Australian Journal of Crop Science
AJCS

AJCS 17(11):855-861 (2023) ISSN:1835-2707
doi: 10.21475/ajcs.23.17.11.p4013

A field study on the combined use of pre-emergence herbicide and Clearfield® technology for ryegrass management in wheat crops

Lariane Fontana de Freitas[1], Diogo Luiz Fruet[1], Mayra Luiza Schelter[1], Marissa Prá de Souza[1], Naiara Guerra[2], Antonio Mendes de Oliveira Neto[1]

[1]Universidade do Estado de Santa Catarina (UDESC/CAV), Av. Luiz de Camões, 2090, Conta Dinheiro, 88520-000, Lages, SC, Brazil
[2]Universidade Federal de Santa Catarina (UFSC), Rodovia Ulysses Gaboardi, 3000, 89520-000, Curitibanos, SC, Brazil

***Corresponding author: fontana.lariane@gmail.com**

Abstract

Weed interference in wheat crops are known to cause productivity losses. The objective of this work was to evaluate pre-emergence herbicide application efficiency combined with Clearfield® technology (CL) in ryegrass (*Lolium multiflorum*) management in wheat crops. A field experiment was conducted from July 2020 to December 2021 using randomized block design in a 2×5 factorial arrangement with four replications. Treatments consisted of combinations of pre-emergence herbicide application - without and with pendimethalin at 1365 g a.i. ha^{-1} (in 2020 crop season) or without and with pyroxasulfone at 125 g a.i. ha^{-1} (in 2021 crop season) and post-emergence herbicide application - without application; imazamox at 49, 70, and 91 g a.i. ha^{-1}, or pyroxsulam at 18 g a.i. ha^{-1}. Wheat cultivars used were TBIO Capricho CL® and TBIO Ello CL®. The following characteristics were evaluated: phytotoxicity, ryegrass control, plant height, number of spikes m^{-2}, mean spike weight, 100-grain weight, and grain yield. Treatments phytotoxicity did not exceed 5%, being visible only at 7 DAA, from 14 DAA no injury was observed. The combined application of pre-emergence herbicides pendimethalin or pyroxasulfone with post-emergence herbicides imazamox or pyroxsulam provided superior control of ryegrass than the isolated applications. This management resulted in ryegrass control ranging from 88.8% to 100% in 2020 and from 82.3% to 100% in 2021. In general, grain yield was also higher in treatments with combined pre- and post-emergence applications. The pre-emergence herbicide application in combination with CL technology was effective in managing ryegrass, preventing weed interference, and ensuring the productive potential of wheat crops.

Keywords: chemical control; imazamox; *Lolium multiflorum*; pyroxasulfone; *Triticum aestivum*.
Abbreviations: ACCase_acetyl-CoA carboxylase; Al_aluminium; ALS_acetolactate synthase; CAV_Agroveterinary Science Center; CL_Clearfield® technology; CO_2_Carbon dioxide; CEC_cation exchange capacity; CV_cultivar; DAA_days after the application of post-emergence; DAE_days after emergence; EPSPs_ 5-enolpyruvylshikimate-3-phosphate synthase; K_potassium; N_nitrogen; P_phosphorus; UDESC_Santa Catarina State University; V%_ base saturation; VLCFA_very long chair fatty acids.

Introduction

Wheat is an annual crop species that belongs to the Poaceae family (Liliopsida) and the *Triticum* genus. The species of this genus that presents the highest commercial interest is *Triticum aestivum* L. (common wheat), which is widely used in bakery products, production of cookies, cakes, and confectionery products. When wheat grains do not reach enough quality for bakery products, they can be used as animal feed (Embrapa, 2021). According to data of the Brazilian National Food Supply Company (Conab, 2022), this crop occupies the world's first place in production volume, the largest productions are (million Mg): the European Union (38.9), China (136.9), India (109.5), Russia (75), the USA (44.7), Australia (34), Urania (33), Pakistan (27), Canada (21.6), and Argentina (20.5). It is the main winter crop grown in Brazil. However, the wheat volume produced does not meet the domestic demand, thus, the national wheat supply (grains and flour) depends on imports, mainly from Argentina, the main commercial partner of Brazil in this sector (Souza and Vieira Son, 2021).

Weeds are among the main yield limiting biotic factor of several crops (Shennan, 2007), including wheat, since the interference of weeds is a limiting factor of its economic yield potential and production (Vargas and Bianchi, 2011). Weeds present fast germination, abundant root system, and high-water use efficiency, resulting in aggressiveness and intense competition with crops for environmental resources (Gazziero et al., 2008).

Ryegrass (*Lolium multiflorum*) is one of the main weeds in wheat crops in the South region of Brazil and a challenge for weed management because it is widely used as soil cover crop and is difficult to control, as it belongs to the same crop family as wheat (Vargas et al., 2008). In addition, it is easily dispersed, infesting most winter crops in the South region of Brazil (Vargas and Roman, 2006). In Brazil, there are cases of simple resistance of ryegrass to the herbicides glyphosate

(EPSPs) and iodosulfuron (ALS), and cases of multiple resistance to the herbicides clethodim (ACCase) and glyphosate (EPSPs); clethodim (ACCase) and iodosulfuron (ALS); and glyphosate (EPSPs) and iodosulfuron (ALS) (Heap, 2022). It is mainly due to inappropriate and repeated use of these herbicides, which results in difficulties in controlling ryegrass and in reduced options of herbicides in the national market.

