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RESEARCH ARTICLE

Weed control with diclosulam in soybean

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ABSTRACT

The experiments were conducted in 2017-2018 on soybean (Glycine max L.) in three climatic regions of Russia (Altai Region, Krasnodar Region and Astrakhan Region) to evaluate efficacy of herbicide diclosulam (WG, 750 g/kg). Treatments included diclosulam: 1) applied preemergence (PRE) - 18.75 and 37.5 g i.a. ha^{-1}; 2) applied postemergence (POST) at 1-3 leaves of soybeans (BBCH 11-13) - 11.25 and 22.5 g i.a. ha^{-1}. Monocotyledonous weeds (Echinochloa crusgalli (L.) Beauv. and Panicum miliaceum ssp. ruderale (Kitagawa) Tzvelev) had low sensitivity to diclosulam. Diclosulam efficacy at minimum application rate against Fallopia convolvulus (L.) A. Love and Solanum nigrum L. was 100%. Adjuvant ethoxylated isodecyl alcohol (EIAb) was added to diclosulam to increase treatment efficiency against Chenopodium album L., Amaranthus retroflexus L., Ambrosia artemisiifolia L., Persicaria maculosa S.F. Gray. EIAb with diclosulam was the most effective at minimum application rate. Application of diclosulam did not cause phytotoxicity on 3 soybean cultivars Altom, Bara and Vilana. The maximum increase of soybean yield after herbicide treatment was observed in Krasnodar Region in 2018 at cultivar Bara (+ 9.2 centners per hectare).

Keywords: Diclosulam; Efficacy; Ethoxylated isodecyl alcohol; Soybean; Weed

INTRODUCTION

Field experiments with diclosulam have been conducted since the end of the twentieth century. The most active studies of this herbicide were made mainly in the USA in 1996-2002 on peanuts (Scott et al., 2001; Clewis et al., 2002; Grichar et al., 2004; Grey and Wehtje, 2005; Besler et al., 2008). At the moment diclosulam considered as an alternative imazapic, because it is less persistent and less expensive (Brecke et al., 2002). Diclosulam efficacy was observed at 18 and 26 g ha^{-1} a.i. preplant incorporated (PPI) and preemergence (PRE) (Grey et al., 2003).

Around the same time research of using diclosulam in soybean started (Reddy, 2000). Even 35 g ha^{-1} a.i. diclosulam application did not have a negative effect on soybean (Leite et al., 2000; Gazola et al., 2016). Lower application rates (16-26 g ha-1 a.i.) especially safe for soybean and significantly increase its yield (Jakhar and Sharma, 2015).

Studies conducted in the United States in 1994-1997 showed that diclosulam (35 and 37 g ha^{-1} a.i.) rapidly degraded in soil. Its half-life ranged from 3 to 43 days at four sites (Zabik et al., 2001). Over past two decades it has been established that the use of diclosulam can still have an adverse effect on subsequent crops: sunflower, corn, cotton, cucumber, watermelon, clover and radish (Brighenti et al., 2002; Prostko, E.P. and Webster, 2015; Matte et al., 2019: Ribeiro et al., 2019; Price et al., 2020). The use of green manure and biochar helps to solve this problem (Monquero et al., 2013; Mendes et al., 2019).

Experiments with diclosulam made it possible to identify the weeds most sensitive to this herbicide: Acanthospermum hispidum DC. (ACNHI), Amaranthus palmeri S. Watson (AMAPA), Bonnaya ciliata (Colsm.) Spreng. (LIDCI), Brachiaria ramosa (L.) Stapf (PANRA), Cyperus rotundus L. (CYPRO) Digitaria sanguinalis (L.) Scop. (DIGSA), Echinochloa colona (L.) Link (ECHCO), Eclipta alba (L.) Hassk. (ECLAL), Eleusine indica (L.) Gaertn. (ELEIN), Eragrostis japonica (Thunb.) Trin. (ERAJA), Richardia brasiliensis Gomes (RCHBR) (Grichar, 2007; Singh et al., 2009; Nainwal et al., 2010: Grey and Prostko, 2015; Gallon et al., 2019).

