Weed Technology 2012 26:405–409

Imidazolinone-Resistant Soft Red Winter Wheat Weed Control and Crop Response to ALS-Inhibiting Herbicides

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Inability to control Italian ryegrass in soft red winter wheat can result in reduced yields, reduced quality, or both and cause double-crop planting to be inefficient. Experiments were conducted at Plains, GA, to evaluate diclofop-susceptible Italian ryegrass control in a single-gene imidazolinone (IMI)-resistant wheat using imazamox, mesosulfuron, and diclofop. Treatments were applied at variable rates and tank mixtures to the IMI-resistant soft red winter wheat 'AGS CL7' at Feekes' stages 1 (EMERG) or 2 (POST). Lower Italian ryegrass control of 78% or less was observed with single treatments of EMERG or POST herbicide applications. Diclofop provided maximum Italian ryegrass control of 79% or greater with minimal injury to wheat cultivar AGS CL 7. Sequential applications of diclofop at EMERG followed by imazamox, mesosulfuron, or diclofop POST provided maximum Italian ryegrass control at 86% or greater. The efficacy of the acetolactate synthase (ALS)–inhibiting herbicides registered for wheat weed control for AGS CL7 and 'AGS 2000' (conventional) was also evaluated. Mesosulfuron at 40 g ai ha^{-1} resulted in 17% injury at 7 d after application (DAA), tribenuron at 40 g ai ha^{-1} caused 9% injury 7 DAA, and pyroxsulam at 190 g ai ha^{-1} caused 7% injury at 7 DAA, but was transient and not observed after heading or at harvest. No yield differences were noted between the nontreated control for AGS 2000 and AGS CL 7 for chlorsulfuron, mesosulfuron, thifensulfuron, tribenuron, prosulfuron, and pyroxsulam.

Nomenclature: Chlorsulfuron; dicoflop; imazamox; mesosulfuron; prosulfuron, *N*-[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)amino]carbonyl]-2-(3,3,3-trifluoropropyl)benzenesulfonamide; pyroxsulam, *N*-(5,7-dimethoxy[1,2,4]triazolo[1,5-*a*]pyrimidin-2-yl)-2-methoxy-4- (trifluoromethyl)-3-pyridinesulfonamide; thifensulfuron; tribenuron; Italian ryegrass, *Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot LOLMU; wheat, *Triticum aestivum* L., 'AGS 2000', 'AGS CL 7'.
Key words: Wheat herbicide tolerance, winter wheat weed control, herbicide-resistant wheat.

La inhabilidad para controlar *Lolium perenne* en el trigo rojo suave de invierno puede resultar en reducción de rendimientos y/o calidad y causar que la doble siembra de este cereal sea ineficiente. Se realizaron experimentos en Plains, Georgia para evaluar el control de *L. perenne* susceptible a diclofop en trigo con un solo gen de resistencia a imidazolinone (IMI), usando imazamox, mesosulfuron y diclofop. Los tratamientos se aplicaron a dosis y mezclas variables a la variedad de trigo AGS CL7 resistente a IMI en las etapas Feekes 1 (EMERG) o 2 (POST). Un control bajo de *L. perenne* de 78% o menos, fue observado con tratamientos de una aplicación de herbicida en EMERG o POST. Diclofop proporcionó el mayor control de *L. perenne* de 79% o más, con daño mínimo al cultivar de trigo AGS CL 7. Las aplicaciones secuenciales de diclofop en EMERG seguidas de imazamox, mesosulfuron, o diclofop POST proporcionaron el máximo control de *L. perenne*, 86% o mayor. La eficacia de los herbicidas inhibidores acetolactate synthase (ALS) registrada para el control de malezas en trigo para los cultivares AGS CL7 y AGS 2000 (convencional) también fue evaluada. Mesosulfuron a 40 g ia ha^{-1} resultó en 17% de daño a los 7 días después de la aplicación (DAA); tribenuron a 40 g ia ha^{-1} causó 9% de daño a los 7 DAA; pyroxsulam a 190 g ia ha^{-1} causó 7% de daño a los 7 DAA, pero éste fue transitorio y no fue observado después de la floración o en la cosecha. No se notaron diferencias en el rendimiento entre los testigos no tratados para AGS 2000 y AGS CL 7 y los tratamientos con chlorsulfuron, mesosulfuron, thifensulfuron, tribenuron, prosulfuron y pyroxsulam.

