|---------|--------|--------|
| **Seeding date** | 5 Nov 2009 | 2 Nov 2010 | 18 Nov 2009 | 19 Nov 2010 | 5 Nov 2009 | 2 Nov 2010 |
| **Number of treatments** | 12 | 12 | 12 | 12 | 12 | 14 |
| **PRE application(s)** | 7 Nov 2009 | 8 Nov 2010 | 18 Nov 2009 | 19 Nov 2010 | 6 Nov 2009 | 8 Nov 2010 |
| **POST application(s)** | 14 Jan 2010 | 17 Jan 2010 | 13 Jan 2010 | 24 Jan 2011 | 12 Jan 2010 | 17 Jan 2010 |
| **Harvest date** | 4 June 2010 | 27 May 2010 | 28 May 2010 | 2 June 2010 | 12 May 2011 | 1 May 2012 |

|                | Griffin | Plains | Tifton | Griffin | Plains | Tifton |
|----------------|---------|--------|--------|---------|--------|--------|
| **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(s)** | 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 |
| **Harvest date** | NY | NY | 28 May 2013 | 29 May 2013 | NY | 28 May 2013 |

*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\(^{-1}\)) | Injury (%) | Italian ryegrass (%) | Yield (kg ha\(^{-1}\)) |
|--------------------|--------|-----------------------------|------------|----------------------|-------------------------|
|                    |        | 15 DAP | 90 DAP | 30 DAP | 175 DAP | 30 DAP | 175 DAP |
| Nontreated control |        | 0      | c      | 0      | e      | 0      | e      | 3730 a |
| Pyroxasulfone      | PRE    | 40     | 0      | c      | 0      | e      | 0      | e      | 4110 a |
| Pyroxasulfone      | PRE    | 60     | 3      | c      | 4      | cde    | 72     | abc    | 75     | bc     | 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   | 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 locations*.
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.

| Herbicide                | Timing | Rate (g a.i. ha$^{-1}$) | Injury (%) | Italian ryegrass (%) | Henbit$^c$ | Yield (kg ha$^{-1}$) |
|--------------------------|--------|-------------------------|------------|----------------------|------------|----------------------|
| 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 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.

| Herbicide                | Timing | Rate (g a.i. ha$^{-1}$) | Injury (%) | Italian ryegrass (%) | Henbit$^c$ | Yield (kg ha$^{-1}$) |
|--------------------------|--------|-------------------------|------------|----------------------|------------|----------------------|
| Non-treated control      |        | 0 b 0 f 0 h 0 f         |            |                      |            | 5120 b               |
| Pyroxasulfone            | PRE    | 60                      | 0 b 95 a 93 a 75 e | 4650 a     |
| 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 |
| Metribuzin               | AE     | 476                     | 18 a 85 abc 73 cde 97 a | 6320 a    |
| 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 |
| Pyroxasulam              | 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.
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

| 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 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 | |

*Site year locations: Plains and Griffin, Georgia.

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.

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 pyroxasulfone 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.

**Author details**

Timothy L. Grey* and Larry J. Newsom

*Address all correspondence to: tgrey@uga.edu

1 Crop and Soil Sciences Department, University of Georgia, Tifton, Georgia, United States
2 Crop Protection USA, BASF Corp., Tifton, Georgia, United States

**References**

[1] Bond J.A., Eubank T.W., Bond R.C., Golden B.R., Edwards H.M. Glyphosate-resistant Italian ryegrass control with fall residual herbicides. 2014. *Weed Technology* 28:361–370.

[2] Hasherm A., Bowran D., Piper T. Dhammu H. Resistance of wild radish (*Raphanus raphanistrum*) to acetolactate synthase-inhibiting herbicides in the Western Australia Wheat Belt. 2001. *Weed Technology* 15:68–74.

[3] Lacefield G., Collins M., Henning J., Phillips T., Rasnake M., Spitaleri R., Grigson D., Turner K. Annual Ryegrass AGR-179. 2003. University of Kentucky Cooperative Extension Service, University of Kentucky College of Agriculture, Lexington, and Kentucky State University, Frankfort, KY.

[4] Heap I. The international survey of herbicide resistant weeds. 2016. www.weedscience.org [Accessed 2016-09-12].

[5] Henderson J. Italian ryegrass. In Henderson’s Hand-book of the grasses of Great Britain and America. 1875. Suffolk County Journal and Publishing Company, Northport, L.I., NY.

[6] Webster T.M., MacDonald G.E. A survey of weeds in various crops in Georgia. 2001. *Weed Technology* 15:771–790.

[7] Webster T.M. Weed survey—southern states: small grains and wheat subsections. 2000. *Proceedings of Southern Weed Science Society*. Tulsa, OK. pp. 263–274.
[8] Webster T.M. Weed survey—southern states: small grains and wheat subsections. 2004. *Proceedings of Southern Weed Science Society*. Memphis, TN. pp. 417–426.

