Imidazolinone-tolerant maize as a tool for weed control in flooded rice production systems

Leandro Galon[1], Germani Concenço[2]*, Jesus Juarez Oliveira Pinto[3], Rodolpho Freire Marques[2], André Andres[4]

[1]Federal University of the Southern Border, campus Erechim, Rio Grande do Sul state, Brazil, ZIP: 99.700-000
[2]Embrapa Western Agriculture, Sustainable weed management, Dourados, Mato Grosso do Sul state, Brazil, ZIP: 79.804-970
[3]Federal University of Pelotas, Capão do Leão, Rio Grande do Sul state, Brazil, ZIP: 96.010-900
[4]Embrapa Temperate Agriculture, Pelotas, Rio Grande do Sul state, Brazil, ZIP: 96.001-970
*Corresponding author: E-mail: germani.concenco@embrapa.br

Abstract

This study aimed to (1) evaluate the optimal dose of the herbicide [imazapic + imazapyr], for control of red rice, as well as its selectivity to imidazolinone-tolerant maize; (2) to identify the most suitable adjuvant to be added to the optimal dose for maximizing red rice and barnyardgrass control; and (3) to evaluate its carryover effect on winter species commonly planted after maize in Southern Brazil. Three studies were carried out (two under field conditions, one under greenhouse) in completely randiomized blocks design. Experiment one consisted of application of [Imazapic + Imazapyr] and nicosulfuron, at increasing rates, on OnDuty® maize crop; experiment two consisted of application of the optimal dose of [Imazapic + Imazapyr] determined in experiment 1, plus atrazine, with distinct adjuvants, and experiment 3 consisted of planting rapeseed (*Brassica napus*), tall fescue (*Festuca arundinacea*), birdsfoot trefoil (*Lotus corniculatus*), ryegrass (*Lolium multiflorum*), white clover (*Trifolium repens*) and vetch (*Vicia sativa*) after applying [Imazapic + Imazapyr] at 1x and 2x the label dose in order to verify its toxicity effects. Application of [imazapic + imazapyr] at dose of 0.100 kg c.p. ha^{-1} (equivalent to 52.5 + 17.5 g a.i. ha^{-1}) on imidazolinone-tolerant maize was effective in controlling red rice and barnyardgrass when using Cicol or Dash as adjuvants, being also selective to the crop cv C 909 CL. Residues of these herbicides can affect winter crops in succession. Further studies should be conducted to evaluate the use of vetch in phytoremediation following imidazolinone-tolerant maize.

Keywords: Zea mays, chemical control, ALS inhibitors

Introduction

The Brazilian state of Rio Grande do Sul has more than three million hectares of lowlands, which are mainly used for rice production in summer, followed by extensive cattle raising as the primary option in fall/winter. The profitability of this activity has declined in recent years due to increasing competition from new producing regions of Brazil, as well as rice import from neighboring Countries Argentina and Uruguay. Another factor that hinders rice farmers to continue this productive activity is the high weed infestation levels for most areas, mainly composed by weedy rice (*Oryza sativa*), barnyardgrass (*Echinochloa crusgalli*) and junglerice (*Echinochloa colona*) (Ottis and Talbert, 2007).

Alternative production systems, based on cultivation of maize, soybeans and sorghum in rotation to rice, are being developed by research institutions (Andres et al, 2012). Farmers, however, do not easily adopt these options due to the additional requirement of knowledge for profitably managing these crops in lowland areas where efficient drainage system are demanded (Nyalemegbe et al, 2011). It is necessary to provide a technological package for crop rotation with rice in lowlands which provides technical, economic and environmental benefits. Among the advantages of crop rotation, the efficient suppression of weed species, especially red rice, is highlighted. In the Technical Recommendation for Maize in Southern Brazil, there is no chemical option for controlling this weed after crop emergence.

The available technologies aiming to control weedy Oryza biotypes to the moment have partially failed to contain its infestation and dissemination in rice; therefore, integrated control of this pest is demanded. One of such efforts is the imazapyr-resistant maize (IRM) technology which utilizes herbicide resistant maize allowing application of the commercially available mixture of imidazolinone herbicides imazapyr and imazapic (Mignouna et al, 2011), which are letal to non-resistant maize varieties. The adoption of this technology is presented as an option for reducing dissemination of red rice in Southern Brazil (Andres et al, 2012).

