NARDI FUNDULEA, ROMANIA ROMANIAN AGRICULTURAL RESEARCH, NO. 34, 2017
www.incda-fundulea.ro Print ISSN 1222-4227; Online ISSN 2067-5720

THE YIELD PROTECTION FUNCTION OF SELECTED HERBICIDES IN PROSO MILLET (*PANICUM MILIACEUM* L.) CROPS

Cezary A. Kwiatkowski[1], Małgorzata Haliniarz[1*], Alena Yakimovich[2], Elżbieta Harasim[1], Magda Drabowicz-Żybura[1]

[1] Department of Herbology and Plant Cultivation Techniques, University of Life Sciences in Lublin, 20-950 Lublin, Akademicka 13, Poland

[2]Institute of Plant Protection in Priluki, Mira 2, 223011 District Minsk, Belarus

[*]Corresponding author. E-mail: malgorzata.haliniarz@up.lublin.pl

ABSTRACT

This paper presents the results of a study on the tolerance of proso millet to herbicides (2,4-D + fluroxypyr; tribenuron-methyl + fluroxypyr; MCPA; dicamba + triasulfuron) applied foliarly at the tillering stage of proso millet, at the maximum rate (100%) and at a rated reduced by 50%. Plots without herbicide application were the control treatment. The experiment was carried out on light loess-derived soil (soil class II) under the climatic conditions of the central Lublin region, Poland. It was proved that some foliar-applied herbicides (2,4-D + fluroxypyr and tribenuron-methyl + fluroxypyr) provided an effective reduction in the quantitative indicators of weed infestation in the proso millet crop and thereby contributed to higher productivity of this cereal. Moreover, the above-mentioned herbicides did not cause damage of proso millet plants both when they were applied at the rate reduced by ½ and at the 100% rate. This means that efforts can be taken to register these herbicides for use in proso millet crops. The herbicide dicamba + triasulfuron showed a lower yield-protective effect in growing proso millet, whereas the herbicide MCPA, due to its high phytotoxicity to proso millet plants, resulted in a significant decrease in yield of this crop.

Key words: proso millet, herbicides, plant protection, infestation weeds, yield.

INTRODUCTION

Proso millet (*Panicum miliaceum* L.) is one of the cereals that has been longest known to humanity. The first records about its cultivation come from the times of ancient China. Currently, proso millet is most often grown in Russia, Belarus, India, China, Japan, and the USA. In Africa and Asia, it is the main source of food for people (Shahidi and Chandrasekara, 2013). Moreover, it is used as feed for birds and other animals (Luis et al., 1982), and also as a raw material for the production of ethanol (Rose and Santra, 2013) and beer (Zarnkow et al., 2010). Preliminary research has shown that a diet rich in proso millet in patients subjected to chemotherapy prevents hair loss (Gardani et al., 2007).

In Poland proso millet is an unpopular cereal and is included, alongside buckwheat and herbal plants, in the so-called small-scale crops. The reason is low yields of this crop (0.5-2.7 t ha^{-1}), its low economic importance, and difficult weed control (low competitiveness against weeds). Proso millet is very sensitive to herbicide application, in particular to herbicide residues in the soil. Weed control is generally carried out during the period from emergence until tillering using a light harrow or a weeder harrow. The herbicide Chwastox Extra can also be used at an amount of 1.2-1.8 l ha^{-1} when plants reach a height of 10-15 cm. An earlier or later herbicides application causes plant damage and delays plant growth. In the case of heavy weed infestation, the herbicides used in the cultivation of oats can also be applied, but at low rates (Robinson, 1973; Nelson, 1990; Seefeldt et al., 1995; Stahlman et al., 2009).

Proso millet is a popular crop in the USA, in particular in the states of Nebraska, Wyoming, and Colorado. American scientists have long attempted to determine the tolerance of proso millet to various herbicides (Hanna et al., 2004; Lyon et al., 2008; Lyon and Kniss, 2010). Similar attempts are made in some countries of Western Europe (Rottevel, 200) and also in Belarus (Tomilina and Soroka, 2002; Yakimovich, 2010).

Received 27 July 2016; accepted 7 February 2017. First online: May, 2017. DII 2067-5720 RAR 2017-91

The knowledge of the specificity of agriculture in a particular country and the regional limits of the cultivation of small-scale crops as well as of the diversity of weed communities accompanying such crops can be an important element for chemical companies in applying for minor uses of registered herbicides. It is assumed that in small-scale crops classified in the same taxonomic unit as cereals, beets, oilseed rape or maize the same selective and effective weed control products can be used which are used to kill weeds occurring in this category of crops (Gołębiowska et al., 2011).

The guidelines of the European and Mediterranean Plant Protection Organization (EPPO PP1/224 (1)) state that we have to do with a minor use of a plant protection product in the situation where the respective crop plant is of low economic importance relative to the national level or if agricultural pests are of no importance for the main crop.

As provided for in the Plant Protection Act, plant protection products can only be used in crops for which they have been registered. The lack of recommended plant protection products for crops grown on small areas is primarily due to high registration costs, but it also results from a review of active substances that has significantly reduced the list of useful pesticides. In certain cases, the Plant Protection Act provides for the possibility of using unregistered products (Art. 40. 1., Art. 49.1., Art. 53.1.). The absence of recommendations creates plant protection problems, sometimes leads to an illegal use of plant protection agents and environmental contamination, and creates the possibility of toxicological hazards (Rotteveel, 2003).