[9] Webster T.M. Weed survey—southern states: small grains and wheat subsections. 2008. *Proceedings of Southern Weed Science Society*. Jacksonville, FL. pp. 235–243.

[10] Webster T.M. Weed survey—southern states: small grains and wheat subsections. 2012. *Proceedings of Southern Weed Science Society*. Charleston, SC. pp. 278–288.

[11] Stone, M. J., Cralle H.T., Chandler J.M., Miller T.D., Bovey R.W., Carson K.H. Above- and below ground interference of wheat by Italian ryegrass. 1998. *Weed Science* 46:438–441.

[12] Ball D.A. Comparative above-ground development rates for several annual grass weeds and cereal grains. 1995. *Weed Science* 43:410–416.

[13] Liebl R., Worsham A.D. Interference of Italian ryegrass in wheat. 1987. *Weed Science* 35:819–823.

[14] Appleby A.P., Colbert D.R., Olson P.D. Winter wheat yield reduction from interference by Italian ryegrass. 1976. *Agronomy Journal* 68:463–466.

[15] Eslami S.V., Gill G.S., McDonald G. Wild radish interference in wheat. 2006. *Weed Science* 54:749–756.

[16] Schroeder J. Wild radish control in soft red winter wheat. 1989. *Weed Science* 37:112–116.

[17] Hashem A., Radosevich S.R., Dick R. Competition effects on yield, tissue nitrogen, and germination of winter wheat and Italian ryegrass. 2000. *Weed Technology* 14:718–725.

[18] Walsh M.J., Fowler T.M., Crowe B., Ambe T., Powles S.P. The potential for pyroxasulfone to selectively control resistant and susceptible rigid ryegrass (*Lolium rigidum*) biotypes in Australian grain crop production systems. 2011 *Weed Technology* 25:30–37.

[19] Walsh M.J., Powles S.B., Beard Multiple-herbicide resistance across four modes of action in wild radish. 2004. *Weed Science* 52:8–13.

[20] Norman A.G., Minarik C.E., Weintraub R.L. Herbicides. 1950. *Annual Review of Plant Physiology* 1:141–168.

[21] Kuk Y.I., Burgos N.R., Talbert R.E. Cross- and multiple resistance of diclofop resistant *Lolium* spp. 2000. *Weed Science* 48:412–419.

[22] Betts, K.J., Ehlke N.J., Wyse D.L., Gronwald J.W., Somers D.A. Mechanism of inheritance of diclofop resistance in Italian ryegrass. 1990. *Weed Science* 40:184–189.

[23] Stranger C. E., Appleby A.P. Italian ryegrass accessions tolerant to diclofop. 1989. *Weed Science* 37:350–352.

[24] Bravin F., Zanin G., Preston C. Diclofop-methyl resistance in populations of *Lolium* spp. from central Italy. 2001. *Weed Research* 41:49–58.

[25] De Prado J.L., De Prodo, R.A., Shimabukuro R.H. The effect of diclofop on membrane potential, ethylene induction, and herbicide phytotoxicity in resistant and susceptible biotypes of grasses. 1999. *Pesticide Biochemistry and Physiology* 63:1–14.
[26] De Prado R.A., Gonzalez-Gutierrez J., Menendez J., Gasquez J., Gronwald J.W., Gimenez-Espinosa R.E. Resistance to acetyl CoA carboxylase-inhibiting herbicides in *Lolium multiflorum*. 2000. *Weed Science* 48: 311–318.

[27] Eberlein C.V., Guttieri J.J., Berger P.H., Fellman J.K., Mallory-Smith C.A., Thill D.C., Baerg R.J., Belknap W.R. Physiological consequences of mutation of ALS-inhibitor resistance. 1999. *Weed Science* 47: 383–392.

[28] Marth P.C., Mitchell J.W. 2,4-Dichlorophenoxyacetic acid as a differential herbicide. 1944. *Botanical Gazette* 106:224–232.

[29] Klingman D.L. Effects of spraying cereals with 2,4-dichlorophenoxyacetic acid. 1947. *Journal of American Society of Agronomy* 39:445–447.

[30] National Agricultural Statistics Service (NASS). National Agricultural Statistics Service U.S. Dept. of Agri. Published Estimates Database. NASS-USDA, Washington, DC. 2016. http://www.nass.usda.gov/Statistics_by_Subject/Environmental/index.asp [Accessed 2016-09-15].

[31] Grey T.L., Bridges D.C. Alternatives to diclofop for the control of Italian ryegrass in winter wheat. 2006 *Weed Technology* 17:219–223.

[32] Larson E. 2014 wheat variety evaluations for tolerance to metribuzin herbicide. Mississippi St. University Extension publication. 2014. http://www.mississippi-crops.com/2014/12/12/2014-wheat-variety-evaluations-for-tolerance-to-metribuzin-herbicide/ [Accessed 2016-09-15].