Imidazolinone herbicides present physico-chemical characteristics that allow them to persist in the environment for long periods (Monks et al, 1996; Vencill, 2002). Thus, these herbicides can persist in soil lon-

 RECEIVED 03/17/2014

ger than the rice cycle, causing phytotoxicity to crops planted in succession (carryover) or even leaching to deeper layers in soil profile reaching groundwater (Kraemer et al, 2009).

Damage of these herbicides to plants can be assessed by its indirect effect on variables associated to photosynthesis (Concenço et al, 2012). The photosynthetic activity of plants is influenced directly or indirectly by water deficiency, thermal stress, leaf internal and external gas concentration, composition and intensity of light (Sharkey and Raschke, 1981) and, to a greater extent, by damages caused by herbicides, besides other factors. According to Dal Magro et al (2006) plants may exhibit distinct responses to different herbicides and doses.

Based on the above, we aimed with these studies to (1) evaluate the optimal dose of the herbicide [imazapic + imazapyr], for control of red rice, as well as its selectivity to imidazolinone-tolerant maize; (2) to identify the most suitable adjuvant to be added to the optimal dose for maximizing red rice and barnyardgrass control; and (3) to evaluate its carryover effect on winter species commonly planted after maize in Southern Brazil.

Materials and Methods

Experiment 1

Experiment 1 was installed in field conditions, at the Agricultural Research Center of Palma (CAP), owned by the Federal University of Pelotas (UFPel), city of Capão do Leão, state of Rio Grande do Sul, Brazil. The soil on which the experiment was installed is a lowland (Albaqualf) with 18% clay and 2.0% organic matter. Soil tillage was accomplished by standard disking and harrowing. Soil fertility was corrected at planting by applying 200 kg ha^{-1} of N P K 5 20 20 at the planting furrow, plus topdressing of 145 kg ha^{-1} of N as urea, applied in two halves when corn plants had four and six leaves, respectively. Crop was managed according to the Technical Recommendation for Maize in Southern Brazil (Embrapa, 2012).

The experiment was installed in completely randomized blocks design with four replications, with total plot area of 18.0 m^2 (4.5 x 4 m) and useful area of 10.8 m^2 (4.0 x 2.7 m). Mayze hybrid C 909 CL was drill planted in rows spaced in 0.90 m, at density of 5.5 plants m^{-2} by using a drill brand «Semeato», model SHM 1113.

Treatments are listed in Table 1, being applied in low light (partially cloud) conditions, temperature of 24ºC, air relative humidity of 91.8%, adequate soil moisture and winds of about 1.1 m s^{-1}. Herbicides were sprayed by using a backpack CO_2 propelled equipment at pressure of 35 PSI connected to a bar containing four spray nozzles 110.02 spaced in 0.5 m, which provided flow rate of 150 L ha^{-1}. At the time of herbicide application, spontaneous plant canopy was dominated by a population of 180 plants m^2 of red rice, at the three-leaf to two-tillers stage, and maize was at the three-to-four leaves stage.

Weed control and crop selectivity were evaluated visually, using a percentage scale adapted from EWRC (1964). Control efficiency was evaluated 15, 60 and 120 days after treatment (DAT) using scores from zero (0) for highly infested plots indicating no weed control, to one hundred (100) for plots where weeds were totally controlled. Selectivity for maize was evaluated 7 and 15 days after herbicide treatment (DAT), attributing a score of zero (0) to complete absence of injury and one hundred (100) to complete plant death.

Experiment 2

Experiment 2 was installed after the completion of experiment one, in area located at the Lowlands Experimental Station, owned by the Brazilian Agricultural Research Corporation (EMBRAPA), Temperate Agriculture Research Center (CPACT), located in Capão do Leão, RS, about five kilometers far from the area where experiment 1 was installed. Soil tillage was performed by the standard disking and harrowing and crop was managed according to the Technical Recommendation for Maize in Southern Brazil (Embrapa, 2012).

The experiment was installed in completely randomized blocks design with four replications. The same maize cultivar (C 909 CL) was planted with plot size, row spacing and planting density similar to Experiment 1. Fertilization at planting consisted of application of 400 kg ha^{-1} of organo-mineral fertilizer formulation. Topdressing fertilization consisted of application of 150 kg ha^{-1} of N as urea, split in three applications (maize plants with four, six and eight completely developed leaves).