Soft red winter wheat is an important winter crop throughout much of the southern United States, and it is a component of many double-crop production systems in which soybean or cotton are seeded immediately after wheat harvest (Culpepper and York 1997). Italian ryegrass in wheat is a common and troublesome weed throughout this region (Webster 2008; Webster and MacDonald 2001). However, Italian ryegrass is widely used for hay and pasture forage in the southeast, with commercial seed production in the northwestern United States. It is yearly sown in the region, which perpetuates its spread. Inability to control Italian ryegrass in soft red winter wheat can result in reduced yields, reduced quality, or both and can cause double-crop planting to be inefficient. Producer's burn wheat stubble after harvest to improve double-crop planting efficiency, but this is an environmental issue. Producers can use a subsoil shank as they plant double crops to promote root growth; wheat stubble can hinder this operation by building up on the shank.

Diclofop can be used for PRE or POST control of Italian ryegrass (Justice et al. 1994; Robinson and Banks 1983; Shaw and Wesley 1991) but can be ineffective or have unacceptable crop injury. Diclofop control failures have also been associated with diclofop-resistant Italian ryegrass. Italian ryegrass resistance to diclofop was first reported in 1987 in Oregon (Betts et al. 1992; Stranger and Appleby 1989). It has subsequently been noted in the southeastern United States (Heap 2003; Kuk et al. 2000) and throughout the world (Betts et al. 1992;

DOI: 10.1614/WT-D-11-00122.1

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Bravin et al. 2001; De Prado, et al. 1999, 2000; Eberlein et al. 1999). Grass resistance to diclofop in the United States has increased rapidly since 1990 and has been reviewed by Kuk et al. (2000). The widespread evolution of diclofop resistance in Italian ryegrass reduces control options in wheat and decreases the potential of wheat in double-crop production systems.

Imidazolinone herbicide–resistant wheat was first developed in 1992 (Newhouse et al. 1992) using mutagenesis and, with breeding, subsequently developed as Clearfield® cultivars. The development history was reviewed by Hanson et al. (2006). In 2000, the University of Georgia small grains breeding program began using traditional breeding techniques and screening with imazamox in greenhouse and field experiments to develop Clearfield cultivars with the single resistance gene. In 2007, the first cultivar from the University of Georgia was identified for release as 'AGS CL 7' containing the single resistance gene on the D-genome (Johnson 2010).

Imazamox is registered for use on Clearfield wheat cultivars. Imazamox is a member of the imidazolinone (IMI) family of herbicides, along with imazapic, imazethapyr, and several other herbicides that are used in Clearfield crop production. Currently Clearfield corn (*Zea mays* L.), rice (*Oryza sativa* L.), canola (*Brassica napus* L.), wheat, and sunflower (*Helianthus annuus* L.) are cropping systems used in the United States. However, until recently, no Clearfield wheat cultivars were adapted to the southeastern United States, so the use of this technology has been unavailable to farmers of this region.

