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Effective Preemergence Herbicides for Rigid Ryegrass (*Lolium rigidum* Gaud.) Control in Irrigated Bread Wheat (*Triticum aestivum* L.)

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Abstract

Three on-farm weed control experiments were conducted in irrigated bread wheat in the Doukkala perimeter, Morocco, in 2015-16 and 2016-17 in order to study the efficacy of 4 pre-emergence herbicide treatments for controlling rigid ryegrass that is resistant to 13 post-emergence herbicides. Results showed that 3 pre-emergence herbicides [i) chlorotoluron, 2000 g/ha + isoxaben, 74.8 g/ha; ii) prosulfocarb, 4000 g/ha; iii) prosulfocarb, 2000 g/ha + s-metolachlor, 300 g/ha] reduced rigid ryegrass shoot biomass by > 90% 1 to 3 months after treatments (MAT). Pendimethalin (1320 g ha^{-1}) achieved 83-99% rigid ryegrass control 1 to 3 MAT. The four herbicide treatments were safe on wheat in one experiment, but reduced wheat density in 2 other experiments due to heavy rain (about 100 mm) after herbicide treatments and before crop emergence. Grain yields in sprayed plots ranged from 6.6 to 9.8 t ha^{-1}, 4.4 to 7.4 t ha^{-1}, 7.3 to 8.9 t ha^{-1} in experiments 1 to 3, respectively. Straw yields were 11.4 to 15.4, 9.6 to 15.8, and 10.1 to 14.5 t ha^{-1} in the 3 experiments, respectively. These preemergence herbicides need to be used by wheat growers as part of an integrated weed management program. Further research is needed to explore ways to avoid wheat injury, that could be occasionally caused by heavy rain or irrigation, after preemergence herbicide application and before crop emergence.

Keywords: rigid ryegrass, *Lolium rigidum*, preemergence herbicides, resistance to herbicides, irrigated wheat

1. Introduction

Because of over reliance on herbicides, rigid ryegrass (*Lolium rigidum* Gaud.) has evolved resistance to 13 different herbicide mode of action groups in 12 countries (Heap, 2018). It is the first example of a weed that demonstrated multiple resistance to many herbicide families, including aryloxyphenoxyproprionates, cyclohexanediones, sulfonylureas, and others. The patterns of resistance are variable, reflecting the genetic diversity of the species and the management practices imposed. Resistance in rigid ryegrass is one of the most economically important examples of herbicide resistance in world agriculture. The mechanisms of resistance in rigid ryegrass have been demonstrated to be i) target site mutations within ACCase (acetyl coenzyme A carboxylase) and ALS (acetolactate synthase) and ii) enhanced herbicide metabolism of ACCase-, ALS-, and PS II–inhibiting herbicides (Délye, 2005; Scarabel et al., 2011; Malone et al., 2014; Yu & Powles, 2014; Saini et al., 2015; Han et al., 2016; Loureiro et al., 2017).

Rigid ryegrass has many features that contribute to the evolution of resistance, including i) a very well adapted species to the Mediterranean climate, ii) a propensity to occur in large densities, iii) the high genetic diversity within populations, iv) a self-incompatibility and cross-pollinated species, v) the potential to set a large amount of seed, allowing any resistant survivors to significantly increase the resistance status of a population, vi) the short-lived innate dormancy, which results in a large amount of the seedbank germinating in the next season, vii) the short soil seedbank life, and viii) the ability to rapidly evolve resistance to herbicides (Castellanos-Frias et al., 2016; Bararpour et al., 2017).

In Morocco, rigid ryegrass has infested Tadla irrigated perimeter since 2010 (Baye, 2014) and Doukkala since 2000 (Tanji, 2009, 2011, 2013; Tanji et al., 2012; El Aimani & Tanji, 2016). Rigid ryegrass is now resistant to 13 herbicides (7 wheat herbicides: clodinafop, diclofop, fenoxaprop, mesosulfuron, pinoxaden, pyroxsulam, and tralkoxydim, and 6 sugar beet (and other broadleaf crops) herbicides: cycloxydim, fluazifop, haloxyfop, propaquizafop, quizalofop, and tepraloxydim). All these herbicides that are no longer effective on rigid ryegrass have two modes of action: inhibition of acetyl coenzyme A carboxylase (ACCase) (group A) such as clodinafop, cycloxydim, diclofop, fenoxaprop, fluazifop, haloxyfop, pinoxaden, propaquizafop, quizalofop, tepraloxydim, and tralkoxydim, and inhibition of acetolactate synthase (ALS) (group B) such as mesosulfuron and pyroxsulam. Temporarily, clethodim has the ability to control rigid ryegrass populations having resistance to other ACCase-inhibiting herbicides (Tanji, 2013).

