Journal of Plant Protection Research ISSN 1427-4345

ORIGINAL ARTICLE

Study of postemergence-directed herbicides for redroot pigweed (*Amaranthus retroflexus* L.) control in winter wheat in southern Russia

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Vol. 60, No. 1: 7–13, 2020

DOI: 10.24425/jppr.2019.131272

Received: June 28, 2019
Accepted: August 19, 2019

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Abstract

Redroot pigweed (*Amaranthus retroflexus* L). is a broadleaf weed in autumn crop fields in Russia. Four field experiments were performed in Stalskiy region, southern Russia in two growing seasons, 2016 and 2017, to investigate the effects of postemergence applications of applied alone or in tank mixtures in winter wheat cultivars Tanya and Bagrat. Redroot pigweed control was greatest with tribenuron and all herbicide treatments containing tribenuron. The lowest redroot pigweed control was with aminopyralid/florasulam (study 1) and triasulfuron (study 2), respectively, whereas redroot pigweed had intermediate responses to the other examined herbicides. Tribenuron plus fluroxypyr sprayed on wheat cultivar 'Tanya', and tribenuron plus triasulfuron on wheat cultivar 'Bagrat' resulted in increased wheat grain yields. Overall, tribenuron and herbicides containing tribenuron provided the most efficient redroot pigweed control compared with the other herbicides and consistently maintained optimal winter wheat yields. Tribenuron could ameliorate redroot resistance to herbicides in wheat fields in southern Russia.

Keywords: post herbicide, redroot pigweed, weed control, winter wheat

Introduction

The major difficulty in efforts to expand winter wheat cultivation on Russian prairies is the lack of applying appropriate agronomic practices to maximize crop growth and yield (Johnson *et al.* 2017). Profitable winter wheat production on Russian prairies hinges upon direct sowing of cultivars into standing stubble in late summer (Zargar *et al.* 2017a). Beres *et al.* (2010) stated that winter wheat is competitive against summer annual weeds. However, potentially winter annual weeds can be highly competitive against winter wheat (Blackshaw 1993).

Redroot pigweed (*Amaranthus retroflexus* L.) is a troublesome C_4 broadleaf weed that is widespread in farmlands of Iran, central Asia (Sheibany *et al.* 2009), and Russia (Spiridonov and Shestakov 2013). It is difficult to control because of its high seed production and extended germination period (Francischini *et al.* 2014). It competes aggressively with crops for light, nutrients and water and severely affects the yield and quality of crops. In southern Russia, redroot pigweed poses a potential threat to winter wheat production as it is highly endemic in this region (Poska 2018). It has developed resistance to herbicides with different modes of action, such as acetolactate synthase (ALS) inhibitors, protoporphyrinogen oxidase (PPO) inhibitors, and photosystem II inhibitors (Heap 2018). The first case of ALS-inhibitor-resistant redroot pigweed was reported in Ontario in 1997. This population was characterized by high-level resistance to imazethapyr and high-level cross-resistance to thifensulfuron (Ferguson *et al.* 2001; Mennan *et al.* 2011). Poska (2018) reported that redroot pigweed has recently become one of the most important weeds of wheat fields in Russia. The timely application of herbicides and the use of competitive and high yielding varieties can potentially reduce yield losses caused by redroot pigweed in winter wheat on Russian prairies (Spiridonov and Shestakov 2013).

Herbicides are now an integral part of Russian agriculture (Zargar *et al.* 2017b). Previous studies have evaluated the efficacy of postemergence herbicides on redroot pigweed. Sarabi *et al.* (2011) evaluated the efficacy of mixtures of 2,4-D plus MCPA with foramsulfuron and dicamba. Mixtures of postemergence herbicides are recommended to sustain seasonal long-term control of redroot pigweed. According to Beckie and Harker (2017), herbicide rotation and tank-mixing can be a key component of an Integrated Weed Management program, as repeated herbicide application of herbicides with the same mode of action can result in herbicide-resistant biotypes. However, only a few studies have reported on postemergence herbicide programs for redroot pigweed management in winter wheat in Russia. The objective of this study was to determine winter wheat tolerance and redroot pigweed response to postemergence-directed herbicides and herbicide mixtures.