Taking into account the above considerations, the study hypothesized that the use of foliar-applied herbicides (recommended for weed control in oat crops) in proso millet crops, in particular at rates reduced by ½, would contribute to an effective elimination of weeds in the crop compared to mechanical weed control alone (double harrowing), which would in turn contribute to satisfactory crop productivity. An assumption was also made that the herbicides applied at the reduced rates would not have a phytotoxic effect on the crop plant.

The aim of this study was to determine the tolerance of proso millet to selected foliar-applied herbicides both at the maximum rates (100%) and at rates reduced by 50%.

MATERIAL AND METHODS

Experimental design

A field experiment in growing proso millet (cv. 'Jagna') was conducted in the period 2010-2012 at the Czesławice Experimental Farm belonging to the University of Life Sciences in Lublin, Poland. The experiment was established on grey-brown podzolic soil derived from loess (soil class II). Before the experiment, the soil was characterized by high availability of essential nutrients (P=158-165, K=186-197, Mg=68-73 mg kg^{-1} soil). The humus content was 1.49-1.54%, while the soil pH (in 1 mole of KCl) - 6.0-6.4.

The size of a single plot was 3 m x 5 m (15 m^2). The plots were drawn by lot using a split-plot design, in 4 replicates. Proso millet was sown with a precision seed drill at a rate of 4 kg ha^{-1}, at 15 cm row spacing, in the second 10 days of May. In each year of the study, spring wheat was the previous crop for proso millet. Mineral NPK fertilization, adjusted to the high soil nutrient availability, was as follows: N – 40, P – 30, K – 50 kg ha^{-1}. Conventional tillage was used. The experiment tested herbicides that were not approved for application in proso millet crops, but recommended for weed control in oat plantations (the Calendar of the Institute of Plant Protection in Poznań (2009, 2015) does not list any herbicides recommended for use in millet proso crops).

The experiment included the following factors:

I. *Herbicide type*: A: without herbicide (control treatment); B: Gold 450 EC – 2,4-D + fluroxypyr (1.0 l ha^{-1}) – from 3-leaf stage to 1st node stage; C: Granstar Strong – tribenuron-methyl + fluroxypyr (15 g ha^{-1}) – from beginning till end of tillering; D: Chwastox Extra 300 SL – MCPA (1.2 l ha^{-1}) – from beginning till end of tillering; E: Lintur 70 WG – dicamba + triasulfuron (0.12 kg ha^{-1}) – from beginning till end of tillering.

II. *Herbicide rate*: 1. 100%; 2. 50%.

The herbicides were applied at the above specified rates and at rates reduced by 50%, i.e.: Gold 450 EC (0.5 l ha^{-1}), Granstar Strong (7.5 g ha^{-1}), Chwastox Extra 300 SL (0.6 l ha^{-1}), Lintur 70 WG (0.06 kg ha^{-1}).

Weed management in the control treatment (A) consisted in mechanical weed control (harrowing) before proso millet emergence (spike tooth harrow) and at the 2-3-leaf stage (weeder harrow). The herbicides (treatments B-E) were applied using a field sprayer under a pressure of 0.25 MPa. The proso millet crop was harvested in the third 10-day period of August/first 10-day period of September (in 2010 the harvest in the third 10-day period of August was prevented by persistent rainfall).

Measurements

The following traits were analyzed:

1. Evaluation of weed damage (using a 9-point scale) – 3 weeks after herbicide application;
2. Evaluation of damage of proso millet plants due to herbicide application (using a 9-point scale) – 3 weeks after herbicide application;
3. Evaluation of the number and dry weight of weeds per unit area as well as the species composition of weeds (dry-weight-rank method) at the dough stage (BBCH 83-85);
4. Harvest of the proso millet (determination of the proso millet grain yield in t ha^{-1} after bringing grains to the same moisture content – 14%).

All study results were statistically tested by analysis of variance, determining the significance of differences using Tukey's test at a significance level of p=0.05.

Weather conditions during the study period

The weather conditions during the experiment are shown in Tables 1 and 2. The annual total rainfall at the Czesławice Experimental Farm in 2010 was 778 mm and higher by 169.3 than the long-term mean. The year 2010 should therefore be considered to be wet. The highest monthly total rainfall throughout the entire growing season of proso millet was recorded in August (147.1) and September (137.5). The abundant August rainfall prevented the harvest of proso millet, which was carried out in the first 10 days of September. The year 2011 should be considered to be dry, since the annual total rainfall was 531.2 mm and lower by 77.5 mm than the long-term mean. The monthly total rainfall in May was almost identical with the long-term mean calculated, in June the total rainfall was 53.1 mm (it was lower by 27.1 mm than the long-term mean), whereas the total rainfall in August was lower only by 8.1 mm than the long-term mean. Thus, the rainfall conditions in 2011 were favorable for growing proso millet. Likewise 2010, the year 2012 belonged to wet years. The highest monthly total rainfall was recorded in May, July, and August (respectively: 70.9 mm, 105.0 mm, and 74.2 mm). Nevertheless, the rainfall events did not prevent the harvest to be done on time (the third 10-day period of August).