Treatments of experiment 2 are listed in Table 1, being based on results from experiment 1. Treatments were sprayed in post-emergence of maize (three-to-four leaves stage) and weeds (red rice and barnyardgrass at three-leaf to two-tillers stage), by using a backpack CO_2 propelled equipment at pressure of 35 PSI connected to a bar containing four spray nozzles 110.02 spaced in 0.5 m, which provided flow rate of 150 L ha^{-1}. At the time of application, air relative humidity was 85%, temperature was 22°C, average wind speed was about 1.6 m s^{-1} and the sky was partially cloudy.

Weed control and crop selectivity were evaluated visually, using a percentage scale adapted from EWRC (1964). Control efficiency was evaluated 15, 30 and 95 days after treatment (DAT) using scores from zero (0) for highly infested plots indicating no weed control, to one hundred (100) for plots where weeds were totally controlled. Crop toxicity was not evaluated once it had already been quantified in Experiment 1. Maize grain yield was not analyzed due to severe attack of birds.

Table 1 - Chemical and mechanical weed control treatments studied throughout the study.

Treatment	Formulation (g kg-1 or g L-1)	Dose c.p. (ha-1)	Active Ingredient (g ha-1)
Experiment 1 - UFPel/CAP			
1. Weedy check	-	-	-
2. Weed-free check (hoeing)	-	-	-
3. [Imazapic + Imazapyr] + Cicol	525 + 175	80	42 + 14
4. [Imazapic + Imazapyr] + Cicol	525 + 175	100	52.5 + 17.5
5. [Imazapic + Imazapyr] + Cicol	525 + 175	120	63 + 21
6. Nicosulfuron	40	1300	52
7. Nicosulfuron	40	1500	60
Experiment 2 - Embrapa/CPACT			
1. Weedy check	-	-	-
2. Weed-free check (hoeing)	-	-	-
3. [Imazapic + Imazapyr] + Cicol	(525+175)	100	52.5+17.5
4. [Imazapic + Imazapyr] + Assist	(525+175)	100	52.5+17.5
5. [Imazapic + Imazapyr] + Dash	(525+175)	100	52.5+17.5
6. [Atrazine + Metolachlor] + Assist	(200+300)	5000	1000+1500
7. Atrazine + [Imazapic + Imazapyr] + Assist	500+(525+175)	5000+(1000)	2500+52.5+17.5
8. Atrazine	500	5000	2500
Experiment 3 - Unipampa/DFT			
1. Weedy check	-	-	-
2. [Imazapic + Imazapyr] + Dash	525 + 175	140	73.5 + 24.5
3. [Imazapic + Imazapyr] + Dash	525 + 175	280	147 + 49

Herbicides inside square brackets represent commercially available mixtures; mineral adjuvants added at the following proportions: Cicol = 0.15% v/v; Assist = 0.5% v/v; Dash = 0.5% v/v. Treatments applied in post-emergence with grass weeds at the 3- to 4- leaf stage. Treatments at experiment 3 were applied on the following plant species: rapeseed (*Brassica napus*), tall fescue (*Festuca arundinacea*), birdsfoot trefoil (*Lotus corniculatus*), ryegrass (*Lolium multiflorum*), white clover (*Trifolium repens*) and vetch (*Vicia sativa*).

Experiment 3

Experiment 3 was installed under greenhouse after completion of the previous experiments at the Federal University of Pampa, Itaqui city, RS, from June to September in a completely randomized blocks design, with three replications. Experimental plots consisted of plastic pots with capacity of 6 dm^3, filled with soil previously corrected according to soil analysis and recommendations for maize (Embrapa, 2012).

The following winter species were planted with ten seeds per pot: rapeseed (*Brassica napus*), tall fescue (*Festuca arundinacea*), birdsfoot trefoil (*Lotus corniculatus*), ryegrass (*Lolium multiflorum*), white clover (*Trifolium repens*) and vetch (*Vicia sativa*). After germination, thinning was accomplished being maintained only four plants per plot.

The commercially available herbicide [imazapic + imazapyr] was applied according to rates in Table 1 over all species, being also maintained for each species a check treatment with no herbicide. Herbicide rates were applied in pre-emergence, one day after planting, by using a backpack CO_2 propelled equipment at pressure of 35 PSI connected to a bar containing four spray nozzles 110.02 spaced in 0.5 m, which provided flow rate of 150 L ha^{-1}.

Sixty days after emergence (DAE) evaluations of photosynthetic rate were performed by using an infrared gas analyzer (IRGA), ADC model LCA PRO (Analytical Development Co Ltd, Hoddesdon, UK), under open greenhouse, allowing free circulation of air. Plants were also harvested and packed in paper bags being placed inside a forced air circulation oven set for temperature of 65±5°C until constant weight.