Materials and Methods

This research consisted of four experiments that were conducted in 2016 and 2017. Experimental fields were established in southern Russia, namely Stalskiy region, Zardian (42°57' N, 38°39' E and 150 m altitude). The winter wheat cultivar 'Tanya' was sown in experiments 1 and 2 (study 1) and 'Bagrat' in experiments 3 and 4 (study 2). The soil of the experimental area was classified as C sand (fine-loamy, thermic Typic Kandiudults) with pH 6.1 and organic matter 1.8%. During the experiments temperature and rainfall data was obtained from the nearby Caspian Scientific Research Institute of Arid Agriculture (Fig. 1).

The experimental design used for all experiments was a randomized complete block design with four replicates, with plots 4 m wide by 20 m long, comprising 11 crop rows (row width = 32 cm). Seven products

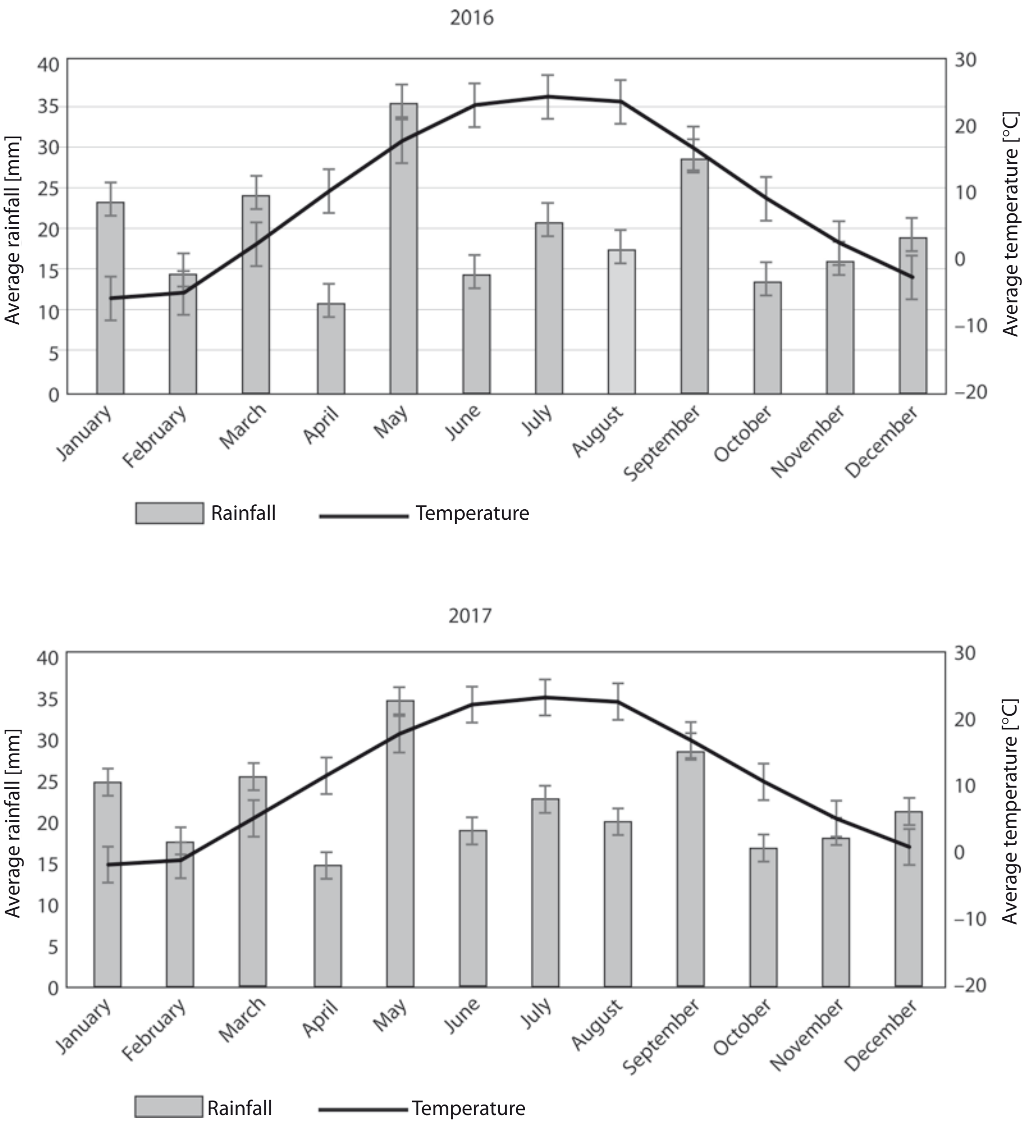

Fig. 1. Weather and precipitation data during experimental years

(active ingredients) were used for all experiments: triasulfuron, aminopyralid/florasulam, 2,4-D, fluroxypyr, tribenuron, pyroxsulam, pyroxsulam and sulfosulfuron. The treatments' detailed description is given in Table 1. Postemergence herbicides were applied at the beginning of April when the winter wheat plants were at the tillering stage and the redroot plants were 5 to 11 cm tall with three to eight leaves. A CO_2 pressurized knapsack sprayer calibrated to produce a spray volume of 200 l · ha^{-1} at 207 kPa using four Hypro ultra-low drift 120-02 nozzles spaced 55 cm apart was used.