Table 1. Total rainfall and rainfall distribution (mm) in Czesławice in the period 2010-2012

Specification		Month												Annual total
		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	
Monthly total in	2010	41.9	53.3	11.6	29.0	116.2	58.4	84.8	147.1	137.5	11.1	54.6	32.5	778.0
	2011	35.3	30.7	18.9	25.4	60.2	53.1	70.6	60.5	80.4	25.7	38.8	31.6	531.2
	2012	38.1	49.2	16.5	34.8	70.9	79.2	105.0	74.2	60.3	20.2	44.7	50.3	643.4
Long-term mean (1966-1996)		31.5	26.9	29.6	44.5	59.5	80.2	79.4	68.6	57.6	48.7	39.8	42.4	608.7

The distribution of mean temperatures throughout the entire growing season was subject to predicted fluctuations. All the months in which the proso millet grew had a temperature higher than the long-term mean, but the year 2011 proved to be coldest. In the months of proso millet growth, the lowest temperature was recorded in May and June, while July and August were the warmest months. To sum up, the mean annual air temperature in 2011 was lower by 0.9°C than the long-term mean, in 2010 it differed only slightly (by 0.2°C) from the long-term mean, while in 2012 it exceeded the long-term mean by 0.4°C.

Table 2. Mean air temperatures (°C) in Czesławice in the period 2010-2012

Specification		Month												Annual mean
		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	
Monthly mean in	2010	-8.3	-2.0	2.2	8.8	13.9	17.5	20.8	20.0	11.9	4.8	6.3	-5.4	7.5
	2011	-7.9	-2.8	2.1	7.7	13.5	17.1	19.2	18.6	10.8	4.8	4.7	-5.7	6.8
	2012	-4.1	-1.8	2.4	8.9	14.5	17.8	20.5	20.2	12.1	5.6	6.4	-4.6	8.1
Long-term mean (1966-1996)		-3.2	-2.1	2.2	7.6	13.4	16.3	17.9	17.4	13.0	8.1	2.6	-1.0	7.7

RESULTS

On average during the study period, the degree of weed damage due to herbicide application in the proso millet crop was significantly dependent on both experimental factors (Table 3). Regardless of the herbicide form, the application of the 100% rates of the herbicides resulted in almost twice greater damage of weeds compared to the application of the rates reduced by half. However, the 50% reduction of the herbicide rates resulted in visible damage of weeds at a level of 4.4 points (in a 9-point scale) and thus showed satisfactory efficacy.

Table 3. Degree of weed damage in the proso millet crop in a 1-9 scale* – 3 weeks after herbicide application (on average during the study period)

Weed control method	Herbicide rate		Mean
	100%	50%	
A. Control treatment – without herbicide	-	-	9.0
B. 2,4-D + fluroxypyr	2.6	3.4	3.0
C. Tribenuron-methyl + fluroxypyr	3.1	3.9	3.5
D. MCPA	2.5	5.3	3.9
E. Dicamba + triasulfuron	3.9	5.0	4.4
Mean	2.9	4.4	-
$LSD_{(0.05)}$ for: weed control methods = 0.92; herbicide rates = 0.97			

*1 – complete destruction of weeds; 9 – no symptoms of destruction of weeds.

When considering the efficacy of weed control by the individual herbicides, we notice that the greatest damage of weeds was found under the influence of the herbicides 2,4-D + fluroxypyr and tribenuron-methyl + fluroxypyr, followed by MCPA. The herbicide dicamba + triatulfuron proved to be least effective in this respect, since the damage of weeds caused by this chemical was lowest and significantly lower compared to the effect of the herbicide 2,4-D + fluroxypyr. The variation in the herbicide rates used in the proso millet crop (tillering stage) did not have a significant effect on the degree of damage of proso millet plants (Table 4). This suggests that the application of 100% herbicide rates is relatively safe to proso millet plants and plant damage in this cereal due to the application of the full rates was higher by only about 8% compared to that caused by the 50% rates.

Regardless of the herbicide rate, MCPA caused significantly the greatest damage of proso millet plants relative to the other herbicides tested. The damage of the crop caused by this chemical was higher by 35% than that caused by the herbicide dicamba + triasulfuron and higher by 41% relative to the herbicides 2,4-D + fluroxypyr and tribenuron-methyl + fluroxypyr (which did not cause any damage of proso millet plants at all).

Significantly the greatest damage of proso millet plants was caused by the herbicide MCPA at the 100% rates. No statistically significant differences were found in the degree of damage of weeds and proso millet plants between years.

Table 4. Degree of damage of proso millet plants in a 1-9 scale* – 3 weeks after herbicide application (on average during the study period)

Weed control method	Herbicide rate		Mean
	100%	50%	
A. Control treatment – without herbicide	-	-	1.0
B. 2,4-D + fluroxypyr	1.0	1.0	1.0
C. tribenuron-methyl + fluroxypyr	1.0	1.0	1.0
D. MCPA	5.1	3.9	4.5
E. Dicamba + triasulfuron	2.4	1.6	2.0
Mean	2.3	1.8	-
LSD $_{(0.05)}$ for: weed control methods = 1.01; herbicide rates = differences not significant interaction: weed control method x herbicide rate = 0.98			

*9 – complete destruction of proso millet plants; 1 – no symptoms of destruction of proso millet.

Herbicide rate caused statistically significant differences in the number of weeds per unit area in the proso millet crop at the dough stage (Table 5). The reduction of the herbicide rates by half resulted in almost four times greater weed infestation of the proso millet crop as expressed by the number of weeds per 1 m^2. Regardless of the herbicide rate, all the chemicals tested caused a significantly greater reduction in the number of weeds in the proso millet crop relative to the control treatment (without herbicide), respectively by: tribenuron-methyl (750%), 2,4-D + fluroxypyr (650%), MCPA (460%), dicamba + triasulfuron (350%). At the same time, the herbicides tribenuron-methyl + fluroxypyr and 2,4-D + fluroxypyr contributed to a significantly lower number of weeds in the proso millet crop relative to that found in treatments D and E, respectively by 39% and 54% (tribenuron-methyl + fluroxypyr) as well as by 30% and 47% (2,4-D + fluroxypyr). The above relationships were similar in all study years (there were no significant differences in the period 2010-2012).