Statistical analysis

For all experiments, data residues were submitted to the normality and homogeneity tests (Shapiro-Wilk and Bartlett), being transformed by Box Cox procedure when needed (Box and Cox, 1982), and submitted to analysis of variance by the F test. When significant, means were compared by Tukey's multiple comparison test. All tests were performed at $p \leq 0.05$ by using the statistical environment R (R project, 2013).

Results and Discussion

Experiment 1

Data for red rice control is shown in Table 2. Results showed that the herbicide [imazapic + imazapyr] was highly efficient in controlling this weed 15 DAT. Dose of 0.080 kg c.p. ha^{-1} controlled 98% of a population of 180 plants m^{-2} of red rice. Control levels achieved at 15 DAT remained practically unchanged up to 120 DAT.

For all evaluations from 15 to 120 DAT, control levels of 98, 99 and 100% were observed under application of [imazapic + imazapyr] (Table 2). Statistical differences were observed at 120 DAT for doses of the herbicide, being the dose of 52.5 + 17.5 g a.i. ha^{-1}

Table 2 - Red rice control, rice phytotoxicity and grain yield of rice at the UFPel/CAP experiment.

Treatment	Dose (kg ha^{-1} a.i.)	Red Rice Control (%) 15 DAT	60 DAT	120 DAT
1. Weedy check	-	0 c	0 c	0 c
2. Weed-free check (hoeing)	-	100 a	100 a	100 a
3. [Imazapic + Imazapyr] + cicol	42 + 14	98 b	99 a	98 b
4. [Imazapic + Imazapyr] + cicol	52.5 + 17.5	98 b	100 a	99 a
5. [Imazapic + Imazapyr] + cicol	63 + 21	98 b	100 a	100 a
6. Nicosulfuron	52	0 c	0 b	0 c
7. Nicosulfuron	60	0 c	0 b	0 c

Treatment		Crop Phytotoxicity (%) 7 DAT	15 DAT	Grain Yield (Kg ha^{-1})
1. Weedy check	-	-	-	2,986 c
2. Weed-free check (hoeing)	-	-	-	5,270 ab
3. [Imazapic + Imazapyr] + cicol	42 + 14	0	0	4,457 bc
4. [Imazapic + Imazapyr] + cicol	52.5 + 17.5	0	0	6,151 a
5. [Imazapic + Imazapyr] + cicol	63 + 21	0	0	5,578 ab
6. Nicosulfuron	52	0	0	3,024 c
7. Nicosulfuron	60	0	0	3,429 c

Herbicides inside square brackets represent commercially available mixtures; mineral adjuvants added at the following proportions: Cicol = 0.15% v/v; Assist = 0.5% v/v; Dash = 0.5% v/v. Treatments applied in post-emergence with grass weeds at the 3- to 4- leaf stage. Means followed by the same letter, in the column, do not differ according to Tukey's test at 5% probability.

(100 mL c.p. ha^{-1}) enough to achieve the highest red rice control level (Table 2). These results show that [imazapic + imazapyr], besides controlling emerged weed seedlings, also presents pre-emergent activity preventing new infestation at least during the critical period of interference of red rice with maize. According to Bedmar et al (1999) the critical period of weed interference on corn, lies between 8 and 30 days after crop emergence.

Results for phytotoxicity (Table 2) show no harm to crop plants at 07 and 14 DAT. These results indicate that the herbicide [imazapic + imazapyr] in any of the doses tested is selective for maize cv. C 909 CL. Nicosulfuron has differential selectivity for the maize genotypes, but this study allow us to state that this product is selective to the genotype C 909 CL. Similar results for nicosulfuron were also reported by Gallaher et al (1999), where authors observed no herbicide injury from nicosulfuron on crop plants.

With respect to grain yield (Table 2), all treatments involving [imazapic + imazapyr] did not differ statistically from the plot with no infestation (hoeing). Nicosulfuron applied at rate of 52 or 60 g a.i. ha^{-1} did not differ from the check with no weed control. It was also observed that the pressure of competition exerted by weeds, reduced grain yield of maize by 43% when the check free of competition was compared to the check under competition (Table 2).

Experiment 2

At the first evaluation of weed control (15 DAT), the herbicide [imazapic + imazapyr] reached in average 58% of control efficiency for red rice, being effective only when atrazine was added to the mixture (Table 3). Control levels improved at 30 DAT reaching average 77% control, being the effect of adjuvants observed only at the final assessment (95 DAT) where cicol or dash allowed the highest control levels, but assist resulted in lower red rice control levels (Table 3). The persistence of high control levels from treatment application until 95 DAT highlights the same residual effect for [imazapic + imazapyr] observed in Experiment 1.