Weed control in wheat crops is still a challenge regarding management strategies; thus, the launching of cultivars resistant to herbicides of the imidazolinone chemical group, known as Clearfield® (CL) technology (Basf, 2004), is one of the current alternatives for the management of ryegrass. According to Breccia et al. (2018), herbicides of this chemical group control mainly *Avena fatua* and *Lolium multiflorum*, which are grass species of world-occurrence in wheat crops. The resistance of these wheat cultivars was the result of a mutation induced in the seeds; the mechanism of resistance of these cultivars is due to the presence of a mutated form of the enzyme acetolactate synthase (ALS), which decreased the affinity of the enzyme with herbicides of the imidazolinone chemical group (Jimenez et al., 2016). The ALS enzyme is responsible for synthesis of the branched chain amino acids valine, leucine, and isoleucine (Tan et al., 2005).

According to Bremer et al. (2011), herbicides of the imidazolinone chemical group have a broad spectrum of control. They are applied in post-emergence, have favorable toxicological profile and can be used in no-tillage and conventional soil preparation systems. However, despite it is an efficient system, it requires a repeated and continued use, since the selection of weeds resistant to these herbicides can occur, decreasing the effectiveness and useful life of this technology (Tomm et al., 2017). The preservation of its efficiency requires crop rotation and searching for practices focused on minimizing the selection of plants resistant to ALS. The adequate use of herbicide-tolerant cultivars and the adoption of combined agronomic practices can increase the biodiversity of agricultural areas and reduce the risk of development of weeds resistant to herbicides (Domínguez et al., 2017).

Despite the increases in availability of post-emergence herbicides, pre-emergence herbicide application is an important strategy for prevention or management of resistant weeds (Inoue et al., 2011). Pre-emergence herbicides have higher residual effects, maintaining the crop free from competition with weeds in the critical period of weed interference (Velini et al., 2000). Pendimethalin is a pre-emergence herbicide whose mechanism of action is the inhibition of cell division by preventing polymerization of tubulin, inhibiting the growth of the radicle and the formation of secondary roots (Oliveira Neto et al., 2011), and is selective for wheat crops (Borgo and Rosito, 1977). Pyroxasulfone is among the recently launched molecules in Brazil for weed control (Novais et al., 2021); it is also selective for wheat crops (Daily of Unity, 2020). It inhibits the biosynthesis of very long chain fat acids (VLCFA), providing the control of mainly grass species when using pre-emergence application (Tanetani et al., 2009; Tanetani et al., 2012).

Therefore, the hypothesis is that the combining pre-emergence application with post-emergence application can ensure a higher ryegrass control when compared to their isolated pre- or post-emergence applications. Therefore, the objective of this work was to evaluate the efficiency of pre-emergence herbicide application combined with the CL technology the management of ryegrass in wheat crops.

Results and discussion

2020 Crop season – Cultivar TBIO Capricho CL®

Injury and ryegrass control

The phytotoxicity was considered mild at 7 DAA in all treatments; the highest grade (3.5%) was found in the treatment with pre-emergence application of pendimethalin (1365 g a.i. ha^{-1}) and post-emergence application of imazamox (49 g a.i. ha^{-1}) (Table 2). The evaluation at 14 DAA showed no visual symptoms of phytotoxicity (data not shown).

The ryegrass control at 7 DAA presented no significant differences between treatments (Table 2); the highest control (73.8%) was found in the treatment with pendimethalin (1365 g a.i. ha^{-1}) + imazamox (49 g a.i. ha^{-1}). Significant difference was found at 14 DAA, mainly between the combined pre- and post-emergence applications, which presented control of 87.0% in the treatment with pendimethalin (1365 g a.i. ha^{-1}) + imazamox (70 g a.i. ha^{-1}) (Table 2).

Effective control was found at 28 DAA, with results higher than 89.0% of control in all treatments, except for the isolated application of pendimethalin (1365 g a.i. ha^{-1}), which reached 63.8% (Table 2). No significant difference between the combined pre-emergence and post-emergence applications were found at the wheat pre-harvest (Table 2), but a 100% control was found in the treatment with pendimethalin (1365 g a.i. ha^{-1}) + imazamox (70 g a.i. ha^{-1}). In addition, lowest control was found in the treatment with isolated pre-emergence application of pendimethalin (1365 g a.i. ha^{-1}), resulting in 62% control of ryegrass (Table 2).

The control efficiency of post-emergence application of imazamox, isolated or combined with pre-emergence application was evaluated by Bond et al. (2005), who showed that sequential post-emergence applications of imazamox or combined with pre-emergence applications of pendimethalin were needed to optimize ryegrass control and increase CL wheat grain yield. They also reported that the combination pendimethalin (1.120 g a.i. ha^{-1}) + imazamox (54 g a.i. ha^{-1}) resulted in a ryegrass control higher than 94% at 30, 49, and 150 days after the wheat emergence.

In general, the combined pre- and post-emergence applications resulted in more efficient control of ryegrass in wheat crops. According to Clemmer et al. (2004), pendimethalin (1.120 g a.i. ha^{-1}) increases significantly the ryegrass control only when used combined with imazamox (35 g a.i. ha^{-1}). Tucker et al. (2002) also reported higher ryegrass control when pendimethalin was applied with imazamox.

Height, components of yield and grain yield

Plant height, number of spikes m^{-2}, mean spike weight and 100-grain weight presented no significant differences between treatments (Table 3). Grain yield (Table 3) presented significant difference between the control without herbicides and isolated application of pendimethalin (1365 g a.i. ha^{-1}), which showed means of 3.284 kg ha^{-1} and 4.412 kg ha^{-1}, respectively. Significant difference was also between the treatments without pre-emergence application of pendimethalin (1365 g a.i. ha^{-1}), with the highest grain yield (4.650 kg ha^{-1}) found in the treatment with imazamox (49 g a.i. ha^{-1}). This mean yield denotes that post-emergence application of imazamox at lower rates, with no pre-emergence application of pendimethalin, results in high grain yields, presenting economic advantage.