Although Clearfield wheat is associated with imidazolinone herbicides, other acetolactate synthase (ALS)–inhibiting herbicides can be used in all soft red wheat systems. Mesosulfuron is a sulfonylurea that provides annual ryegrass control in winter wheat (Bayer 2007). Injury in conventional wheat (Culpepper 2007), oat (*Avena* spp.), and rye (MacCrae et al. 2007) have been reported that occurred after treatment with mesosulfuron. However, farmers often must use mesosulfuron because it is their only option if they have diclofop-resistant Italian ryegrass. It can be applied POST for Italian ryegrass control from the two-leaf stage to the end of wheat tillering, providing effective residual weed control (Crooks and York 2002). Other ALS-inhibiting herbicides registered for soft red winter wheat production include thifensulfuron, chlorsulfuron, prosulfuron, and tribenuron. These herbicides control many different weeds but have warnings about potential wheat injury (Culpepper 2007).

With the introduction of Clearfield AGS CL 7 wheat in the southeastern United States, farmers will soon have the option to incorporate newer technologies into their crop production. Currently, little information is available about the spectrum of weeds controlled with imazamox in wheat for this region. Additionally, other ALS-inhibiting herbicides could also be used in Clearfield wheat, but no information is available as to their effect on growth, development, or yield on AGS CL 7 compared with a conventional cultivar, 'AGS 2000'.

To evaluate the use of ALS-inhibiting herbicides in Clearfield wheat systems, field experiments that emphasize weed control, crop response, and yield as standards to measure their potential use were conducted. The objectives of the experiments were (1) to evaluate Italian ryegrass control for the wheat cultivar AGS CL7 with diclofop and other ALS-inhibiting herbicides and (2) to evaluate efficacy of ALS-inhibiting herbicides labeled for wheat production at various rates on AGS CL7 and a non–IMI-resistant cultivar, AGS 2000.

Materials and Methods

Experiments were conducted from 2007 to 2008 and 2008 to 2009 in the same field at the Southwest Georgia Branch Experiment Station located near Plains, GA. Soil was a Faceville sandy loam (clayey, kaolinitic, thermic, Typic Kandiudults) with 1.6% organic matter and pH 6.0 to 6.1. All plots were disk harrowed and moldboard plowed 25 to 30 cm deep, then rotary tilled. Single plots were drilled 1.8 m wide and 9.1 m long, with six rows of wheat per plot, 19 cm apart. All herbicides were applied with a CO_2-pressurized sprayer calibrated to deliver 140 L ha^{-1} at 172 kPa.

Weed Control. For the weed control experiments, a Clearfield cultivar developed at the University of Georgia, AGS CL7 (Johnson 2010) was planted at 112 kg ha^{-1} on November 19, 2007, and November 25, 2008. Herbicide treatments were applied on December 4, 2007, when wheat was in coleoptile Feekes' stage 1 (EMERG) and on December 18, 2007, when wheat was in Feekes' stage 2 (POST); for the repeated experiment, the EMERG treatments were applied December 9, 2008, and POST treatments were applied on January 7, 2009. Treatments included imazamox at 40 or 80 g ai ha^{-1} at EMERG or POST; mesosulfuron at 20 or 40 g ai ha^{-1} at EMERG or POST; diclofop at 570 or 1,130 g ai ha^{-1} at EMERG or POST; diclofop at 570 g ai ha^{-1} at EMERG followed by (fb) imazamox at 40 g ai ha^{-1} POST; diclofop at 570 g ai ha^{-1} at EMERG fb mesosulfuron at 20 g ai ha^{-1} POST; or diclofop at 570 g ai ha^{-1} at EMERG fb diclofop at 570 g ai ha^{-1} POST. All treatments except diclofop received a non-ionic surfactant at 0.25% (v/v) and UAN (30%) at 4.7 L ha^{-1}. After planting wheat, Italian ryegrass seed was drilled perpendicular to the back 1.8 m of each plot at 45 kg ha^{-1}. Italian ryegrass emerged with wheat, and the final population was 250 plants m^{-2} each year. Italian ryegrass control was visually estimated on a scale of 0% (no injury) to 100% (death), and wheat injury was evaluated on the same scale. All grain was harvested using a small-plot combine, moisture was determined, and then final yields were established.