Table 5. Number of weeds in the crop per 1 m^2 at the dough stage of proso millet (on average during the study period)

Weed control method	Herbicide rate		Mean
	100%	50%	
A. Control treatment – without herbicide	-	-	68.5
B. 2,4-D + fluroxypyr	2.5	18.3	10.4
C. Tribenuron-methyl + fluroxypyr	1.8	16.4	9.1
D. MCPA	8.3	21.5	14.9
E. Dicamba + triasulfuron	9.5	29.8	19.6
Mean	5.5	21.5	-
LSD $_{(0.05)}$ for: weed control methods = 4.13; herbicide rates = 5.87			

The level of weed infestation of the proso millet crop as expressed by air-dry weight of weeds was significantly dependent on both experimental factors and showed a linear relationship with the number of weeds in the crop (Table 6). The reduction of the herbicide rates by half had an effect on increasing the air-dry weight of weeds, on average two times, relative to the 100% rates.

The use of the herbicides in weed control in proso millet caused a huge loss in the weed biomass in the crop compared to the control treatment. The herbicide tribenuron-methyl +

fluroxypyr reduced the weed weight on average by as much as thirty times, 2,4-D + fluroxypyr 22 times, MCPA 3 times, whereas dicamba + triasulfuron 2.6 times. Statistically significant differences in the air-dry weight of weeds were also found for the individual herbicides analyzed, since the herbicides tribenuron-methyl + fluroxypyr and 2,4-D + fluroxypyr resulted in a huge reduction in the weed weight (to a minimum level of about 2-2.5 g m^{-2}), which was lower by about 9-11 times compared to that found in treatments C (MCPA) and D (dicamba + triasulfuron).

Table 6. Air-dry weight of weeds in the crop (in g m^{-2}) at the dough stage of proso millet (on average during the study period)

Weed control method	Herbicide rate		Mean
	100%	50%	
A. Control treatment – without herbicide	-	-	56.9
B. 2,4-D + fluroxypyr	1.6	3.6	2.6
C. Tribenuron + fluroxypyr	0.9	2.9	1.9
D. MCPA	12.2	23.4	17.8
E. Dicamba + triasulfuron	14.2	29.8	22.0
Mean	7.2	14.9	-
LSD $_{(0.05)}$ for: weed control methods = 3.98; herbicide rates = 1.94			

Regardless of the herbicide type, a significantly higher air-dry weight of weeds in the proso millet crop was found in the wettest year 2010, relative to the years 2011-2012, when the herbicide rates were reduced by 50% (Table 7). In 2010 statistically significant differences associated with an increase in the air-dry weight of weeds in the control treatment (without herbicide) as well as in treatments D (MCPA) and E (dicamba + triasulfuron) were also found relative to the years 2011-2012 (Table 8).

Table 7. Air-dry weight of weeds in the proso millet crop in g m^{-2} in the individual years depending on the herbicide rate

Year	Herbicide rate	
	100%	50%
2010	7.6 a*	23.3 a
2011	7.1 a	10.4 b
2012	6.8 a	11.2 b

*Means in columns with different letters (a-b) are significantly different (p=0.05).

Table 8. Air-dry weight of weeds in the proso millet crop in g m^{-2} in the individual years depending on the weed control method

Year	Weed control method				
	A**	B	C	D	E
2010	70.4 a	2.9 a	2.2 a	25.6 a	29.5 a
2011	48.2 b	2.3 a	1.6 a	13.6 b	18.4 b
2012	52.1 b	2.5 a	1.8 a	14.2 b	17.2 b

*Means in columns with different letters (a-b) are significantly different (p=0.05).
** Explanation of symbols A-E in Table 3.

The highest number of weed species (18) per 1 m^2 of the proso millet crop was found in the control treatment (Table 9). Herbicide application, irrespective of the type of active substance, contributed to a significant reduction in the number of weed species, with the highest reduction caused by tribenuron-methyl + fluroxypyr (11 weed species less) and 2,4-D + fluroxypyr (10 weed species less), followed by MCPA and dicamba + triasulfuron (respectively 8 and 6 weed species less than in treatment A). Four weed species in particular: *Echinochloa crus-galli*, *Chenopodium album, Galinsoga parviflora*, and *Viola arvensis*, were dominant in the proso millet crop. The herbicides Granstar Strong and Gold provided the most effective reduction in the number of species and in the total number of weeds in the crop. In treatments B and C, the numbers of the four major weed species did not exceed a value of 1.4-2.5 plants per 1 m^2. The other herbicides (treatments D and E) also effectively decreased the numbers of the dominant weed species, since their contribution in the unit area (1 m^2) did not exceed 1.6-5.2 plants. No compensation of weeds due to the application of the individual herbicides was found, either (Table 9).

Table 9. Dominant weed species in the crop per 1 m^2 at the dough stage of proso millet depending on the herbicide rate, on average during the study period

Dominant weed species	Weed control method				
	A*	B	C	D	E
Average number of weeds per 1 m^2					
Echinochloa crus-galli L.	12.5	2.1	1.9	3.2	4.3
Chenopodium album L.	11.4	2.5	1.7	3.8	5.2
Galinsoga parviflora Cav.	9.9	1.8	1.4	2.9	1.9
Viola arvensis Murr.	9.3	2.2	1.6	1.6	2.5
Other species	25,4	1.8	2.5	3.4	6,0
Total number of weeds	68.5	10.4	9.1	14.9	19.9
Number of weed species	18	8	7	10	12
LSD $_{(0.05)}$ for number of weed species = 2.2					

* Explanation of symbols A-E in Table 3.