Herbicide treatments were compared to weedy (nontreated) and weed-free (treated) control treatments in each block. In the weed-free control treatment, hand-weeding was done every week until complete wheat canopy closure. The weather conditions and height of the pigweed plants when the herbicide treatments were applied in the two seasons are summarized in Table 2.

Each year, at the beginning of September, wheat seeds were directly sowed using a tractor-mounted drill at 185 to 210 kg · ha^{-1} at a depth of 3 cm. The fertilizer application rate for all plots was 220 kg · ha^{-1}, the formulation applied was $N_{12}P_{12}K_{36}$ which was applied side-banded or mid-row banded in the plots. A top dressing of 180 kg · ha^{-1} N was added when the winter wheat was in the early stem stage.

In all experiments, weed sampling was done 1 to 4 weeks after treatments (WAT) in all experiments. Winter wheat and redroot pigweeds were randomly chosen from two sampling areas based on the plant maturity level. Two one meter rows were selected in each plot. Weed density in these areas was counted at 1 WAT, 2 WAT, 3 WAT and 4 WAT. In addition, the sampled weed plants were dried at 70°C in the oven for dry matter (biomass) assessment.

Before statistical analysis, all data were tested for normality and homogeneity of variance. Data analyses were conducted using the GLIMMIX procedure of SAS (Version 9.4, SAS Institute Inc., Cary, NC, USA) using the mixed procedure with block as the random factor. Each experimental year was analysed individually. The least squares mean statement in SAS with the Tukey adjustment at $p = 0.05$ was used for comparison of means. Data obtained from several dates, such as winter wheat and redroot pigweed counts were analysed using the repeated measure.

Table 1. Active ingredients, trade names, doses and concentration/formulation of treatments in study 1 and 2

Active ingredients	Trade name	Dose [g a.i. · ha^{-1}]	Concentration/Formulation
Study 1 (experiments 1 and 2)			
Weedy	–	–	
Tribenuron	Express™	20	750 g · kg^{-1} WDG
Aminopyralid/florasulam	Lancelo™	(15 + 7)	355/150 g · kg^{-1} WG
2,4-D	Esteron®	360	600 g · l^{-1} EC
Tribenuron + aminopyralid/florasulam	Express™ + Lancelo™	20 + (15 + 7)	750 g · kg^{-1} WDG + 355, 150 g · kg^{-1} WG
Fluroxypyr	Demeter^{EC}	150	350 g · l^{-1} EC
Tribenuron + fluroxypyr	Express™ + Demeter^{EC}	20 + 150	750 g · kg^{-1} WDG + 350 g · l^{-1} EC
Fluroxypyr + aminopyralid/florasulam	Demeter^{EC} + Lancelo™	150 + (15 + 7)	350 g · l^{-1} EC + 355, 150 g · kg^{-1} WG
Tribenuron + 2,4-D	Express™ + Esteron®	360 + 20	750 g · kg^{-1} WDG + 600 g · l^{-1} EC
Weed-free	–	–	
Study 2 (experiments 3 and 4)			
Weedy	–	–	–
Tribenuron	Express™	20	750 g · kg^{-1} WDG
Pyroxsulam	Pallas™ 45	15	45 g · l^{-1} OD
Sulfosulfuron	Sulfos®	30	750 g · kg^{-1} WDG
Triasulfuron	Amber®	20	750 g · kg^{-1} WDG
Tribenuron + pyroxsulam	Express™ + Pallas™ 45	20 + 15	750 g · kg^{-1} WDG + 45 g · l^{-1} OD
Pyroxsulam + sulfosulfuron	Pallas™ 45 + Sulfos®	15 + 30	45 g · l^{-1} OD + 750 g · kg^{-1} WDG
Tribenuron + triasulfuron	Express™ + Amber®	20 + 20	750 g · kg^{-1} WDG
Weed-free	–	–	–