[33] Shaw D. R., Wesley M.T. Wheat cultivar tolerance and Italian ryegrass control with diclofop, BAY SMY 1500, and metribuzin. 1991. *Weed Technology* 5:776–781.

[34] Bhardwaj G. From pioneering invention to sustained innovation: herbicides at DuPont. 2007. *Chemical Heritage* 25:34–36.

[35] Maheswari S.T., Ramesh A. Adsorption and degradation of sulfosulfuron in soils. 2007. *Environmental Monitoring and Assessment* 127:97–103.

[36] Sarmah A.K., Sabadie J. Hydrolysis of sulfonylurea herbicides in soils and aqueous solutions: a review. 2002. *Journal of Agricultural and Food Chemistry* 50: 6253–6265.

[37] Ray T. B. The mode of action of chlorsulfuron: a new herbicide for cereals. 1982. *Pesticide Biochemistry and Physiology* 17:10–17.

[38] LaRossa R.A., Schloss J.V. The sulfonylurea herbicide sulfometuron methyl is an extremely potent and selective inhibitor of acetolactate synthase in Salmonella typhimurium. 1984. *Journal of Biological Chemistry* 259:8756–8757.

[39] Shaner D. Herbicide Handbook. 10th ed. 2014. Lawrence, KS: Weed Science Society of America.

[40] Chandi A., York A.C., Jordan D.L., Beam J.B. Resistance to acetolactate synthase and acetyl Co-A carboxylase inhibitors in North Carolina Italian ryegrass. 2011. *Weed Technology* 25:659–666.
[41] Liu M., Hulting A.G. Mallory-Smith C. Characterization of multiple herbicide-resistant Italian ryegrass populations from winter wheat fields in Oregon. 2016. *Weed Science* 64:331–338.

[42] Boutsalis P, Gill GS, Preston C. Control of rigid ryegrass in Australian wheat production with pyroxasulfone. 2014. *Weed Technology* 332–339.

[43] Nakatani M., Yamaji Y., Honda H., Uchida Y. Development of the novel pre-emergence herbicide pyroxasulfone. 2016. *Journal of Pesticide Science* 41:107–112.

[44] Tanetani Y., Fujioka T., Kaku K., Shimizu T. Studies on the inhibition of plant very-long-chain fatty acid elongase by a novel herbicide pyroxasulfone. 2011. *Journal of Pesticide Science* 36:221–228.

[45] Mueller T.C., Steckel L.E. Efficacy and dissipation of pyroxasulfone and three chloroacetamides in a Tennessee field soil. 2011. *Weed Science* 59:574–579.

[46] Westra E.P., Westra P.H., Chapman P.L. Dissipation and leaching of pyroxasulfone and S-metolachlor. 2014. *Weed Technology* 28:72–81.

[47] Anonymous A. Zidua Herbicide Specimen Label, 2016-FIE-0001-form1886-D. Research Triangle Park, MC: BASF Corporation. 2016. http://www.cdms.net/Label-Database [Accessed 2016-09-14].

[48] Anonymous B. Anthem FLEX Herbicide Specimen Label. FMC Corporation, Ag. Products Group 1735 Market Street, Philadelphia, PA 19103. 2016. http://www.cdms.net/Label-Database [Accessed 2016-09-14].

[49] Anonymous C. Fierce Herbicide Specimen Label, 59639-193. Valent USA Corporation. P.O. Box 8025 Walnut Creek, CA 94596-8025. 2016. http://www.cdms.net/Label-Database [Accessed 2016-09-14].

[50] Grier L.A. Winter wheat tolerance to and weed control with pyroxasulfone. 2016. Thesis submitted to the Graduate Faculty of N.C. State University. Online at www.repository.lib.ncsu.edu [Accessed 2016-09-14].

[51] Lawrence N.C., Burke I.C. Control of rattail fescue in no-till winter wheat. 2014. *Weed Technology* 28:471–478.

[52] Hutling AG, Dauer JT, Hinds-Cook B, Curtis D, Koepke-Hill RM, Mallory-Smith C. Management of Italian ryegrass in western Oregon with preemergence applications of pyroxasulfone in winter wheat. 2012. *Weed Technology* 26:230–235.

[53] Zadoks JC, Chang TT, Konzak DF. A decimal code for the growth stages of cereals. 1974. *Weed Research* 14:415–421.

[54] SAS Institute I. SAS/STAT® 9.2 User’s Guide: World Headquarters. 2012. SAS Institute Inc. 100 SAS Campus Drive, Cary, NC.

[55] Sikkema P.H., Shropshire C., Soltani N. Dry bean response to preemergence-applied KIH-485. 2007. *Weed Technology* 21:230–234.