2021 Crop season - Cultivars TBIO Capricho CL® and TBIO Ello CL®

Injury and ryegrass control

The cultivar TBIO Ello CL® presented no significant phytotoxicity symptoms (Table 2). The cultivar TBIO Capricho CL® presented higher phytotoxicity at 7 DAA, reaching the maximum grade of 5% in the treatment with pyroxasulfone (125 g a.i. ha^{-1}) + imazamox (91 g a.i. ha^{-1}). The injuries found in plants of the cultivar TBIO Capricho CL® were similar to those reported by Clemmer et al. (2004) for the cultivar 9804; the injury percentages were low, lower than 5%, and the symptoms were mainly related to transitory chlorosis. This is a similar result to those reported by Ball and Peterson (2007) for the cultivar 9804 when applying imazamox (105 g a.i. ha^{-1}); they found 4% injury and transitory symptoms that disappeared over the evaluations.

The ryegrass control at 7 DAA for the cultivar TBIO Capricho CL® presented significant differences between the treatments with imazamox (91 g a.i. ha^{-1}) (22.5%) and pyroxsulam (18 g a.i. ha^{-1}) (12.0%) when compared these same rates combined with pre-emergence application of pyroxasulfone (125 g a.i. ha^{-1}), which resulted in means of 41.8% and 36.3%, respectively (Table 2). The evaluation at 14 DAA showed that treatments with combined pre- and post-emergence applications resulted, in general, in controls higher than those found with only post-emergence applications, with control percentages higher than 46.3%. (Table 2).

The same result of control was repeated at 28 DAA, with treatments with combined pre- and post-emergence applications resulting in higher control of ryegrass (>73.5%), when compared to treatments with only post-emergence applications (Table 2). The ryegrass control at the wheat pre-harvest for the cultivar TBIO Capricho CL® was, in general, higher in the treatments with combined pre- and post-emergence applications; the treatment with pyroxasulfone (125 g a.i. ha^{-1}) + pyroxsulam (18 g a.i. ha^{-1}) stood out with 97.5% control (Table 2).

The control at 7 DAA for the cultivar TBIO Ello CL® showed significant differences between treatments, mainly between imazamox (49 g a.i. ha^{-1}) without pyroxasulfone (125 g a.i. ha^{-1}) (23.5% control) and pyroxasulfone (125 g a.i. ha^{-1}) + imazamox (49 g a.i. ha^{-1}) (43.8% control) (Table 2). The ryegrass control at 14 DAA using pyroxsulam (18 g a.i. ha^{-1}) was significantly lower than that using pyroxasulfone (125 g a.i. ha^{-1}) + pyroxsulam (18 g a.i. ha^{-1}), presenting 45.5% and 82.5% control, respectively (Table 2).

The treatments with pre- and post-emergence applications of pyroxasulfone (125 g a.i. ha^{-1}) + imazamox (49 g a.i. ha^{-1}) and pyroxasulfone (125 g a.i. ha^{-1}) + imazamox (91 g a.i. ha^{-1}) were more effective for the ryegrass control at 28 DAA, with 76.8% and 81.5% control, respectively. These means were different for imazamox (49 g a.i. ha^{-1}) and imazamox (91 g a.i. ha^{-1}) only in the post-emergence application (Table 2).

A ryegrass control higher than 92.3% was found in most treatments at the wheat pre-harvest, except for post-emergence application of pyroxsulam (18 g a.i. ha^{-1}), which presented 83.5% control (Table 2). The ryegrass control means found at the wheat pre-harvest for the cultivar Ello CL® with no pre-emergence applications are consistent with those of Clemmer et al. (2004), who found ryegrass control between 90% and 98% at ten weeks after application of imazamox (35, 44 and 53 g a.i. ha^{-1}).

Height, components of yield and grain yield

The cultivar Capricho CL® presented no significant differences in plant height, whereas the cultivar Ello CL® presented lower plant height (76.0 cm) in the the treatment with isolated application of imazamox (49 g a.i. ha^{-1}), when compared to that with pyroxasulfone (125 g a.i. ha^{-1}) and imazamox (49 g a.i. ha^{-1}), which showed plant height of 87.3 cm (Table 3).

Regarding the production components of the Capricho CL®, the number of spikes m^{-2} showed the lowest mean in the control treatment, with 192 spikes m^{-2}, differing from the other treatments. The results found for the cultivar Ello CL® showed a mean of 222 spikes m^{-2} the treatment with imazamox (49 g a.i. ha^{-1}), differing from the treatment with imazamox (49 g a.i. ha^{-1}) + pyroxasulfone (125 g a.i. ha^{-1}), which presented mean of 329 spikes m^{-2}. The mean spike weight showed no significant differences for the cultivar Capricho CL®, whereas differences were found for the cultivar Ello CL®, mainly in the control treatment and in the treatment with the lowest imazamox rate (49 g a.i. ha^{-1}). The results of 100-grain weight showed no significant differences between treatments, regardless of the cultivar.

The grain yield of the cultivar Capricho CL® was, in general, higher in treatments with combined pre- and post-emergence applications, mainly for that with pyroxasulfone (125 g a.i. ha^{-1}) + imazamox (49 g a.i. ha^{-1}), which resulted in a grain yield of 3,206 kg ha^{-1}, whereas the isolated application of imazamox (49 g a.i. ha^{-1}) resulted in a grain yield of 1,711 kg ha^{-1}.