At the last evaluation, the highest red rice control levels were achieved with use of [atrazine + s metolachlor] or atrazine + [imazapic + imazapyr] and also for atrazine applied alone (≥ 92%). Statistically similar results were obtained with [imazapic + imazapyr] + cicol (Table 3). To achieve success in rotating rice with crops like maize in lowland fields, it is critical to reduce the presence of red rice in the cropping system when maize is present, so farmers will have lower red rice infestation when rice is back in the system (Tamado et al, 2002).

Control of barnyardgrass was not effective 15 DAT with [imazapic + imazapyr] for all adjuvants, being highest control levels observed for atrazine alone or mixed with s metolachlor (Table 3). At 30 DAT, however, all herbicides presented equal efficiency on barnyardgrass with average of 83% control efficiency (Table 3). At 95 DAA, control levels improved and treatments with [imazapic + imazapyr] averaged 90% control. Atrazine applied alone was inferior to the remainder of the chemical treatments.

The use of [imazapic + imazapyr] in imidazolinone-tolerant maize, in addition to the selectivity to the crop, allows efficient control of Alexandergrass (*Brachiaria plantaginea*) and beggar stick (*Bidens pilosa*) in post-emergence (Ulbrich et al, 2005). López-Martinez et al (1997) reports that barnyardgrass is moderately susceptible to atrazine, metolachlor and to its mixture, applied in post-emergence, which was also observed in this study. As for red rice, data from

Table 3 - Red rice and barnyardgrass control at the Embrapa/CPACT experiment.

Treatment	Dose (kg ha^{-1} a.i.)	Red Rice Control (%) 15 DAA	30 DAA	95 DAA
1. Weedy check	-	0 d	0 c	0 d
2. Weed-free check (hoeing)	-	99 a	99 a	88 a
3. [Imazapic + Imazapyr] + cicol	(525+175)	60 c	82 b	84 ab
4. [Imazapic + Imazapyr] + assist	(525+175)	55 c	70 b	60 c
5. [Imazapic + Imazapyr] + dash	(525+175)	60 c	80 b	83 b
6. [Atrazine + Metolachlor] + assist	(200+300)	88 b	94 a	92 a
7. Atrazine + [Imazapic + Imazapyr] + assist	500+(525+175)	90 ab	96 a	98 a
8. Atrazine	500	80 b	97 a	95 a
		Barnyardgrass Control (%)		
Treatment		15 DAA	30 DAA	95 DAA
1. Weedy check	-	0 d	0 c	0 c
2. Weed-free check (hoeing)	-	99 a	95 a	94 a
3. [Imazapic + Imazapyr] + cicol	(525+175)	70 c	85 b	88 ab
4. [Imazapic + Imazapyr] + assist	(525+175)	65 c	80 b	87 ab
5. [Imazapic + Imazapyr] + dash	(525+175)	60 c	80 b	95 a
6. [Atrazine + Metolachlor] + assist	(200+300)	78 b	84 b	90 ab
7. Atrazine + [Imazapic + Imazapyr] + assist	500+(525+175)	74 bc	86 b	95 a
8. Atrazine	500	80 b	85 b	85 b

Herbicides inside square brackets represent commercially available mixtures; mineral adjuvants added at the following proportions: Cicol = 0.15% v/v; Assist = 0.5% v/v; Dash = 0.5% v/v. Treatments applied in post-emergence with grass weeds at the 3- to 4- leaf stage. Means followed by the same letter, in the column, do not differ according to Tukey's test at 5% probability.

Kawahigashi et al (2005) describes that this weed is moderately susceptible (less than 50% control) to atrazine alone or in mixture with s metolachlor. At the present study, however, both red rice and barnyardgrass were controlled with more than 92% efficiency at 95 DAA, which also agrees with reports from Andres et al (2012) which found efficient control of both species with atrazine.

It should be reported that 72 hours after herbicide treatment there was a 25 mm precipitation, and this abundance of water may have contributed to the high control levels achieved with atrazine for red rice and barnyardgrass at this study (above 84%). In addition, reduction in the residual activity of this herbicide as a consequence of the heavy rain was not observed. The addition of [imazapic + imazapyr] to atrazine, helped to eliminate Alexandergrass from the experimental area; and the presence of atrazine in the mixture supplied higher consistency in red rice control.