Crop Tolerance. For the cultivar tolerance experiment, two wheat cultivars were sown on November 16, 2007, and November 19, 2008. The cultivars AGS 2000 (Johnson et al. 2002) and AGS CL7 were planted at 112 kg ha^{-1}. Treatments for the efficacy experiment included chlorsulfuron at 30 or 60 g ai ha^{-1} applied PRE, mesosulfuron at 20 or 40 g ai ha^{-1} applied to one- to two-leaf wheat when in Feekes' stage 1 (EPOST), thifensulfuron at 30 or 60 g ai ha^{-1} at EPOST, tribenuron at 20 or 40 g ai ha^{-1} at EPOST, prosulfuron at 30 or 60 g ai ha^{-1} at EPOST, and pyroxsulam 190 g ai ha^{-1} at EPOST. All treatments except chlorsulfuron received a non-ionic surfactant at 0.25% (v/v) and UAN

Table 1. Effect of herbicide treatment on Italian ryegrass control and Clearfield soft red winter wheat cultivar AGS CL 7 in Georgia.

Treatment	Rate	Timing	Injury[b]	Italian ryegrass[b]	Yield
g ai ha^{-1}	g ai ha^{-1}		%		kg ha^{-1}
Imazamox	40	EMERG[a]	0 c[c]	71 c–f	4,690 ab
		POST	5 bc	54 f	4,850 a
	80	EMERG	8 b	78 a–d	4,620 ab
		POST	22 a	70 c–f	3,760 c
Mesosulfuron	20	EMERG	3 bc	75 b–e	4,600 ab
		POST	0 c	60 ef	4,750 ab
	40	EMERG	7 c	60 ef	4,370 ab
		POST	0 c	69 d–f	4,800 ab
Diclofop	570	EMERG	0 c	86 a–c	4,840 ab
		POST	0 c	82 a–d	4,810 ab
	1,130	EMERG	0 c	95 a	4,700 ab
		POST	0 c	79 a–d	4,710 ab
Diclofop fb imazamox	570 fb 40	EMERG fb POST	1 c	86 a–c	4,860 a
Diclofop fb mesosulfuron	570 fb 20	EMERG fb POST	1 c	94 a	4,900 a
Diclofop fb diclofop	570 fb 570	EMERG fb POST	1 c	90 ab	4,940 a

[a] Abbreviations: EMERG, herbicides applied at wheat emergence in coleoptile at Feekes' stage 1; POST, herbicides applied to wheat in Feekes' stage 2.

[b] Data for site year experiments were considered fixed effects; therefore, data were combined for 2008 and 2009 injury, Italian ryegrass control, and yield data.

[c] Means within a variable followed by the same letter are not significantly different from each other according to Fisher's Protected LSD test at $P \leq 0.05$.

(30%) at 4.7 L ha^{-1}. Wheat injury and yield data were collected as previously described.

Statistical Analysis. Plots for all experiments were arranged in a randomized complete block design with four replications of treatments. Percentage data were arcsine–square root transformed to improve normality before analysis. All data were subjected to mixed model ANOVA. Data analysis using mixed model procedure indicated no differences for herbicide by cultivar interaction; therefore, data for cultivars were combined for presentation. Data for site year experiments were considered fixed effects; therefore, data were combined for 2008 and 2009 yield data. Means were separated using Fisher's protected LSD at the $P \leq 0.05$ level (SAS 2001). Data were back-transformed for presentation.

Results and Discussion

Differences for environmental measures were detected during the course of each experiment (data not shown). However, all experiments were conducted at times when herbicide applications could potentially occur in Georgia wheat production and are thus representative of producer practices. For the efficacy experiment comparing AGS 2000 and AGS CL7, no difference for any variable was detected; therefore, data for the two cultivars were combined for presentation.