The isolated treatments with imazamox (49 and 70 g a.i. ha^{-1}) and pyroxsulam (18 g a.i. ha^{-1}) resulted in the lowest yields for the cultivar TBIO Ello CL®, with yields of 3,878 kg ha^{-1}, 3,720 kg ha^{-1}, and 3,541 kg ha^{-1}, respectively. Despite the other treatments showed no significant difference, the treatment with pyroxasulfone (125 g a.i. ha^{-1}) + imazamox (49 g a.i. ha^{-1}) stood out with the highest mean grain yield of the experiment, 5,019 kg ha^{-1}.

The isolated treatment with the highest rate of imazamox (91 g a.i. ha^{-1}) resulted, in general, in higher mean yields for both cultivars, compared to the other treatments without combination with pre-emergence application. This result is the opposite to that found by Ball and Peterson (2007), who evaluated the cultivars Idaho 587, ORCF-102, and ClearFirst and found the lowest grain yields in the treatments with the highest imazamox rate (105 g a.i. ha^{-1}). This difference may be due to the cultivars used, which were more sensitive to high rates of the herbicide when compared to cultivars with the Clearfield® (CL) technology, thus decreasing grain yield. Additionally, it is possible to observe that the grain yield of the two cultivars in the two seasons using the pyroxsulam treatment (18 g ha^{-1}) without pre-emergence application was 3,795 kg ha^{-1} (TBIO Capricho CL®) and 3,541 kg ha^{-1} (TBIO Ello CL®), with results similar to those found by Viecelli et al. (2019). These authors reported a productivity of 3,557.32 kg ha^{-1} using 16 g ha^{-1} of pyroxsulam, applied to the cultivar ORS Vintecinco.

Grain yield in wheat crops is affected by inefficient control of ryegrass. It was elucidated by Paula et al. (2011), who showed the high level of effects of ryegrass on wheat grain

Table 1. Crop seasons, application time, commercial name, active ingredient, and rate of the herbicides evaluated. Lages, SC, Brazil, 2020/2021.

Crop season	Application time	Commercial name	Active ingredient (rate)
2020	Pre-emergence	Herbadox® 400 EC	Pendimethalin (1365 g a.i. ha^{-1})
	Post-emergence	Raptor™ 70 DG	Imazamox (49 g a.i. ha^{-1})
			Imazamox (70 g a.i. ha^{-1})
			Imazamox (91 g a.i. ha^{-1})
		Tricea®	Pyroxsulam (18 g a.i. ha^{-1})
2021	Pre-emergence	YAMATO SC	Pyroxasulfone (125 g a.i. ha^{-1})
	Post-emergence	Raptor™ 70 DG	Imazamox (49 g a.i. ha^{-1})
			Imazamox (70 g a.i. ha^{-1})
			Imazamox (91 g a.i. ha^{-1})
		Tricea®	Pyroxsulam (18 g a.i. ha^{-1})

Table 2. Evaluation of phytotoxicity and control of ryegrass (*L. multiflorum*) in the 2020 and 2021 crop seasons. Lages, SC, Brazil.

Post-emergence	Phytotoxicity at 7 DAA (%)					
	Capricho CL 2020		Capricho CL 2021		Ello CL 2021	
	Pre-emergence		Pre-emergence		Pre-emergence	
	Without	With$^{/1}$	Without	With$^{/2}$	Without	With$^{/2}$
Without herbicide	0.0 ^{NS}	1.3 ^{NS}	0.0 ^{NS}	0.0 Ab	0.0 ^{NS}	0.0 ^{NS}
Imazamox (49 g ha^{-1})	2.3	3.5	1.5	0.0 Ab	0.0	0.5
Imazamox (70 g ha^{-1})	0.0	1.3	2.8	2.3 Aab	0.5	0.0
Imazamox (91 g ha^{-1})	2.0	0.0	3.8	5.0 Aa	0.5	0.5
Pyroxsulam (18 g ha^{-1})	1.5	0.0	1.5	0.5 Aab	0.0	0.0
Post-emergence	Ryegrass control at 7 DAA (%)					
	Capricho CL 2020		Capricho CL 2021		Ello CL 2021	
	Pre-emergence		Pre-emergence		Pre-emergence	
	Without	With$^{/1}$	Without	With$^{/2}$	Without	With$^{/2}$
Without herbicide	0.0 Bb	66.3 ^{NS}	0.0 Aa	17.8 ^{NS}	0.0 Bb	22.5 Ab
Imazamox (49 g ha^{-1})	64.5 Aa	73.8	17.0 Aa	30.0	23.5 Bab	43.8 Aab
Imazamox (70 g ha^{-1})	53.8 Aa	63.8	23.3 Aa	37.5	40.8 Aa	45.3 Aab
Imazamox (91 g ha^{-1})	60.8 Aa	57.5	22.5 Ba	41.8	37.8 Aa	48.8 Aab
Pyroxsulam (18 g ha^{-1})	53.3 Aa	63.3	12.0 Ba	36.3	43.5 Aa	54.3 Aa
Post-emergence	Ryegrass control at 14 DAA (%)					
	Capricho CL 2020		Capricho CL 2021		Ello CL 2021	
	Pre-emergence		Pre-emergence		Pre-emergence	
	Without	With$^{/1}$	Without	With$^{/2}$	Without	With$^{/2}$
Without herbicide	0.0 Bb	72.5 Ab	0.0 Ab	17.8 Ab	0.0 Bb	64.5 ^{NS}
Imazamox (49 g ha^{-1})	84.5 Aa	84.5 Aab	30.5 Aab	46.3 Aab	55.0 Aa	75.0
Imazamox (70 g ha^{-1})	80.8 Aa	87.0 Aa	48.8 Aa	53.5 Aa	60.8 Aa	72.5
Imazamox (91 g ha^{-1})	83.8 Aa	79.5 Aab	48.0 Aa	57.8 Aa	53.8 Aa	67.5
Pyroxsulam (18 g ha^{-1})	73.8 Aa	80.8 Aab	50.5 Aa	56.8 Aa	45.5 Ba	82.5
Post-emergence	Ryegrass control at 28 DAA (%)					
	Capricho CL 2020		Capricho CL 2021		Ello CL 2021	
	Pre-emergence		Pre-emergence		Pre-emergence	
	Without	With$^{/1}$	Without	With$^{/2}$	Without	With$^{/2}$
Without herbicide	0.0 Bb	63.8 Ab	0.0 Bc	60.5 Ab	0.0 Bc	60.8 Ab
Imazamox (49 g ha^{-1})	97.5 Aa	98.5 Aa	48.0 Bab	74.3 Aab	51.8 Bb	76.8 Aab
Imazamox (70 g ha^{-1})	89.0 Aa	97.5 Aa	40.0 Bb	73.5 Aab	73.8 Aa	76.5 Aab
Imazamox (91 g ha^{-1})	97.0 Aa	99.3 Aa	59.8 Ba	79.0 Aa	63.8 Bab	81.5 Aab
Pyroxsulam (18 g ha^{-1})	89.5 Aa	96.0 Aa	46.8 Bab	74.5 Aab	72.5 Aab	82.8 Aa
Post-emergence	Pre-harvest control of ryegrass (%)					
	Capricho CL 2020		Capricho CL 2021		Ello CL 2021	
	Pre-emergence		Pre-emergence		Pre-emergence	
	Without	With$^{/1}$	Without	With$^{/2}$	Without	With$^{/2}$
Without herbicide	0.0 Bb	62.0 Ab	0.0 Bc	68.8 ^{NS}	0.0 Bc	85.0 Ab
Imazamox (49 g ha^{-1})	91.3 Aa	96.8 Aa	41.5 Bb	96.8	92.3 Aab	99.5 Aa
Imazamox (70 g ha^{-1})	91.3 Aa	100.0 Aa	81.0 Aa	82.3	95.5 Aa	100.0 Aa
Imazamox (91 g ha^{-1})	95.8 Aa	92.5 Aa	83.0 Aa	94.3	93.0 Aab	100.0 Aa
Pyroxsulam (18 g ha^{-1})	88.8 Aa	88.8 Aa	68.5 Bab	97.5	83.5 Bb	100.0 Aa