With the ineffectiveness of post-emergence herbicides on the herbicide-resistant rigid ryegrass, pre-emergence herbicides (prosulfocarb, s-metolachlor, and others) were registered in Australia, USA, Europe, and other countries for use in wheat (Negre et al., 2006; Chauhan et al., 2007; Boutsalis et al., 2014; Kleemann et al., 2014; Preston et al., 2017). In Morocco, there were recently registrations of pre-emergence herbicides (chlorotoluron, isoxaben, prosulfocarb, s-metolachlor, and others) that have provided an effective tool for control of multiple-herbicide-resistant rigid ryegrass populations. According to Heap (2018), Chlorotoluron belongs to the urea that inhibits photosynthesis at photosystem II (group C2). Isoxaben is a Benzamide that inhibits cell wall (cellulose) synthesis (group L). Pendimethalin is a dinitroaniline that inhibits microtubule assembly (group K1). Prosulfocarb is a herbicide belonging to the thiocarbamates (group N) which inhibits lipid synthesis without inhibiting acetyl coenzyme A carboxylase (ACCase). S-metolachlor is a chloroacetamide herbicide that inhibits cell division (group K3). All these herbicides are able to control emerging rigid ryegrass and other weeds when applied preemergence in wheat and other crops. The objective of this paper is to present results on the efficacy of 4 preemergence herbicide treatments on rigid ryegrass that has evolved resistance to several postemergence herbicides.

2. Materials and Methods

2.1 Experiment Site and Design

Three on-farm weed control experiments were conducted in the Doukkala irrigated perimeter, Morocco: experiment 1 in 2015-16 and experiments 2 and 3 in 2016-17. Cultural practices are indicated in table 1. Each experiment was a randomized complete block design with 3 replications. Three herbicide treatments were used in experiment 1 in 2015-16 (Table 3) and four herbicide treatments were used in experiments 2 and 3 in 2016-17 (Tables 4 and 5). Herbicide treatments were applied by a backpack sprayer using 200 L ha^{-1}. Plots were 10 m × 3 m. Rigid ryegrass was the most abundant weed in the experiments (101, 140, and 940 plants m^{-2}, in experiments 1, 2, and 3, respectively). Several broadleaf weeds were found in the sites including burning nettle (*Urtica urens*), goosefoot (*Chenopodium murale*), sowthistle (*Sonchus oleraceus*), curly dock (*Rumex pulcher*), and spiny emex (*Emex spinosa*) (Table 2).

2.2 Measurements

Weeds were collected from one 0.50 m × 0.50 m quadrat in each plot. They were clipped at ground level, bagged, and fresh weight measured 1, 2, and 3 months after treatment. Rigid ryegrass shoot biomasss reduction due to herbicide treatments was calculated as follows:

% rigid ryegrass shoot biomass reduction = [(Rigid ryegrass shoot biomass in weedy plots – Rigid ryegrass shoot biomass in treated plots)/Rigid ryegrass shoot biomass in weedy plots] × 100 (1)

At full maturity, wheat was harvested at ground level in an area of 1 m² per plot. Wheat was threshed by a small combine and grain was cleaned and weighed. Wheat yield loss due to weed competition and yield increase due to herbicide use were calculated as follows:

% yield loss = [(Wheat yield in weed-free plots – Wheat yield in weedy plots)/ Wheat yield in weed-free plots] × 100 (2)

% yield increase = [(Wheat yield in weed−free plots – Wheat yield in weedy plots)/ Wheat yield in weedy plots] × 100 (3)

2.3 Statistical Analyses

Measured variables (weed shoot fresh weight, wheat grain yield, and wheat straw yield) varied across experiments and cropping seasons, primarily due to differences in environmental conditions (irrigation, rainfall, soil type, crop rotation). Therefore, data analysis was performed for each experiment to determine the significance of the herbicide treatments. Weed biomass and wheat yield were subjected to the ANOVA using SAS (SAS Institute, Cary, NC, USA). Means were compared using the Fisher's protected LSD at $p = 0.05$.