Control Experiment. In the weed control experiment, wheat injury (> 5%) occurred with EMERG applications of mesosulfuron at 20 and 40 g ha^{-1} and imazamox at 80 g ha^{-1} (Table 1). Previously, it has been reported that 12 and 23% injury with mesosulfuron and imazamox treatments, respectively, can occur (Crooks et al. 2003; Frihauf et al. 2005). In hexaploid wheat, ALS resistance is conferred by gene(s) in the A, B, and D genomes. Some IMI-resistant wheat cultivars have been shown to carry a gene that is not resistant to IMI herbicides at high rates. Thus, when resistance is conferred only by a single gene, plant injury can occur (Pozniak et al. 2004a,b).

Severe wheat injury (21%) occurred with POST-applied imazamox at 80 g ha^{-1} (Table 1), which is similar to imazamox injury reported in experiments by Frihauf et al. (2005). However, no differences for grain yield among treatments were detected in this experiment, which is similar to results from Deeds et al. (2006). They reported that wheat recovered from imazamox injury by the end of the growing season had no effect on yield. However, recovery from imazamox injury can vary even between near-isogenic lines. Factors that can affect tolerance to imazamox application include the physiological state of the plant at application, the expression of resistant genes, and other fitness factors (Hanson et al. 2007).

Less Italian ryegrass control (< 60%) was observed with all treatments containing only POST applications. These findings are consistent with other experiments that concluded that POST treatments are not effective in controlling Italian ryegrass when treatments are applied PRE (Liebl and Worsham 1987; Wilson and Hines 1997). Italian ryegrass has greater resistance to ALS-inhibiting herbicides at the whole-plant level, indicating that metabolism is involved (Kuk and Burgos 2007). This suggests that mature plants are more able to metabolize herbicide treatments and survive.

Diclofop achieved the highest levels of Italian ryegrass control and allowed for minimal crop injury. However, other treatments evaluated could be used in cases of Italian ryegrass resistance to diclofop. Several Italian ryegrass accessions resistant to diclofop have been shown to have multiple resistances to herbicides with the same or different modes of action (Kuk and Burgos 2007). Another major issue in ALS-resistant ryegrass has been reported by multiple scientists around the world (Ellis et al. 2008; Yu et al. 2008). From previous experiments, it has been reported that Italian ryegrass accessions resistant to mesosulfuron were also resistant to other ALS inhibitors, such as chlorsulfuron, imazamox, and sulfometuron. However, these accessions were not resistant to diclofop or glyphosate (Kuk and Burgos 2007). (transpose) This lack of cross-resistance between modes of action indicates that Italian ryegrass can be controlled by rotating modes of action.

https://doi.org/10.1614/WT-D-11-00122.1 Published online by Cambridge University Press

Table 2. Effect of herbicide treatment on soft red winter wheat[a] in Georgia.

Treatment	Rate	Timing	Injury	Yield
	g ai ha^{-1}		—— % ——	——kg ha^{-1}——
Chlorsulfuron[c]	30	PRE[b]	0 c[d]	3,120 a
	60	PRE	4 bc	3,280 a
Mesosulfuron	20	EPOST	9 ab	2,810 a
	40	EPOST	17 a	2,920 a
Thifensulfuron	30	EPOST	3 bc	3,100 a
	60	EPOST	3 bc	3,180 a
Tribenuron	20	EPOST	5 bc	3,230 a
	40	EPOST	9 ab	3,280 a
Prosulfuron	30	EPOST	0 c	3,250 a
	60	EPOST	2 bc	3,260 a
Pyroxsulam	190	EPOST	7 bc	3,180 a
Nontreated	—	—	0 c	3,320 a

[a] Wheat cultivars evaluated included AGS 2000 and AGS CL7, a Clearfield cultivar. Data analysis using mixed model procedure indicated no differences for herbicide by cultivar interaction; therefore, data for cultivars were combined for presentation. Data for site year experiments were considered fixed effects; therefore, data were combined for 2008 and 2009 yield data.