Means followed by the same lowercase letter in the columns or uppercase letter in the rows are not significantly different from each other by the Tukey's test (p>0.05). $^{/1}$ pendimethalin (1365 g ha^{-1}). $^{/2}$ pyroxasulfone (125 g ha^{-1}). NS = not significant.

Table 3. Evaluations of growth, production components, and grain yield of CL wheat cultivars in the 2020 and 2021 crop seasons. Lages, SC, Brazil.

Post-emergence	Plant height (cm)					
	Capricho CL 2020		Capricho CL 2021		Ello CL 2021	
	Pre-emergence		Pre-emergence		Pre-emergence	
	Without	With$^{/1}$	Without	With$^{/2}$	Without	With$^{/2}$
Without herbicide	78.3 ^{NS}	84.0 ^{NS}	84.8 ^{NS}	84.0 ^{NS}	76.5 Aa	81.3 ^{NS}
Imazamox (49 g ha^{-1})	83.5	77.5	82.8	84.8	76.0 Ba	87.3
Imazamox (70 g ha^{-1})	78.3	79.0	81.8	84.0	83.0 Aa	81.8
Imazamox (91 g ha^{-1})	76.8	76.3	85.5	82.3	84.0 Aa	82.8
Pyroxsulam (18 g ha^{-1})	75.8	74.0	83.8	84.3	81.8 Aa	79.0
Post-emergence	Number of spikes m^{-2}					
	Capricho CL 2020		Capricho CL 2021		Ello CL 2021	
	Pre-emergence		Pre-emergence		Pre-emergence	
	Without	With$^{/1}$	Without	With$^{/2}$	Without	With$^{/2}$
Without herbicide	446 ^{NS}	463 ^{NS}	192 Bb	258 ^{NS}	212 Ab	253 ^{NS}
Imazamox (49 g ha^{-1})	516	519	304 Aa	295	222 Bab	329
Imazamox (70 g ha^{-1})	544	463	302 Aa	299	243 Aab	286
Imazamox (91 g ha^{-1})	624	542	295 Aa	299	309 Aa	281
Pyroxsulam (18 g ha^{-1})	503	534	296 Aa	305	232 Aab	269
Post-emergence	Mean spike weight (g spike^{-1})					
	Capricho CL 2020		Capricho CL 2021		Ello CL 2021	
	Pre-emergence		Pre-emergence		Pre-emergence	
	Without	With$^{/1}$	Without	With$^{/2}$	Without	With$^{/2}$
Without herbicide	0.9 ^{NS}	0.9 ^{NS}	1.2 ^{NS}	1.3 ^{NS}	0.8 Ab	1.0 ^{NS}
Imazamox (49 g ha^{-1})	1.0	1.1	1.3	1.4	0.9 Bab	1.2
Imazamox (70 g ha^{-1})	1.0	1.1	1.3	1.4	1.1 Aa	1.0
Imazamox (91 g ha^{-1})	1.0	1.1	1.4	1.3	1.0 Aab	1.1
Pyroxsulam (18 g ha^{-1})	1.0	1.0	1.2	1.2	1.0 Aab	1.0
Post-emergence	100-grain weight (g)					
	Capricho CL 2020		Capricho CL 2021		Ello CL 2021	
	Pre-emergence		Pre-emergence		Pre-emergence	
	Without	With$^{/1}$	Without	With$^{/2}$	Without	With$^{/2}$
Without herbicide	3.4 ^{NS}	3.5 ^{NS}	3.4 ^{NS}	3.4 ^{NS}	3.9 ^{NS}	3.8 ^{NS}
Imazamox (49 g ha^{-1})	3.5	3.7	3.6	3.4	3.7	3.6
Imazamox (70 g ha^{-1})	3.6	3.6	3.3	3.5	3.6	3.8
Imazamox (91 g ha^{-1})	3.6	3.5	3.6	3.4	3.6	3.7
Pyroxsulam (18 g ha^{-1})	3.5	3.5	3.4	3.3	3.5	3.7
Post-emergence	Grain yield (kg ha^{-1})					
	Capricho CL 2020		Capricho CL 2021		Ello CL 2021	
	Pre-emergence		Pre-emergence		Pre-emergence	
	Without	With$^{/1}$	Without	With$^{/2}$	Without	With$^{/2}$
Without herbicide	3284 Bb	4412 ^{NS}	2116 Aab	2609 ^{NS}	3344 Ba	4163 ^{NS}
Imazamox (49 g ha^{-1})	4650 Aa	4161	1711 Bb	3206	3878 Ba	5019
Imazamox (70 g ha^{-1})	4090 Aab	4292	2602 Aab	3137	3720 Aa	3979
Imazamox (91 g ha^{-1})	4067 Aab	4264	3146 Aa	3497	4245 Aa	4189
Pyroxsulam (18 g ha^{-1})	3795 Aab	3817	2988 Aab	3055	3541 Ba	4493