On average for the three-year study period and regardless of the weed control method, the proso millet grain yield was significantly lower (on average by about 12%) in the case of the herbicide rates reduced by 50%. The application of the 100% herbicide rates resulted in a grain yield higher by 0.52 t ha^{-1} (Table 10). Each experimental variant of chemical weed control in the proso millet crop contributed to a clear, statistically significant increase in grain yield compared to the control treatment: 2,4-D + fluroxypyr (1.6 times), tribenuron + fluroxypyr (1.5 times), dicamba + triasulfuron (1.3 times), and MCPA (by 11%). It should also be noted that the proso millet grain yield obtained from treatments B and C was significantly higher than the yield obtained from treatments D and E, while at the same time the proso millet grain yield from treatment E was significantly higher than that found under the conditions of treatment D. To sum up, among the herbicides tested, 2,4-D + fluroxypyr and tribenuron-methyl + fluroxypyr had the most beneficial effect on the high productivity of proso millet, whereas MCPA had the least effect. This was directly related to the efficacy of these chemicals in eliminating weeds (competing with proso millet plants in the crop) and their phytotoxicity to proso millet plants (MCPA).

Table 10. Proso millet grain yield (in t ha^{-1}) – on average during the study period

Weed control method	Herbicide rate		Mean
	100%	50%	
A. Control treatment – without herbicide			2.97
B. 2,4-D + fluroxypyr	5.19	4.30	4.74
C. Tribenuron-methyl + fluroxypyr	4.96	4.41	4.68
D. MCPA	3.51	3.16	3.33
E. Dicamba + triasulfuron	4.25	3.96	4.10
Mean	4.47	3.95	-
LSD (0.05) for: weed control methods = 0.351; herbicide rates = 0.342			

A significant variation in proso millet yields was found in relation to the weed control methods depending on the year of the study (Table 11). Significantly lower grain yields were found in the wettest year 2010 under the conditions of the control plots and treatments D (MCPA) and E (dicamba + triasulfuron) relative to the years 2011-2012. This demonstrates that the efficacy in weed control in the proso millet crops provided by the herbicides 2,4-D + fluroxypyr and tribenuron-methyl + fluroxypyr (treatments B and C) affected the stability of crop yields, regardless of weather conditions.

Table 11. Proso millet grain yield (in t ha^{-1}) in the individual years depending on the weed control method

Year	Weed control method				
	A**	B	C	D	E
2010	2.64 a	4.62 a	4.56 a	3.19 a	3.81 a
2011	3.06 b	4.73 a	4.79 a	3.53 b	4.21 b
2012	3.20 b	4.84 a	4.68 a	3.41 b	4.29 b

*Means in columns with different letters (a-b) are significantly different (p=0.05).
** Explanation of symbols A-E in Table 3.

DISCUSSION

Weed control in small-scale crops is a very important issue from the point of view of agricultural practice. In most cases, these are crop plants that are very sensitive to both soil- and foliar-applied biologically active substances. In the case of proso millet, they can inhibit germination and the subsequent growth of this species. Evaluating the resistance of proso millet to soil-applied CGA-152005, metsulfuron, and triasulfuron in pot and field studies, Uludag et al. (1997) showed proso millet to be the most tolerant to CGA-152005, whereas metsulfuron reduced biomass accumulation by plants to the greatest extent. The studies of some authors (Anderson, 1990; Anderson and Greb, 1987; Robinson, 1973) reveal that the application of active substances such as atrazine and propazine produced positive effects in weed management. The use of triazine herbicides is now being abandoned across the world. In China the research on the use of monosulfuron, which exhibited similar activity as other sulfonylurea herbicides, for weed control in proso millet yielded positive effects (Fan et al., 2005). In recent years, a lot of attention has been paid to the response of proso millet to saflufenacil. Lyon and Kniss (2010) showed positive effects associated with increased proso millet yields in the case of weed control using saflufenacil at a rate of 100 g ha^{-1} applied 7-14 days before sowing as well as at 50 g ha^{-1} and 100 g ha^{-1} applied 1 day after sowing. However, post-sowing application of saflufenacil at a rate of 100 g ha^{-1} caused significant damage of plants, which was as much as 93% in the second year of the study. At the same time, these authors stress that the herbicide spraying conditions significantly affected the degree of damage of proso millet plants. Reddy et al. (2014) found that the application of saflufenacil at a rate of 50 g ha^{-1}, seven or more days before sowing seed in soils with an organic matter content of more than 2% and with a neutral or acidic pH, was most beneficial. If it is necessary to use this active substance after sowing, the rate should be reduced to 36 g ha^{-1}. Lyon and Kniss (2010) also showed soil conditions to have a great influence on the activity of saflufenacil. They found increased damage of proso millet plants after saflufenacil in soils with a high pH and a low content of organic compounds. Stahlman et al. (2009) claimed that the tolerance of proso millet to saflufenacil is a complex issue and requires further research to determine the optimal rate of the herbicide and the most appropriate time of its application.