3. Results and Discussion

3.1 Weed Control

Chlorotoluron (2000 g ha^{-1}) + isoxaben (74.8 g ha^{-1}), prosulfocarb (4000 g ha^{-1}), and prosulfocarb (2000 g ha^{-1}) + s-metolachlor (300 g ha^{-1}) reduced rigid ryegrass shoot biomass by > 90% during 3 months after treatments (MAT) (Tables 3 to 5). Pendimethalin (1320 g ha^{-1}) provided 83-99% rigid ryegrass control 1 to 3 MAT. Therefore, pre-emergence herbicides provided good to excellent control of rigid ryegrass that is resistant to 13 post-emergence herbicides having 2 modes of action (inhibition of ACCase and ALS). Thus, they would give acceptable season-long control. However, the few resistant ryegrass plants that were present in treated plots grew vigorously and produced seed.

Table 1. Characteristics of the 3 experiments conducted in the Doukkala irrigated perimeter in 2015-16 and 2016-17

	Experiment 1	Experiment 2	Experiment 3
	2015-16	2016-17	2016-17
Location	Sidi Bennour	Tnine Gharbia	Sidi Bennour
Crop	«Amal» Bread wheat	«Amal» Bread wheat	«Amal» Bread wheat
Preceding crop	melon	sugarbeet	sugarbeet
Tillage	1 tandem disc + manual fertilizer spreading + 1 tandem disc + Planting with a drill	1 deep plow + 1 tandem disc + manual fertilizer spreading + 1 tandem disc + Planting with a drill	1 deep plow + 1 tandem disc + manual fertilizer spreading + 1 tandem disc + Planting with a drill
Date of planting	Nov 20, 2015	Nov 15, 2016	Nov 16, 2016
Date of crop emergence	Dec 1, 2015	Dec 1, 2016	Dec 1, 2016
Seeding rate	200 kg ha^{-1}	200 kg ha^{-1}	200 kg ha^{-1}
Fertilizer at planting	200 kg ha^{-1} 15-15-15	300 kg ha^{-1} 15-15-15	300 kg ha^{-1} 15-15-15
Top dressing nitrogen	100 kg ha^{-1} ammonium nitrate 33% at tillering + 100 kg ha^{-1} ammonium nitrate 33% at jointing	100 kg ha^{-1} ammonium nitrate 33% at tillering + 100 kg ha^{-1} ammonium nitrate 33% at jointing	100 kg ha^{-1} ammonium nitrate 33% at tillering + 100 kg ha^{-1} ammonium nitrate 33% at jointing
Irrigation system	Flood irrigation	Sprinkle irrigation	Flood irrigation
Fungicides	Epoxiconazole (125 g ha^{-1}) followed by propiconazole (125 g ha^{-1})	Epoxiconazole (125 g ha^{-1}) followed by propiconazole (125 g ha^{-1})	Epoxiconazole (125 g ha^{-1}) followed by propiconazole (125 g ha^{-1})
Date of spraying weed control experiments	Nov 25, 2015 after planting before emergence	Nov 22, 2016 after planting before emergence	Nov 26, 2016 after planting before emergence

Table 2. Weed density in plants m^{-2} after wheat emergence in the untreated plots in 3 experiments conducted in the Doukkala irrigated perimeter, Morocco, in 2015-16 and 2016-17

Weed species	2015-16	2016-17	2016-17
	Experiment 1	Experiment 2	Experiment 3
Rigid ryegrass (*Lolium rigidum*)	101	140	940
Burning nettle (*Urtica urens*)	332	4	0
Goosefoot (*Chenopodium murale*)	8	0	0
Curly dock (*Rumex pulcher)*	4	0	0
Spiny emex (*Emex spinosa*)	1	0	0
Chickweed (*Stellaria media*)	0	0	0
Catchfly (*Silene gallica*)	0	0	0
Others	12	2	0
Total density (plants m^{-2})	458	146	940

In general, maximum weed densities and weed fresh weights were recorded in the weedy plots while minimum weed densities and fresh weights were observed in plots treated with pre-emergence herbicides. In Australia, Boutsalis et al. (2014) and Kleemann et al. (2014) found that prosulfocarb at 2000 g ha^{-1} + s-metolachlor at 300 g ha^{-1} provided > 64% control of herbicide resistant rigid ryegrass. Pendimethalin at 720 g ha^{-1} provided 75% control of herbicide resistant rigid ryegrass (Chauhan et al., 2007).