[b] Abbreviations: PRE, preemergence herbicides applied at planting; POST, herbicides applied to wheat in Feekes' stage 1; EPOST, herbicides applied at wheat emergence in coleoptile at Feekes' stage 1.

[c] All treatments, except diclofop, received a non-ionic surfactant at 0.25% (v/v) and UAN (30%) at 4.7 L ha^{-1}.

[d] Means within a variable followed by the same letter are not significantly different from each other according to Fisher's Protected LSD test at $P \leq 0.05$.

A continuation of this experiment is needed to further evaluate other ALS-inhibiting herbicides that could be used in this capacity.

Crop Tolerance. Efficacy experiments indicated no herbicide by cultivar interactions for any variables were detected; therefore, data were combined by cultivar for presentation (Table 2). Mesosulfuron caused significant stunting 7 d after application (DAA; 9 and 17% for 20 and 40 g ha^{-1}, respectively) and continued to have significant stunting through 34 DAA (data not shown). Bailey et al. (2004) reported 29% stunting for mesosulfuron at 21 DAA for AGS 2000. Stunting occurred with pyroxsulam (7%) at 190 g ha^{-1} 7 DAA. All other treatments were not different from the nontreated control. By harvest, no injury was observed. In contrast, Grey and Bridges (2003) reported 18% wheat injury from chlorsulfuron at 44 DAA and 10% at 151 DAA for the wheat cultivar 'Dozier'. Wheat rapidly metabolizes chlorsulfuron, which is why it is tolerant to this and other sulfonylurea herbicides (Brown 1990). Thus, as plants mature, they are able to grow out of any initial injury sustained from sulfonylurea herbicides. This was observed for the wheat cultivars AGS 2000 and AGS CL 7. The highest yield of 3,320 kg ha^{-1} was observed with the nontreated control (Table 2). No differences were detected for any wheat herbicide treatment. On the basis of these data, it is concluded that AGS CL 7 imidazolinone-resistant wheat exhibits similar responses to ALS-inhibiting herbicides compared with AGS 2000.

Control of a diclofop-sensitive population of Italian ryegrass in conventional-tillage wheat plantings was only achieved with diclofop applied at Feekes' stage 1 (EMERG) followed by POST-applied imazamox, mesosulfuron, or diclofop (Table 1). Imazamox or mesosulfuron alone at Feekes' stages 1 or 2 (EMERG or POST applications) to AGS CL 7 wheat resulted in < 78% Italian ryegrass control, which growers would find unacceptable because of reduced yield and foreign material contamination, lowering test weights and increasing dockage fees. Although diclofop alone at these same timings controlled Italian ryegrass 79 to 95%, the many reports of diclofop-resistant Italian ryegrass predict that diclofop treatments will not continue to be effective (Betts et al. 1992; Bravin et al. 2001; De Prado et al. 1999, 2000; Eberlein et al. 1999) and that alternatives will be needed for successful wheat production. Additionally, the ALS-inhibiting herbicides chlorsulfuron, mesosulfuron, thifensulfuron, and tribenuron did not negatively affect yield of the single-gene imidazolinone-resistant AGS CL 7 cultivar compared with the conventional cultivar AGS 2000.

Future research should emphasize the use of other imidazolinone herbicides used in this region for weed control in wheat. Two-gene imidazolinone-resistant wheat (Hanson et al. 2006) cultivars are currently in development at the University of Georgia for the southeastern United States and should be evaluated similarly for weed control and efficacy.

Acknowledgments

The authors thank Charlie Hilton, Jess Parker, Rebekah Wallace, Dan Bland, Steve Sutton, Ronnie Pines, and the Southwest Georgia Research and Education Center. The University of Georgia Coastal Plain Experiment Station provided land and irrigation for crop production.

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Received September 3, 2011, and approved February 14, 2012.

https://doi.org/10.1614/WT-D-11-00122.1 Published online by Cambridge University Press