Means followed by the same lowercase letter in the columns or uppercase letter in the rows are not significantly different from each other by the Tukey's test ($p>0.05$). $^{/1}$ pendimethalin (1365 g ha^{-1}). $^{/2}$ pyroxasulfone (125 g ha^{-1}). NS = not significant.

yield. They found a yield of 4,967 kg ha^{-1} without, and 1,790 kg ha^{-1} with interference of weeds, representing a decrease of 64% in grain yield. The yield results found in the present work confirm that an effective weed control, mainly using combined pre- and post-emergence applications, result in ryegrass controls higher than 82.3%. These findings are important, since ryegrass is a significant problem in the wheat crops throughout the world and is considered the main weed species in wheat production system in many countries (Kuk et al., 2000).

Materials and methods

Site description

The experiment was conducted under field conditions at the experimental area of the Center for Agro-Veterinary Sciences (CAV) of the Santa Catarina State University (UDESC), in the municipality of Lages, SC, Brazil (27°47'34''S, 50°18'05''W, and 904 m of altitude), in two crop seasons, from July 2020 to December 2021. The soil of the experimental area was classified as Humic Dystrudept (Cambissolo Humico Aluminico) (Embrapa, 2018); the chemical analysis of the soil 0-0.2 m layer showed: pH in water of 5.9; 600 g kg^{-1} of clay; 29 g kg^{-1} of organic matter; 10.2 mg dm^{-3} of P; 97 mg dm^{-3} of K; 0.4 cmol$_c$ dm^{-3} of Al; 9.99 cmol$_c$ dm^{-3} of cation exchange capacity (CEC); and base saturation (BS) of 58.1%. The experimental area had history of spontaneous infestation of glyphosate-resistant ryegrass plants.

Plant material

The wheat cultivars evaluated were: TBIO Capricho CL® (2020 and 2021 crop seasons) and TBIO Ello CL® (2021 crop season). The CL® wheat cultivars were developed through a mutation induced in the seeds. The resistance mechanism of these cultivars is due to the presence of a mutated form of the acetolactate synthase (ALS) enzyme, which reduces the affinity of the enzyme for herbicides in the imidazolinone chemical group (JIMENEZ et al., 2016). The ALS enzyme is involved in the synthesis of valine, leucine, and isoleucine, the branched-chain amino acids (TAN et al., 2005). The seeds were sown on July 23, 2020, and on July 09, 2021, both with spacing of 0.20 m and density of 300 seeds m^{-2}. Soil fertilizers were applied at planting using 400 kg ha^{-1} of the N-P-K formulation 09-33-12.

Experimental design and treatments

A randomized block experimental design was used, in a 2×5 factorial arrangement, with four replications. The treatments consisted of two levels of pre-emergence herbicide application (without and with pendimethalin at 1365 g a.i. ha^{-1} in the 2020 crop season or without and with pyroxasulfone at 125 g a.i. ha^{-1} in the 2021 crop season) and post-emergence herbicide application (without herbicide application, imazamox at 49, 70, and 91 g a.i. ha^{-1}, and pyroxsulam at 18 g a.i. ha^{-1}). The herbicides used in the experiments are detailed in Table 1. The plots consisted of nine 5-meter sowing rows spaced 0.2 m apart, totaling an area of 9 m^2.

The treatments were applied using a CO_2-pressurized backpack sprayer equipped with four anti-drift nozzles (AD110.02) at constant pressure of 207 kPa, monitored by a pressure gauge in the spray boom, run speed of 1.0 m s^{-1}, and volume rate equivalent to 200 L ha^{-1}. The climate conditions at the time of applications were monitored using a digital thermo-hygro-anemometer, which showed air temperature from 18.6 to 28.0 °C, relative air humidity from 50% to 63%, and wind speed from 0.7 to 2.3 km h^{-1}.

The pre-emergence herbicide treatments were applied soon after the sowing (plant and apply system) and post-emergence treatments were applied at the wheat tillering stage, when the ryegrass were at the 2 to 4 leaf stage. However, some regrowth ryegrass plants were found in the 2021 crop season in the experimental area of the cultivar TBIO Capricho CL®.