3.2 Wheat Injury

The four herbicide treatments [i) chlorotoluron (2000 g ha^{-1}) + isoxaben (74.8 g ha^{-1}), ii) prosulfocarb (4000 g ha^{-1}), iii) prosulfocarb (2000 g ha^{-1}) + s-metolachlor (300 g ha^{-1}), and iv) pendimethalin (1320 g ha^{-1})] reduced wheat emergence and density in both experiments in 2016-17 (data not shown). However, none of the herbicide treatments visibly injured wheat in 2015-16. It is highly possible that wheat injury was due to heavy rain (about 100 mm) after herbicide treatments and before crop emergence. Kleemann et al. (2014) found that prosulfocarb (2000 g ha^{-1}) + s-metolachlor (300 g ha^{-1}) reduced wheat density 25 to 57% when planting was associated with heavy post-planting rainfall. Such rainfall events after planting could cause movement of the herbicides into the furrow. The risk of wheat injury from preemergence applications could be lessened if planting or preemergence herbicide applications are postponed when heavy rain (and/or irrigation) is forecast. Prosulfocarb + s-metolachlor occasionally resulted in a significant reduction in wheat emergence but not crop yield (Boutsalis et al., 2014).

3.3 Wheat Grain Yields

Although reductions in wheat plant density due to injury from all herbicides, there was still a significant yield increase relative to the nontreated plots as a result of the effective control. These results suggest that wheat can compensate for early reduction in wheat density, the crop was able to fully recover and did not suffer any yield penalty. Thus, no significant differences were observed between yields obtained in various treated plots. Yield variations between experiments and years were probably due to different preceding crops and irregular durations between irrigations. Grain yields in sprayed plots ranged from 6.6 to 9.8 t ha^{-1}, 4.4 to 7.4 t ha^{-1}, 7.3 to 8.9 t ha^{-1}, in experiments 1 to 3, respectively (Tables 3 to 5).

Using the highest yields obtained in treated plots, potential grain yield increases due to weed control were 100 to 197% in experiment 1 (2015-16), 126 to 174% in experiment 2 (2016-17), and 92 to 134% in experiment 3 (2016-17), compared to the yields observed in nontreated plots (Tables 3 to 5). Weed control improved grain yields through better utilization of available resources like water, fertilizer, sunlight, and space. Other appropriate practices that could have increased grain yield were November planting, certified seeds, disease control with two fungicide treatments, and irrigation (Tanji et al., 2017). Kleemann et al. (2014) found that the highest wheat grain yields were observed in plots where rigid ryegrass resistant to postemergence herbicides was effectively controlled with preemergence herbicides such as prosulfocarb (2000 g ha^{-1}) + s-metolachlor (300 g ha^{-1}).

In untreated plots, grain yields were low compared to treated plots (Tables 3 to 5). Potential yield losses due to weed competition throughout the growing season were 66, 63, and 57% compared to the highest yields observed in treated plots in experiments 1, 2, and 3, respectively. Rigid ryegrass and broadleaf weeds left in the nontreated plots appeared to cause significant crop production losses; hence, herbicide selection should be based on knowledge of weed species present within the weed flora. This is consistent with previous research that has emphasized the potential for irrigated bread wheat yield loss due to rigid ryegrass competition (Tanji et al., 1997).

Table 3. Rigid ryegrass shoot fresh biomass (g m^{-2}) and wheat yield (t ha^{-1}) in experiment 1 in the Doukkala irrigated perimeter, Morocco, in 2015-16

Herbicide (rate ha^{-1})		Shoot fresh biomass of rigid ryegrass (g m^{-2})			Wheat yield (t ha^{-1})	
		1 MAT	2 MAT	3 MAT	Grain	Straw
Chlorotoluron (2000 g) + Isoxaben (74.8 g)	AUBAINE (4 L)	7	213	53	9.8	15.4
Prosulfocarb (4000 g)	BOXER (5 L)	13	93	607	6.6	12.1
Pendimethalin (1320 g)	PROWL (4 L)	80	260	167	7.2	11.4
Untreated check		460	2307	6113	3.3	5.6
LSD (0.05)		256	1362	2241	1.6	3.1

Note. MAT: month after treatment; Prosulfocarb (2000 g) + s-metolachlor (300 g) was not evaluated in this experiment.