Experiment 3

Analyzing the dry mass of plants, it was observed that rapeseed, tall fescue, birdsfoot trefoil and white clover did not survive the application of any of the doses (Table 4). When ryegrass plants were grown in soil treated with [imazapic + imazapyr] there was 82% mass reduction under application of the first dose (140 g c.p. ha^{-1}) and total plant death with application of the second dose (280 g c.p. ha^{-1}). Vetch was the only species to tolerate the highest dose, but with a significant reduction in dry mass (Table 4). The herbicide [imazapic + imazapyr] reduced vetch growth in 42 and 55% when plants were exposed to the first and second dose, respectively.

Dry mass of plants did not correlate directly with photosynthesis rate, because plant growth results from biomass accumulation from emergence up to the time of evaluation, while punctual inference of photosynthesis is highly dependent on environmental conditions at the time of assessment (Galon et al, 2009), being particularly useful for inferences among distinct treatments since they are applied on the same species and evaluated at the same time, under similar environmental conditions.

Although imidazolinone herbicides act by inhibiting the enzyme acetolactate synthase (ALS), which is essential for the biosynthesis of branched chain amino acids - valine, leucine and isoleucine (Sprague et al, 1997), damage to plants caused by these herbicides can be evaluated for their indirect influence on variables associated to photosynthesis (Taiz and Zeiger, 2010), because the plant stress shifts this parameter directly or indirectly, depending on the nature of stress and plant metabolism (Gurevitch et al, 2006).

Vetch (*Vicia sativa*) should be further investigated as a potential species to be used in phytoremediation in areas with history of [imazapic + imazapyr] application, as it can help mitigating the environmental problem of contamination without the need to excavate the contaminant material and dispose of it elsewhere.

Besides the use of imidazolinone tolerant maize in lowland rice areas for management of red rice, in the Center-West region of Brazil, mainly in the states of Goiás, Mato Grosso, Mato Grosso do Sul and Paraná, it is possible to perform two cropping cycles per year in the same area (Ceccon et al, 2013). The most planted crop is soybean (October-February) with maize (March-July) being planted in succession (Ceccon et al, 2013).

Table 4 - Dry mass (g plot^{-1}) and photosynthesis rate (μmol m^{-2} s^{-1}) of winter species submitted to application of imazapic + imazapyr at distinct doses in pre-emergence at the Unipampa/DFT experiment.

Plant Species	Dose ("x" the label)	Dry Mass (g plot^{-1})	Photosynthesis Rate (μmol m^{-2} s^{-1})
	0	18.2 a	0.4 b
Ryegrass	1.0	3.3 b	0.5 a
	2.0	0.0 c	0.0 c
	0	2.0 a	0.5 a
Birdsfoot trefoil	1.0	0.0 b	0.0 b
	2.0	0.0 b	0.0 b
	0	3.8 a	0.6 a
White clover	1.0	0.0 b	0.0 b
	2.0	0.0 b	0.0 b
	0	6.5 a	0.5 a
Tall fescue	1.0	0.0 b	0.0 b
	2.0	0.0 b	0.0 b
	0	11.4 a	0.5 a
Vetch	1.0	6.7 b	0.4 a
	2.0	5.1 c	0.5 a
	0	11.3 a	0.5 a
Rapeseed	1.0	0.0 b	0.0 b
	2.0	0.0 b	0.0 b
Average		3.63	0.36
CV (%)		5.73	12.71

Means followed by the same letter, in the column inside each species, do not differ according to Tukey's test at 5% probability.

Both in soybean (first crop) and maize following soybean (second crop), weed control is accomplished primarily by pre-planting burndown with glyphosate (Oliveira et al, 2013), which contributed to the higher selection pressure of weeds resistant to this herbicide, especially sourgrass (*Digitaria insularis*) and horseweed (*Conyza spp*), with widespread distribution.

In soybean cultivation, herbicides inhibiting the enzyme acetolactate synthase (ALS) from sulphonylurea group, as chlorimuron and diclosulam, and imidazolinones as imazapic and imazapyr, are suitable options for management of resistant horseweed (Davis et al, 2009), with some days of residual period after application.