WDG – water-dispersible granules; EC – emulsion concentrate; OC – oil concentrate; WG – wet granule; OD – oil dispersion

Table 2. Weather condition and height of redroot pigweed plants when the herbicides were applied in the 2015/16 and 2016/17 season

Location – Year	Sunlight [%]	Temperature [°C]	Relative humidity [%]	Wind speed [km · h^{-1}]	Red root height [cm]
Stalskiy region					
2016	95	17	72	3	3 to 7
2017	87	16	70	4	4 to 11

Results and Discussion

Redroot pigweed control in study 1

Redroot pigweed was reduced by 57 to 88.7% at 1 WAT. At 2 WAT, 3 WAT and 4 WAT the efficacy of redroot control increased from 51.9 to 92.1%, 57.9 to 94% and 59.7 to 84.1%, respectively, for all the experiments. All the treatments were statistically different from the weedy control. Removing the weed-free and weedy control treatments helped us to recognize the differences between experimental treatments. The tank mixture of tribenuron plus fluroxypyr (20 + 150 g a.i. · ha^{-1}) and tribenuron plus aminopyralid/florasulam [20 + (15 + 7) g a.i. · ha^{-1}] applied postemergence were >82% better than the control in all periods in winter wheat cultivar 'Tanya'. The lowest redroot control (51.9%) was attained at 2 WAT with the application of the formulated mixture of aminopyralid/florasulam (15 + 7 g a.i. · ha^{-1}) (Table 3).

The tank mixtures consisting of tribenuron plus aminopyralid/florasulam and tribenuron plus 2,4-D at 3 WAT, tribenuron plus fluroxypyr at 2 WAT indicated a control value statistically similar to the weed-free control plots (Table 3). Results obtained were in agreement with those of Johnson *et al.* (2017), who reported that a postemergence herbicide mixture, consisting of tribenuron, provided favourable weed reduction in wheat. Related to these findings, weed control higher than 80% can be obtained with the use of herbicide mixtures (Mafakheri *et al.* 2012; Maciel *et al.* 2013). Nevertheless, the combinations used in our research can be recommended as being helpful for suppressing redroot pigweed.

Redroot pigweed control in study 2

Postemergence application of tribenuron reduced the weed density to the same extent as the weed free control at 3 WAT in winter wheat 'Bagrat' with the value of 91% (Table 4). However, the effectiveness of a tank mixture of tribenuron plus pyroxsulam (20 + 150 g a.i. · ha^{-1}) did not differ from the weed free control at 2 WAT and 4 WAT with the weed control rate >92%. Herbicide treatments that included tribenuron indicated high success rates during almost all the periods compared with other treatments. The same result was observed in the first study, hence reducing the redroot

Table 3. Redroot pigweed control in wheat cultivar 'Tanya' in study 1, during 2016 and 2017

Active ingredients	Dose [g a.i. · ha^{-1}]	Redroot pigweed control [%]			
		1 WAT	2 WAT	3 WAT	4 WAT
Weedy	—	0.0 g	0.0 f	0.0 f	0.0 f
Tribenuron	20	88.7 b	87.9 b	80.8 bc	79.8 c
Aminopyralid/florasulam	(15 + 7)	60.9 e	51.9 e	61.1 de	71.1 cd
2,4-D	360	79.5 c	75.8 c	65.9 d	59.7 de
Tribenuron + aminopyralid/florasulam	20 + (15 + 7)	82.8 bc	87.9 b	94.0 a	82.2 bc
Fluroxypyr	150	57.0 ef	60.5 de	57.9 e	61.3 de
Tribenuron + fluroxypyr	20 + 150	85.4 b	92.1 ab	88.3 b	84.1 b
Fluroxypyr + aminopyralid/florasulam	150 + (15 + 7)	71.0 d	69.2 d	74.0 cd	71.6 cd
Tribenuron + 2,4-D	360 + 20	77.9 c	84.5 bc	90.2 ab	79.9 c
Weed-free	–	100.0 a	100.0 a	100.0 a	100.0 a
P value	–	0.008	0.0062	0.0022	0.0069
Coefficient of variation [%]	–	10.1	9.6	11.1	4.5

Means followed by different letters are significantly different by Fisher's Protected LSD ($p \leq 0.05$)
WAT – weeks after treatment

Table 4. Redroot pigweed control in wheat cultivar 'Bagrat' in study 2, during 2016 and 2017