Weed control during the growth of a crop plant is much more problematic. With the growth of plants, the possibilities of mechanical weed control in small-scale crops (proso millet, buckwheat, herbal plants) become limited, labor-consuming, and not very effective, whereas there is a lack of herbicides approved for foliar application after emergence of the above-mentioned cultures (Jakubiak, 2005; Jakubiak and Adamczewski, 2006). The presence of unwanted plants in these crops at the initial stage of plant growth causes huge losses in yields (Grabouski, 1971). Proso millet is very sensitive to weed competition especially at the 4-6 true leaf stage when the dynamically developing weed flora dominates over the crop plant and "steals" soil nutrients from it (Hanna et al., 2004; Petersen and Augustin, 2006). Therefore, the present study, which analyzes the efficacy of some herbicides in weed control in proso millet at the tillering stage and tests the possible phytotoxicity of these chemicals, should be considered to be up-to-date, necessary and pioneer research in Poland. In the national literature on proso millet, there are very few results of studies devoted to herbicide-based weed control in this crop, in particular weed management after emergence. But the issue associated with herbicide use in proso millet crops is more frequently presented by authors originating from the countries in which this crop is more popular (e.g. the USA and Belarus) (Lyon et al., 2008; Lyon and Kniss, 2010; Yakimovich, 2010).

The response of proso millet plants to foliar-applied herbicides is very important. In the study conducted by Grabouski (1971), the herbicides 2,4-D, bromoxynil and dicamba contributed to an effective elimination of the weed flora, including *Amaranthus retroflexus* dominant in proso millet crops. This author obtained the highest proso millet yield when applying the herbicide 2,4-D at a rate of 280 g ha^{-1}. In turn, Lyon and Baltensperger (1993) did not find the herbicides used (bromoxynil, clopyralid, dicamba, metsulfuron, 2,4-D) to have a significant effect on proso millet grain yield, number and weight of grains per panicle, and plant height. When using foliar application of dicamba and 2,4-D, Lyon et al. (2008) observed necrotic changes on the proso millet leaves which subsequently contributed to a weaker growth rate of this cereal and this resulted in reduced productivity of proso millet. A recent American study (Lyon and Kniss, 2010) confirmed that foliar application of active substances such as 2,4-D, dicamba, sulfosulfuron and carfentrazone-ethyl does not cause significant damage of proso millet plants and they can be foliar applied in this crop.

The above considerations were an inspiration for testing selected foliar herbicides in proso millet crops. The present authors decided to use chemicals recommended for weed control in oats (a plant related to proso millet in terms of the morphological structure, grain chemical composition, and use) applied at rates of 100% and 50%. The results of this study demonstrate that the herbicides used in the experiment (2,4-D + fluroxypyr, tribenuron-methyl + fluroxypyr, MCPA, dicamba + triasulfuron) produced better results in the form of reduced weed infestation and increased productivity of this cereal compared to the control treatment (without herbicide), both at the 100% rate and at the rate reduced by half. What is important, except for the herbicides MCPA and dicamba + triasulfuron the other chemicals (2,4-D + fluroxypyr and tribenuron-methyl + fluroxypyr) did not exhibit phytotoxicity to proso millet plants and promoted very high yields of this cereal, at a level of more than 4.0 t ha^{-1}. Such high productivity of proso millet (in particular in the treatments with the application of the herbicides (2,4-D + fluroxypyr and tribenuron-methyl + fluroxypyr) suggests the right selection of these herbicides and is valuable guidance in agricultural practice. A proso millet yield of more than 4.0 t ha^{-1} is 2-3 times higher than that reported as the national average (Statistical Yearbook of Poland, 2010, 2015) and compared to some scientific studies (Svirskis, 2009).

The research conducted by Gołębiowska et al. (2011) reveals that as far as weed management in proso millet is concerned, the highest effectiveness in killing both mono- and dicotyledonous species was observed after the application of the herbicide Guardian 840 EC (acetochlor) at a rate of 2.5 l ha^{-1}; it exhibited a phytotoxic effect on the crop plant immediately after spraying, but damage symptoms were transient and did not affect the yield.

The results of foreign studies (Higgins et al., 1998; Lyon and Miller, 1999; Anderson, 2000; Wrage, 2000) also show that herbicide-based weed control in proso millet allows weeds to be eliminated from the crop more effectively and in consequence a higher grain yield to be obtained. Using herbicide weed control in proso millet (saflufenacil), Lyon and Kniss (2010) found proso millet grain yields at a level of 2,4-2.7 t ha^{-1} under the soil and climatic conditions of the state of Wyoming (USA). In Belarus (Priluki near Minsk), Yakimovich (2010) obtained proso millet yields higher than the American ones, while in some cases (with the use of foliar herbicides) similar to those obtained in the present study (2.8-4.0 t ha^{-1}).

The American research (Lyon et al., 2007; Lyon and Kniss, 2010) shows that the application of herbicides (carfentrazone, 2,4-D + dicamba, prosulfuron) after emergence of proso millet produced varying weed-killing and phytotoxic effects in the proso millet crop depending on the study season. Under favorable climatic conditions, the herbicides (in particular prosulfuron and 2,4-D + dicamba) did not cause damage of proso millet plants, which contributed to increased yields of this cereal. In less favorable seasons (lower air temperatures during herbicide treatments), on the other hand, herbicide-induced necrotic changes were observed in 5-20% of proso millet leaves. In the present study, the weather conditions during the study period did not have a significant effect on the efficacy of action of the foliar herbicides used and their phytotoxicity to proso millet. As a matter of fact, the weather conditions in 2010 and 2012 were very similar. Only the year 2011 was slightly colder and drier. In spite of this, the less favorable weather conditions were not found to contribute to weakening the positive weed control effect when the most effective herbicides were used: Gold 400 EC (2,4-D + fluroxypyr) and Granstar Strong (tribenuron-methyl + fluroxypyr). Also, the less favorable year (2011) did not enhance the adverse effect of the herbicide Chwastox Extra (MCPA) on proso millet plants, since the scale of necrotic changes on the leaves was similar to that found in 2010 and 2012.