Using imidazolinone-tolerant maize after soybeans could either be a complementary tool for management of glyphosate-resistant horseweed as well as option for repositioning the ALS inhibitors in the management of this species throughout the year, leaving space for herbicides with other mechanisms of action, such as 2,4-D and saflufenacil, to be added to glyphosate in the burndown prior to planting soybeans. In this sense, the development of imidazolinone-tolerant hybrids, allows selective control both of red rice and barnyardgrass in crop rotation with rice in southern Brazil, and may also be tool for management of glyphosate-resistant horseweed in several regions of Brazil which produces maize and soybean, both in succession and rotation.

Evidently, the intensive use of ALS-inhibiting herbicides may favor the appearance of weeds resistant to these herbicides, a fact already reported by Roso et al (2010) for red rice. These authors also remark, however, that high frequency red rice resistant plants carrying the S653D mutation, which is the same mutation responsible for the resistance in the rice cultivars largely used in Southern Brazil, suggests that gene flow is occurring from the rice cultivar to red rice, as found by Shivrain et al (2007). Thus crop rotation with ALS-resistant maize may be a tool to reduce the spread of red rice resistance to ALS inhibitors by cross-fertilization. In addition, this study reinforces that both atrazine and s metolachlor are important tools for delaying the appearance of resistant red rice biotypes.

Conclusions

The herbicide [imazapic + imazapyr], at doses of 0.080, 0.100 and 0.120 kg ha^{-1} is selective for maize cv. C 909 CL, being also effective on red rice (*Oryza sativa*) control when applied in post-emergence at stages of three leaves to two tillers, in dose of 52.5 + 17.5 g a.i. ha^{-1} (0.100 kg c.p. ha^{-1}). Nicosulfuron was also selective for genotype C 909 CL;

Atrazine applied in early post-emergence added with adjuvant, alone or in mixture with s metolachlor, as well as [imazapic + imazapyr] 52.5 + 17.5 g a.i. ha^{-1} plus atrazine (2.5 kg a.i. ha^{-1}), are effective in controlling red rice and barnyardgrass. At the same dose (0.100 kg c.p. ha^{-1}), [imazapic + imazapyr] with addition of mineral oil Assist (0.5% v v^{-1}) is not effective in controlling red rice, being indicated for greater efficiency, the addition of Cicol or Dash as adjuvants when the aim is red rice control;

The association of imazapic and imazapyr caused death of all winter species tested, except vetches.

Physiological characteristics were influenced by the action of herbicides and doses. Vetch (*Vicia sativa*) should be further investigated as a potential species to be used in phytoremediation in areas with history of [imazapic + imazapyr] application;

Application of [imazapic + imazapyr] at dose of 0.100 kg c.p. ha^{-1} (equivalent to 52.5 + 17.5 g a.i. ha^{-1}) on imidazolinone-tolerant maize was effective in controlling red rice and barnyardgrass and selective to the crop. Control efficiency depends on the nature of the adjuvant used, and residues of these herbicides can affect winter crops in succession. Future studies should be conducted to evaluate the use of vetch in phytoremediation following imidazolinone-tolerant maize.

References

Andres A, Concenço G, Theisen G, Galon L, Tesio F, 2012. Management of red rice (*Oryza sativa*) and barnyardgrass (*Echinochloa crus-galli*) grown with sorghum with reduced rate of atrazine and mechanical methods. Experimental Agriculture 48: 587-596.

Bedmar F, Manetti P, Monterubbianesi G, 1999. Determination of the critical period of weed control in corn using a thermal basis. Pesquisa Agropecuaria Brasileira 34: 88-193.

Box GEP, Cox DR, 1982. An analysis of transformation revisited, rebutted. Journal of the American Statistical Association 77: 209-210.

Ceccon G, Staut LA, Sagrilo E, Machado LAZ, Nunes DP, Alves VB, 2013. Legumes and forage species sole or intercropped with corn in soybean-corn succession in midwestern Brazil. Revista Brasileira de Ciencia do Solo 37: 204-212.

Concenço G, Aspiazú I, Ferreira EA, Galon L, Silva AF, 2012. Physiology of Crops and Weeds Under Biotic and Abiotic Stresses, pp. 258-280. In: Applied Photosynthesis. Najafpour MM ed. Intech, Rijeka

Dal Magro T, Agostinetto D, Silva, AA, Vargas L, Panozzo LE, Galon L, 2006. Physiologic characteristics and development of resistant and susceptible *Cyperus difformis* to pyrazosulfuron-ethyl herbicide. Scientia Agraria 12: 149-156