Active ingredients	Dose [g a.i. · ha^{-1}]	Redroot pigweed control [%]			
		1 WAT	2 WAT	3 WAT	4 WAT
Weedy	–	0.0 f	0.0 f	0.0 e	0.0 e
Tribenuron	20	81.0 c	86.0 b	91.0 ab	81.1 b
Pyroxsulam	15	51.8 e	66.0 d	72.5 c	64.9 d
Sulfosulfuron	30	81.5 c	79.4 bc	66.0 d	70.0 cd
Triasulfuron	20	59.5 e	58.0 e	64.1 d	72.1 c
Tribenuron + pyroxsulam	20 + 15	87.9 b	93.8 a	83.3 b	92.0 ab
Pyroxsulam + sulfosulfuron	15 + 30	67.0 d	72.8 c	82.0 b	80.1 bc
Tribenuron + triasulfron	20 + 20	81.5 c	80.0 bc	81.6 b	79.8 bc
Weed-free	–	100.0 a	100.0 a	100.0 a	100.0 a
P value	–	0.0001	0.0008	0.0041	0.0025
Coefficient of variation [%]	–	3.6	12.5	4.7	8.8

Means followed by different letters are significantly different by Fisher's Protected LSD ($p \leq 0.05$)
WAT – weeks after treatment

pigweed density in winter wheat. Herbicide treatments consisting of tribenuron, tribenuron plus pyroxsulam and tribenuron plus triasulfuron showed an average redroot control higher than 79% in all treatments. The lowest weed control, besides the weedy-control, was with triasulfuron with an average control value of 63% on all observation dates (Table 4). The use of herbicides is seen as the most effective means of redroot pigweed control in cropping systems of wheat fields, allowing for short period management. Hence, Glazunova *et al.* (2015) reported that redroot pigweed density was desirably reduced by the use of postemergence herbicides in wheat fields of Russia.

Wheat grain yield

The results of the tank mixtures of tribenuron plus aminopyralid/florasulam [20 + (15 + 7) g a.i. · ha^{-1}] and tribenuron + fluroxypyr (20 + 150 g a.i. · ha^{-1}) in winter wheat 'Tanya' (study 1) showed that combinations of these herbicides are effective for redroot control while simultaneously improving wheat yield. The highest grain yield was attained using tribenuron application, resulting in about 63% more grain yield than the weedy control. In sprayed plots the lowest yields were in the plots treated with fluroxypyr, because of lower levels of weed control in winter wheat 'Tanya' (Table 5). These findings were consistent with Curran *et al.* (2015) who reported that treatments involving tribenuron-methyl resulted in greater wheat yields. Enhanced grain yields after spring herbicide applications can be related to the appropriate redroot reduction in wheat fields.

The productivity of the mixture of tribenuron plus triasulfuron for winter wheat 'Bagrat' was 48% higher than the weedy control. The lowest grain yield, except the weedy control, was attained with postemergence application of sulfosulfuron (19.5%). This finding is related to the less effective weed density reduction in wheat cultivar 'Bagrat' (Table 5). Increased redroot pigweed density could cause the relative yield losses in winter wheat (Roberts *et al.* 2001; Nurse *et al.* 2007). In similar research, Huang *et al.* (2019) revealed that redroot pigweed reduced wheat yield to various extents, depending upon the year. Thus, redroot pigweed indirectly reduced corn yield through the reduction of corn density. According to findings from this study, the sulfonylurea group of herbicides is effective in reducing and controlling weeds in wheat fields. Tribenuron with its short soil residual activity (Evans *et al.* 2003; Samtani *et al.* 2014) and postemergence application pattern would appear to be suitable to use in southern parts of the Russian Federation. Wheat yield was obviously influenced by the presence of redroot in both studies.

Regardless of the favourable weed reduction, there were still a number of weeds that managed to survive. This fact may complicate weed management practices in the future especially when using herbicides with a single mechanism of action. Redroot pigweed has been recorded as resistant to different types of herbicides such as 'ALS inhibitors herbicides' florasulam, thifensulfuron-methyl, and tribenuron-methyl in Canada, and imazaquin in the US, and multiple resistance (two Sites of Action: ALS Inhibitors & PPO Inhibitors) such as acifluorfen-sodium, fluoroglycofen-ethyl, fomesafen, imazethapyr, and lactofen in China (Heap 2019).