Proso millet is a particularly popular crop plant in Belarus where numerous studies are also conducted on the possibility of using foliar-applied herbicides in crops of this plant. The studies carried out in Belarus reveal that 75 weed species belonging to 27 botanical families occur in proso millet crops, and the average number of weeds per 1 m^2 of plantation is 150 plants (Yakimovich, 2004). It has been proved that the higher rate of growth of proso millet plants is in the individual growth stages, the more effectively this plant competes with weeds and the higher yields it produces (Tomilina and Soroka, 2002; Yakimovich and Soroka, 2004). Similarly as in the present study, the use of foliar herbicides contributed to higher productivity of proso millet (Yakimovich, 2010). This author found that the critical moment in weed competition with proso millet plants is the 21st-26th day of plant growth, regardless of the weed control method. Herbicide application is justified only when the biological and economic threshold of weed harmfulness has been exceeded. High effectiveness of weed management in proso millet crops was also found in the case of foliar-applied herbicides such as dicamba + triasulfuron (120-180 g ha^{-1}), amidosulfuron + iodosulfuron methyl sodium (150-200 g ha^{-1}), and tribenuron-methyl + fluroxypyr (10-15 g ha^{-1}). The above-mentioned herbicides showed 75-80% efficacy in eliminating the dominant weed species from the proso millet crop. Weed control using the herbicides thifensulfuron-methyl and clopyralid showed lower efficacy (60-70%). On the other hand, the herbicide isoproturon + diflufenican applied at a rate of 1.0 l ha^{-1} proved to be phytotoxic to proso millet and due to this 50-60% of proso millet plants died.

To sum up, the results of the study by Yakimovich (2010) demonstrate that weed control in proso millet crops using an appropriate range of herbicides and a proper herbicide rate contributes to a reduction in the level of weed infestation by 79-90% and an increase in grain yield by 0.05-0.08 t ha^{-1}, thus generating a net profit in the range of 53.1-60.4 US$ ha^{-1} and profitability at a level of 158-223%. The results quoted from the Belarusian studies are in agreement with the results presented in this paper in many respects.

CONCLUSIONS

Weed control using foliar-applied herbicides at the tillering stage of proso millet resulted in an effective reduction in the number and weight of weeds in the crop compared to the conventional weed control method (double harrowing of the crop). Moreover, the herbicides contributed to higher productivity of proso millet.

The herbicides Gold 400 EC (2,4-D + fluroxypyr) and Granstar Strong (tribenuron methyl + fluroxypyr) provided the most effective weed management and in consequence high yields of proso millet, while in the case of Lintur 70 WG (dicamba + triasulfuron) this effectiveness was slightly lower. The above-mentioned chemicals did not exhibit phytotoxicity to proso millet plants (at the rates of both 50% and 100%) and contributed to very high yields of this cereal, in the range of 4.1-4.7 t ha^{-1}.

The herbicide Chwastox 300 SL (MCPA) had very high weed-killing efficacy in the proso millet crop, but caused visible damage of the crop plant (inhibition of the growth rate, a slight curling of the leaves) which, as a matter of fact, receded after 2-3 weeks from the time of chemical treatment, but had an effect on lower productivity of this cereal compared to the other herbicide weed control treatments. The herbicides 2,4-D + fluroxypyr and tribenuron-methyl + fluroxypyr can be preliminarily recommended for safe use at the tillering stage of proso millet both at the rate reduced by half and at the 100% rate.

REFERENCES

Anderson, R.L., 1990. *No-till proso millet production*. Agronomy Journal, 82: 577-580.

Anderson R.L., 2000. *A cultural system approach can eliminate herbicide need in semiarid proso millet (Panicum miliaceum).* Weed Technology, 14: 602-607.

Anderson, R.L., Greb, B.W., 1987. *Residual herbicides for weed control in proso millet (Panicum miliaceum L.).* Crop Protection, 6: 61-63.

Fan, Z.J., Al, Y.W., Qian, C.F., Li, Z.M.., 2005. *Herbicide activity of monosulfuron and its mode of action.* Journal of Environmental Sciences-China, 17: 399-403.

Gardani, G, Cerrone, R., Biella, C., Galbiati, B., Proserpio, E., Casiraghi, M., Travisi, O., Meregalli, M., Trabattoni, P., Colombo, L., Giani, L., Messina, G., Arnoffi, J., LISSONI, P., 2007. *A case-control study of Panicum miliaceum in the treatment of cancer chemotherapy-induced alopecia.* Minerva Medica, 98: 661-664.

Gołębiowska, H., Badowski, M., Domaradzki, K., 2011. *Chemical weed control in minor crops.* Progress in Plant Protecion, 51: 825-1830.

Grabouski, P.H., 1971. *Selective control of weeds in proso millet with herbicides*. Weed Science, 19: 207-209.