Table 4. Rigid ryegrass shoot fresh biomass (g m^{-2}) and wheat yield (t ha^{-1}) in experiment 2 in the Doukkala irrigated perimeter, Morocco, in 2016-17

Herbicide (rate ha^{-1})		Shoot fresh biomass of rigid ryegrass (g m^{-2})			Wheat yield (t ha^{-1})	
		1 MAT	2 MAT	3 MAT	Grain	Straw
Chlorotoluron (2000 g) + Isoxaben (74.8 g)	AUBAINE (4 L)	7	180	120	6.8	9.6
Prosulfocarb (4000 g)	BOXER (5 L)	4	40	700	6.1	10.6
Prosulfocarb (2000 g) + s-metolachlor (300 g)	BOXER GOLD (2.5 L)	3	0	513	7.4	15.8
Pendimethalin (1320 g)	PROWL (4 L)	17	727	1780	4.4	10.8
Untreated check		300	4793	10340	2.7	4.4
LSD (0.05)		30	1055	2244	2.3	5.9

Note. MAT: month after treatment.

Table 5. Rigid ryegrass shoot fresh biomass (g m^{-2}) and wheat yield (t ha^{-1}) in experiment 3 in the Doukkala irrigated perimeter, Morocco, in 2016-17

Herbicide (rate ha^{-1})		Shoot fresh biomass of rigid ryegrass (g m^{-2})			Wheat yield (t ha^{-1})	
		1 MAT	2 MAT	3 MAT	Grain	Straw
Chlorotoluron (2000 g) + Isoxaben (74.8 g)	AUBAINE (4 L)	0	0	40	8.9	12.5
Prosulfocarb (4000 g)	BOXER (5 L)	1	93	147	7.3	10.5
Prosulfocarb (2000 g) + s-metolachlor (300 g)	BOXER GOLD (2.5 L)	1	20	187	8.4	14.5
Pendimethalin (1320 g)	PROWL (4 L)	1	107	87	7.5	10.1
Untreated check		933	2107	4280	3.8	7.9
LSD (0.05)		NS	469	1387	1.1	5.4

Note. MAT: month after treatment.

3.4 Wheat Straw Yields

In the 3 experiments, higher wheat straw yields were obtained in treated plots compared to untreated plots: 11.4 to 15.4, 9.6 to 15.8, and 10.1 to 14.5 t ha^{-1} in the 3 experiments, respectively (Tables 3 and 5). However, the lowest wheat straw yields (5.6, 4.4, and 7.9 t ha^{-1}, respectively) were observed in untreated plots which showed severe competition of high stands of rigid ryegrass (101, 140, and 940 plants m^{-2}, respectively) with bread wheat. Using the highest straw yields observed in treated plots, potential yield increases due to weed control were 104 to 175%, 118 to 259%, and 28 to 84%, compared to wheat straw yields measured in nontreated plots in experiments 1 to 3, respectively. Potential straw yield losses due to weed competition were 64, 72, and 46%

compared to the highest straw yields observed in treated plots in experiments 1, 2, and 3, respectively. Previous research showed that weed control with herbicides improved wheat straw yields through better utilization of water and other resources (Tanji et al., 2017).

4. Conclusion

The results of this study indicate that excellent to good control of rigid ryegrass that is resistant to postemergence herbicides (essentially cyclohexanediones and aryloxyphenoxypropionates) can be achieved by the application of preemergence herbicide treatments such as chlorotoluron (2000 g ha^{-1}) + isoxaben (74.8 g ha^{-1}), prosulfocarb (4000 g ha^{-1}), prosulfocarb (2000 g ha^{-1}) + s-metolachlor (300 g ha^{-1}), or pendimethalin (1320 g ha^{-1}). Although preemergence herbicides provide effective new options for the selective control of postemergence herbicide resistant rigid ryegrass, preemergence herbicides need to be used by wheat growers as part of an integrated weed management program. Further research is needed to explore ways to avoid wheat injury, occasionally caused by heavy rain or irrigation after preemergence herbicide application and before crop emergence.

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