Wheat management

Nitrogen topdressing was carried out using urea at a rate equivalent to 80 and 67 kg N ha^{-1} at the end of the tillering stage in the 2020 and 2021 crop seasons, respectively. Fertilizer applications were carried out according to technical recommendations for wheat crops for the state of Santa Catarina (Sbcs, 2016).

A pre-sowing burndown management was carried out at 15 days before the wheat sowing, using the herbicides: glyphosate (1.440 g a.e. ha^{-1}), clethodim (120 g a.i. ha^{-1}), and 2,4-D (670 g a.e. ha^{-1}). Disease control was carried out for the 2020 crop season, using the fungicides: Ativum® (epoxiconazole 60 g a.i. ha^{-1} + fluxapyroxad 60 g a.i. ha^{-1} + pyraclostrobin 97.2 g a.i. ha^{-1}), Fox® XPro (bixafen 62.5 g a.i. ha^{-1} + prothioconazole 87.5 g a.i. ha^{-1} + trifloxystrobin 75 g a.i. ha^{-1}), and Orkestra® SC (fluxapyroxad 58.45 g a.i. ha^{-1} + pyraclostrobin 116.55 g a.i. ha^{-1}). Pest control was carried out through application of: Engeo Full™ S (thiamethoxam 21.15 g a.i. ha^{-1} + lambda-cyhalothrin 15.9 g a.i. ha^{-1}) + Assist® (mineral oil), Fastac® Duo (acetamiprid 30 g a.i. ha^{-1} + alfa-cypermethrin 60 g a.i. ha^{-1}) + Aureo® (ester methyl of soybean oil), and Voraz (methomyl 176 g a.i. ha^{-1} + novaluron 14 g a.i. ha^{-1}) + Aureo®. In the 2021 crop season, only disease control was carried out, using two applications of the fungicide Fox® XPro.

Data collection

The variables evaluated were: phytotoxicity and ryegrass control efficiency at 7, 14, and 28 days after application of the treatments (DAA). Plant height (cm), number of spikes m^{-2}, mean spike weight (g spike^{-1}), 100-grain weight (g), and grain yield (kg ha^{-1}) were determined at the wheat pre-harvest. Phytotoxicity was evaluated visually through a scale of grades from 0% to 100%, where 0% is the absence of symptoms and 100% is the death of the plant (Kuva et al., 2016). The control was also analyzed visually, using a a scale of grades from 0% to 100%, where 0% is the absence of control, and 100% is the complete necrose of the plant. Plant height was determined using of ruler by measuring 10 plants per plot. The number of spikes m^{-2} was determined in an area of 0.25 m^2 (0.5 × 0.5 m), and the mean spike weight was determined after the collection and threshing of 10 spikes per plot. An area of 4.8 m^2 was harvested at the end of the crop cycle for analyzing grain yield and 100-grain weight. The grain moisture was standardized to 13%.

Data analysis

The data were subjected to analysis of variance by the F test and means were compared by the Tukey's test. A significance level of 5% ($p<0.05$) was used for all analyses.

Conclusion

Combining pre-emergence application of pendimethalin or pyroxasulfone with post-emergence application of imazamox or pyroxsulam ensured a higher ryegrass control when compared to their isolated pre- or post-emergence applications in all situations evaluated, contributing to the maintenance of the wheat production potential.

Acknowledgements

This work was financially supported by the Brazilian Coordination for the Improvement of Higher Education Personnel (CAPES; PROAP/AUXPE) and FAPESC/UDESC/PAP.

References

Ball DA, Peterson CJ (2007) Herbicide Tolerance in Imidazolinone-Resistant Wheat for Weed Management in the Pacific Northwest U.S.A. Developments In Plant Breeding. 12:243-250.

Basf Brasileira (2004) Sistema Clearfield® de Produção. Avaliable to: http://agro.basf.com.br/hotsites/clearfield/clearfield_arroz/cleararroz. Acessed in 15 ago 2023.

Breccia G, Bisio MB, Picardi L, Nestares G (2018) A rapid phenotyping method for imazamox resistance in wheat. Planta Daninha. 36:e018179638.

Bremer H, Pfenning M, Kehler R (2011) The Clearfield® production system in oilseed rape–a new herbicide generation in oilseed rape in Europe. In: Proceedings of the 13th International Rapeseed Congress, Abstract Book (Vol. 61).

Bond JA, Stephenson DO, Barnes JW, Bararpour MT, Oliver LR (2005) Diclofop-resistant Italian ryegrass (*Lolium multiflorum*) control in imidazolinone-tolerant wheat. Weed Technology. 19(2):437-442.

Borgo A, Rosito C (1977) Avaliação da eficiência de herbicidas no controle de *Polygonun convolvulus* L. e outras folhas largas em trigo. Trigo e Soja, Porto Alegre. 21:3-7.

Clemmer KC, York AC, Brownie C (2004) Italian ryegrass (*Lolium multiflorum*) control in imidazolinone-resistant wheat. Weed Technology. 18(3):481-489.

Conab, Companhia Nacional de Abastecimento (2022) Histórico mensal do trigo. Brasília: Conab. Avaliable to: https://www.conab.gov.br/info-agro/analises-do-mercado-agropecuario-e-extrativista/analises-do-mercado/historico-mensal-de-trigo/. Accessed in 21 mar 2022.

Diário Oficial da União (2020) Ato CGAA nº 48 de 17 de agosto de 2020. Diário Oficial da União, 160. Ed. s.1, p.17. Avaliable to: https://pesquisa.in.gov.br/imprensa/jsp/visualiza/index.jsp?data=20/08/2020&jornal=515&pagina=17. Accessed in 30 jun 2022.