Hanna, W.W., Baltensperger, D.D., Seetharam, A., 2004. *Pearl millet and other millets*. Moser LE (ed.) Agronomy Monographs 45: Warm-Season (C4) Grasses. Madison, WI: American Society of Agronomy, 537-560

Higgins, R.K., Lyon, D.J., Miller, S.D., 1998. *Chemical weed control in proso millet*. Proceedings of the Western Society of Weed Science, 51: 15-16.

Jakubiak, S., Adamczewski, K., 2006. *Weed control in some minor crops*. Progress in Plant Protection, 46: 71-80.

Jakubiak S., 2005. *Importance, advantages and weed control in minor crops.* Progress in Plant Protection, 45: 185-195.

Luis E.S., Sullivan T.W., Nelson L.A., 1982. *Nutrient composition and feeding value of proso millets, sorghum grains and corn in broiler diets.* Poultry Science, 6: 311-320.

Lyon D.J., Baltensperger D.D., 1993. *Proso millet (Panicum miliaceum) tolerance to several postemergence herbicides.* Weed Technology, 7: 230-233.

Lyon, D.J., Burgener, P.A., Deboer, K.L., et al. 2008. *Producing and marketing proso millet in the Great Plains.* University of Nebraska-Lincoln Extension Circular 137. Available at http://www.ianrpubs.unl.edu/ epublic/live/ec137/build/ec137.pdf. Accessed: December 31, 2009.

Lyon, D.J., Kniss, A., Miller, S.D., 2007. *Carfentrazone improves broadleaf weed control in proso and foxtail millets.* Weed Technology, 21: 84-87.

Lyon, D.J., Kniss, A.R., 2010. *Proso millet tolerance to saflufenacil.* Weed Technology, 24: 349-355.

Lyon, D.J., Miller, S.D., 1999. *Herbicide injury in proso and foxtail millets.* Proceedings of the Western Society of Weed Science, 52: 24.

Nelson, L.A., 1990. *Influence of planting dates, seeding rates, and cultivars on grain yield and other agronomic traits of proso millet.* Journal of Production Agriculture, 3: 184-189.

Petersen, J., Augustin, B., 2006. *Weed control in millet corn (Panicum miliaceum).* Journal of Plant Diseases and Protection, Special Issue, 20: 773-779.

Reddy S.S., Stahlman P.W., Geier P.W., Charvat L.D., Wilson R.G., Moechnig M.J., 2014. *Tolerance of foxtail, proso and pearl millets to saflufenacil*. Crop Protection, 57: 57-62.

Robinson, R.G., 1973. *Proso millet date of planting and tolerance to atrazine.* Weed Science, 21: 260-262.

Rose, D.J., Santra, D.K., 2013. *Proso millet (Panicum miliaceum L.) fermentation for fuel ethanol production.* Industrial Crops and Products, 4: 602-605.

Rotteveel, A.J., 2003. *Progress with resolving minor use crop protection issues in Europe.* The BCPC Conference – Weeds 1: 195-202.

Seefeldt, S.S., Jensen, J.E., Feurst, E.P., 1995. *Log-logistic analysis of herbicide dose – response relationships.* Weed Technology, 9: 218-227.

Shahidi, F., Chandrasekara, A., 2013. *Millet grain phenolics and their role in disease risk reduction and health promotion:* A review. Journal of Functional Food, 5: 570-581.

Stahlman, P.W., Geier, P.W., Charvat, L.D., 2009. *Tolerance of three millet types to saflufenacil.* North Central Weed Science Society Proceeding, 64: 127.

Standard EPPO, Pp 1/224 (1). *Efficacy evaluation of plant protection products – Principles of efficacy evaluation for minor uses.*

Statistical Yearbook of Agriculture, 2015. Central Statistical Office, Warsaw.

Statistical Yearbook of Poland, 2010. Central Statistical Office, Warsaw.

Svirskis, A., 2009. *Consequences and prospects of some non-traditional crops in Lithuania*. Diaulio University, Kiejdany ISSN 132-6144: 79-89.

Tomilina, E.A., Soroka, S.W., 2002. *Влияние гербицидов на засоренность и урожайность проса посевного.* Интегрир. системы защиты растений. Настоящее и будущее, материалы Междунар. науч. конф., Минск – Прилуки, 15-17 июля 2002 г. – Минск: 74.

Uludag, A., Lyon, D.J., Nissen, S.J., Kachman, S.D., 1997. *Proso millet (Panicum miliaceum) response to CGA-152005, metsulfuron, and triasulfuron*. Weed Technology, 11: 138-143.

Wrage, J.L., 2000. *Weed control in small grain and millet. South Dakota*: South Dakota State University: 19-20.

Yakimovich, A., 2010. *Biologitcheskoie owosnowanie chimitcheskoi zastchiti posiewow prosa ot sornych rastienij.* Dissiertacija. Institiut Zastchiti Rastienij. NAN Belarus. UDK 633.171:632.934: 632.51. pp: 124.

Yakimovich, A., Soroka, S.W., 2004. *Эффективность линтура в посевах проса в зависимости от срока внесения.* Земляробства і ахова раслін, 3: 18-19.

Yakimovich, A., 2004. *Фитотоксичность гербицидов рейсер и кугар в посевах проса.* Защита растений: сб. науч. тр./РУП «Институт защиты растений» НАН Беларуси. – Минск: РУП «ИВЦ Минфина», 2004, Вып. 29: 68-72.

Zarnkow, M., Faltermaier, A., Back, W., Gastl, M., Arendt, E.K., 2010. *Evaluation of different yeast strains on the quality of beer produced from malted proso millet (Panicum miliaceum L.).* European Food Research and Technology, 231: 287-295.