Therefore, the application of herbicide mixtures with different modes of action can diminish the problem of herbicide resistance in wheat. In this study,

Table 5. Grain yield of winter wheat cultivars affected by herbicides applied alone or in tank mixtures in 2016 and 2017

Active ingredients	Dose [g a.i. · ha⁻¹]	2016	2017	Enhance [t · ha⁻¹]*	Enhance [%]**
Study 1 'Tanya' grain yield [kg · ha⁻¹]					
Weedy	–	5,000 f	5,245 e	–	–
Tribenuron	20	8,420 a	8,290 a	3,232	63.1
Aminopyralid/florasulam	15 + 7	7,560 c	7,300 c	2,308	45.0
2,4-D	360	7,001 d	7,790 bc	2,273	44.3
Tribenuron + aminopyralid/florasulam	20 + (15 + 7)	8,310 b	8,010 b	3,038	59.3
Fluroxypyr	150	6,020 e	6,900 d	1,338	26.1
Tribenuron + fluroxypyr	20 + 150	8,002 bc	8,550 a	3,154	61.5
Fluroxypyr + aminopyralid/florasulam	150 + (15 + 7)	6,700 d	7,800 bc	2,128	41.5
Tribenuron + 2,4-D	360 + 20	7,880 bc	7,990 b	2,813	54.9
Weed-free	–	8,585 a	8,420 a	–	–
p value	–	0.0008	0.0015	–	–
Coefficient of variation [%]	–	10.0	4.5	–	–
Study 2 'Bagrat' grain yield [kg · ha⁻¹]					
Weedy	–				
Tribenuron	20	5,700 ef	5,190 e	–	–
Pyroxsulam	15	7,520 c	8,155 a	2,392	43.9
Sulfosulfuron	30	6,004 e	7,020 c	1,067	19.5
Triasulfuron	20	7,750 bc	6,605 d	1,732	31.8
Tribenuron + pyroxsulam	20 + 15	8,152 ab	7,800 b	2,531	46.4
Pyroxsulam + sulfosulfuron	15 + 30	6,920 d	7,210 c	1,620	29.7
Tribenuron + triasulfuron	20 + 20	8,100 b	8,045 a	2,627	48.2
Weed-free	–	8,510 a	8,120 a	–	–
p value	–	0.0050	0.0017	–	–
Coefficient of variation [%]	–	9.5	12.8	–	–

Means followed by different letters are significantly different by Fisher's Protected LSD ($p \leq 0.05$)
*wheat yield enhance over weedy control
**enhance percent of wheat yield over weedy control

tribenuron and treatments containing tribenuron provided suitable weed reduction. Similar results were obtained by McNaughton *et al.* (2015). They also noted the efficacy ALS inhibitor herbicides on controlling weeds. For sustainable redroot management, the combinations of postemergence herbicides are recommended. Mohammadi and Ismail (2018) reported that broad spectrum postemergence weed control can be achieved by combining tribenuron and pyroxsulam. Using herbicide combinations can prevent weed resistance due to the use of herbicides with more than one mode of action (Galon *et al.* 2018). Additional experiments are needed to investigate the response of subsequent cereal crops (crop rotation) as influenced by the residue of such herbicides in wheat fields. Combining herbicides has advantages over using a single herbicide: reducing production costs by saving time and labor, reducing soil compaction by diminishing different operations, increasing weed control percentages, and delaying the appearance of resistant weed species to herbicides (Damalas 2004). In this research, postemergence application of tribenuron in combination with fluroxypyr (on wheat cultivar Tanya) and triasulfuron (on wheat cultivar Bagrat) provided greater weed control with very little wheat yield loss. Applications of the mentioned treatments were safe for the wheat and can be used in future trials. According to these results, the tank mixture of tribenuron in combination with fluroxypyr and triasulfuron is recommended for application in winter wheat.

Conclusions

The highest redroot pigweed control was observed for tribenuron and also treatments consisting of tribenuron. Tribenuron plus fluroxypyr applied on wheat cultivar 'Tanya', and tribenuron plus triasulfuron on wheat cultivar 'Bagrat' resulted in increased grain yields. Hence, tribenuron and herbicides containing tribenuron provided the highest efficacy of redroot control compared with the other herbicides and consistently maintained desirable wheat yields in most cases. Herbicide-resistant redroot management can be improved by tribenuron application in wheat. Also, POST applications of these treatments were safe for the winter wheat. The present research suggests that tribenuron in combination with fluroxypyr or triasulfuron can facilitate managing *A. retroflexus* resistant to herbicides in wheat.

Acknowledgements

The publication has been prepared with the support of the RUDN University Program 5-100.

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