Domínguez-Mendez R, Alcántara-de la Cruz R, Rojano-Delgado AM, Fernández-Moreno PT, Aponte R, Prado R (2017) Multiple mechanisms are involved in new imazamox-resistant varieties of durum and soft wheat. Scientific Reports. 7(1):1-11.

Embrapa, Empresa Brasileira de Pesquisa Agropecuária (2018) Sistema brasileiro de classificação de solos. 5. ed. Brasília.

Embrapa Trigo. Lacunas de rendimento de grãos de trigo em áreas de atuação de cooperativas no Brasil (2021). Avaliable to: http://www.infoteca.cnptia.embrapa.br/infoteca/handle/doc/1135313. Accessed in 04 may 2022.

Gazziero DLP, Vargas L, Roman ES (2008) Manejo e controle de plantas daninhas em soja. In: Vargas L, Roman ES. Manual de manejo e controle de plantas daninhas. Passo Fundo: Embrapa Trigo, 681-722.

Heap I (2022) International Survey of Herbicide Resistant Weeds. Avaliable to: < https://www.weedscience.org/Pages/Species.aspx >. Accessed in 01 sep 2022.

Inoue MH, Santana CTC, Oliveira Jr RS, Possamai ACS, Santana DC, Arruda RAD, Dallacort R, Sztoltz CL (2011) Efeito residual de herbicidas aplicados em pré-emergência em diferentes solos. Planta Daninha. 29:429-435.

Jimenez F, Rojano-Delgado AM, Fernández PT, Rodríguez-Suárez C, Atienza SG, Prado R (2016) Physiological, biochemical and molecular characterization of an induced mutation conferring imidazolinone resistance in wheat. Physiologia Plantarum. 158(1):2-10.

Kuk YI, Burgos NR, Talbert RE (2000) Cross-and multiple resistance of diclofop-resistant *Lolium* spp. Weed Science. 48(4):412-419.

Kuva MA, Salgado TP, Revoredo TTO (2016) Experimentos de eficiência e praticabilidade agronômica com herbicidas. Experimentação com herbicidas. 75-97.

Novais JR, Inoue MH, Amorim VHM, Silva JLM, Borges SXS, Massuquini Z, Franco ELP, Santos DM (2021) Seleção de espécies bioindicadoras para os herbicidas pyroxasulfone e pyroxasulfone + flumioxazin em solos contrastantes / Selection of bioindicator species for pyroxasulfone and pyroxasulfone + flumioxazin herbicides in contrasting soils. Brazilian Journal of Development. 7(12):115794-115808.

Oliveira Neto AM, Guerra N, Goes Maciel CD, Silva TRB, Ramos Lima GG (2011) Seletividade de herbicidas aplicados em pré-emergência na cultura do crambe. Revista Brasileira de Herbicidas. 10(1):49-56.

Paula JM, Agostinetto D, Schaedler CE, Vargas L, Silva DRO (2011) Competição de trigo com azevém em função de épocas de aplicação e doses de nitrogênio. Planta Daninha. 29:557-563.

Shennan C (2007) Biotic interactions, ecological knowledge and agriculture. Philosophical Transactions of the Royal Society B: Biological Sciences. 363(1492):717-739.

Sbcs, Sociedade Brasileira de Ciência do Solo (2016) Manual de calagem e adubação para os Estados do Rio Grande do Sul e Santa Catarina. Santa Maria: Palloti. 376p.

Souza RG, Vieira Filho JER (2021) Produção de trigo no Brasil: análise de políticas econômicas e seus impactos. Revista de Política Agrícola. 30(2):45.

Tanetani Y, Kaku K, Kawai K, Fujioka T, Shimizu T (2009) Action mechanism of a novel herbicide, pyroxasulfone. Pesticide Biochemistry and Physiology. 95(1):47-55.

Tanetani Y (2012) Action mechanism of isoxazoline-type herbicides. Journal Of Pesticide Science. 37(3):261-262.

Tan S, Evans RR, Dahmer ML, Singh BK, Shaner DL (2005) Imidazolinone-tolerant crops: history, current status and future. Pest Management Science: Formerly Pesticide Science. 61(3):246-257.

Tomm GO, Lamas Junior GLC, Ferreira PEP, Marsaro Júnior AL (2017) Introdução de tecnologia para controle de plantas daninhas em canola no Brasil – Sistema Clearfield®.

Tucker KP, Miller TD, Bauman PA, Senseman SA (2002) Ryegrass (*Lolium multiflorum* Lam.) management in central Texas wheat. In: Proc. South. Weed Sci. Soc, 55:24-25.

Vargas L, Roman ES, Rodrigues O, Theisen G (2008) Manejo e controle de plantas daninhas em trigo. In: Vargas L, Roman ES. Manual de manejo e controle de plantas daninhas. Passo Fundo: Embrapa Trigo, 723-738.

Vargas L, Roman ES (2006) Características e manejo de azevém resistente ao glyphosate. Passo Fundo: Embrapa Trigo (Embrapa Trigo. Documentos Online, 59). Avaliable to: https://www.infoteca.cnptia.embrapa.br/bitstream/doc/852513/1/pdo59.pdf. Accessed in 04 may 2022.

Vargas L, Bianchi MA (2011) Manejo e controle de plantas daninhas em trigo.

Velini ED, Martins D, Manoel LA, Matsuoka S, Travain JC, Carvalho JC (2000) Avaliação da seletividade da mistura de oxyfluorfen e ametryne, aplicada em pré ou pós-emergência, a dez variedades de cana-de-açúcar (cana-planta). Planta Daninha. 18:123-134.

Viecelli M, Pagnoncelli JrFB, Trezzi MM, Cavalheiro BM, Gobetti RCR (2019) Response of wheat plants to combinations of herbicides with insecticides and fungicides. Planta Daninha. 37:e019187012.