Davis VM, Kruger GR, Stachler JM, Loux MM, Johnson WG, 2009. Growth and seed production of horseweed (*Conyza canadensis*) populations resistant to glyphosate, ALS-inhibiting, and multiple (glyphosate + ALS-inhibiting) herbicides. Weed Science 57: 494-504

Embrapa Maize and Sorghum, 2012. Cultivo do milho. Embrapa CNPMS, Sete Lagoas. Available at: http://sistemasdeproducao.cnptia.embrapa.br/FontesHTML/Milho/CultivodoMilho_8ed/index.htm. Accessed on 29 August 2013

EWRC - European Weed Research Council. Report of the 3rd and 4th meetings of EWRC, 1964. Cittee of Methods in Weed Research, pp. 88. In: Weed Research. Oxford

Gallaher K, Mueller TC, Hayes RM, Schwartz O, Barrett M, 1999. Absorption, translocation and metabolism of primisulfuron and nicosulfuron in broadleaf signalgrass (*Brachiaria platyphylla*) and corn. Weed Science 47: 8-12

Galon L, Concenço G, Ferreira EA, Silva AF, Ferreira FA, Noldin JA, Freitas MAM, 2009. Competition between rice plants and *Echinochloa spp*. biotypes resistant or susceptible to quinclorac. Planta Daninha 27: 701-709

Gurevitch J, Scheiner SM, Fox GA, 2006. The ecology of plants. Sinauer, Sunderland

Kawahigashi H, Hirose S, Ohkawa H, Ohkawa Y, 2005. Transgenic rice plants expressing human CYP1A1 remediate the triazine herbicides atrazine ans simazine. Journal of Agricultural and Food Chemistry 53: 8557-8564

Kraemer AF, Marchesan E, Avila LA, Machado SLO, Grohs M, 2009. Environmental fate of imidazolinone herbicides - a review. Planta Daninha 27: 629-639

López-Martínez N, Marshall G, DePrado R, 1997. Resistance of barnyardgrass (*Echinochloa crus-galli*) to atrazine and quinclorac. Pesticide Science 51: 171-175

Mignouna DB, Mutabazi KDS, Senkondo EM, Manyong VM, 2011. Imazapyr-resistant maize technology adoption for witch weed control in Western Kenya. African Crop Science Journal 19: 173-182

Monks CD, Wilcut JW, Richburg JS, Hatton JH, Patterson MG, 1996. Effect of AC 263, 222, imazethapyr and nicosulfuron on weed control and imidazolinone-tolerant corn (*Zea mays*) yield. Weed Technology 10: 822-827

Nyalemegbe KK, Oteng JW, Darkwa EO, Oti-Boateng C, 2011. Comparative study of lowland rice-based cropping systems on the vertisols of the Accra plains of Ghana. Agricultural Science Research Journal 1: 172-177

Oliveira P, Nascente AS, Kluthcouski J, Castro TAP, 2013. Corn and soybean yields as affected by cover crops and herbicide timing under no-tillage system. Planta Daninha 31: 939-946

Ottis BV, Talbert RE, 2007. Barnyardgrass (*Echinochloa crus-galli*) control and rice density effects on rice yield components. Weed Technology 21: 110-118

Roso AC, Merotto Jr A, Delatorre CA, Menezes VG, 2010. Regional scale distribution of imidazolinone herbicide-resistant alleles in red rice (*Oryza sativa* L) determined through SNP markers. Field Crops Res 119: 175-182

Shivrain VK, Burgos NR, Anders MM, Rajguru SN, Moore J, Sales MA, 2007. Gene flow between Clearfield rice and red rice. Crop Protection 26: 349-356

Sharkey TD, Raschke K, 1981. Effect of light quality on stomatal opening in leaves of *Xanthium stru-*

marium L. Plant Physiol 68: 1170-1174
Sprague CL, Stoller EW, Hart SE, 1997. Preemergence broadleaf weed control and crop tolerance in imidazolinone-resistant and susceptible corn (*Zea mays*). Weed Technology 11: 118-122
Taiz L, Zeiger E, 2010. Plant Physiology. Sinauer, Sunderland
Tamado T, Ohlander L, Milberg P, 2002. Interference by the weed *Parthenium hysterophorus* L with grain sorghum: Influence of weed density and duration of competition. International Journal of Pest Management 48: 183-188
Ulbrich AV, Souza RP, Shaner D, 2005. Persistence and carryover effect of imazapic and imazapyr in Brazilian cropping systems. Weed Technology 19: 986-991
Vencill WK, 2002. Herbicide handbook. Weed Science Society of America, Lawrence