The efficiency of treatment can be increased by joint application of diclosulam and other herbicides (in tank mixtures or in different times). For example, it turned

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out that pure diclosulam controls Cyperus esculentus L. (CYPES) not more than 79% (Grichar et al., 2006). Significant efficiency improving (over 90%) can be obtained by using diclosulam in systems with imazopic and flumioxazin (Grey et al., 2004; Willingham et al., 2008; Ducar et al., 2009). Diclosulam with imazethapyr and flumioxazin are also effective against Raphanus sp. (Santin et al., 2019). In recent years mixture of diclosulam and other herbicides (such as galaxifen-methyl and glyphosate) has been used against Conyza spp., Spermacoce latifolia Aubl. (BOILF) and other weeds, which is difficult to control by conventional methods (Braz et al., 2017: Obiole et al., 2018; Krenchinski et al., 2019; Kalsing et al., 2020). However, not all mixture treatments are safe for crops. Diclosulam with glyphosate and trifluralin or with bentazone can reduce soybean yield (Fornazza et al., 2018; Constantin et al., 2018).

At the beginning of the 21st century, reports of weed resistant forms to diclosulam began to appear in the United States (Chandi et al., 2012). In 2019 in Brazil information on cross-resistance of Bidens pilosa L. (BIDPI) and Bidens subalternans de Candolle (BIDSU) to diclosulam imazethapyr and chlorimuron was published (Mendes et al., 2019).

In Russian Federation diclosulam have not yet been used in agriculture. And most of the weed species controlled by diclosulam in the USA, Brazil and India are rare in Russia. Therefore, this study aimed to evaluate diclosulam efficiency against weed species in 3 different regions of Russian Federation and finding out what yield of soybean varieties can be obtained after herbicide treatment.

MATERIALS AND METHODS

The experiments were conducted in 2017-2018 on soybean in three climatic regions of Russia: Altai Region (on soybean cultivar Altom), in Krasnodar Region (cultivar Bara) and in Astrakhan Region (cultivar Bara - in 2017; cultivar Vilana - in 2018).

The object of research was herbicide of JSC Firm "August" Plector, WG (diclosulam, 750 g/kg). The treatments were made after soybean sowing in two periods: 1) preemergence (PRE) - 18,75 and 37,5 g i.a. ha^{-1}; 2) postemergence (POST) at 1-3 leaves of soybeans (BBCH 11-13) - 11,25 and 22,5 g i.a. ha^{-1}. The experiment was set according to a completely random design with four replications. The experimental plots were 25-40 m^2. The herbicides were applied using pressurized sprayers (Solo 425, Pulverex, Hardi), with a volume of 200-300 L ha-^{1}.

The observations were made: before treatment; 30, 40 days after treatment (DAT); and before harvest. On each date, the number of weeds of each type was counted on each plot 4*0.25 m^2. The efficacy of herbicide (%) was calculated relative to the nontreated control: E = (U- H) / U * 100. U - weeds / m^2 at the untreated control; H - weeds / m^2 at plots with herbicide.

In Astrakhan Region (due to drought) irrigation was carried out with an interval of 7-10 days.

Harvesting was carried out manually in Krasnodar and Astrakhan Regions, but in Altai Region - using a Sampo 130 combine. The harvest results were submitted to the analysis of variance (ANOVA) by F-test, and the means were compared by the Tukey test (5%).

RESULTS AND DISCUSSION

Several groups of weeds were seen in the experiments: monocotyledonous - Echinochloa crusgalli (L.) Beauv. (ECHCG) and Panicum miliaceum ssp. ruderale (Kitagawa) Tzvelev (PANMD); dicotyledonous - Amaranthus retroflexus L. (AMRE**)**, Chenopodium album L. (CHEAL)**,** Ambrosia artemisiifolia L. (AMBEL)**,** Fallopia convolvulus (L.) A. Love (POLCO), Abutilon theophrasti Medik. (ABUTH), Persicaria maculosa S.F. Gray (POLPE**),** Polygonum aviculare L. (POLAV), Solanum nigrum L. (SOLNI), Salsola tragus L. (SASKT)**.**

Some of these weeds (SASKT, POLAV, ABUTH) were found only in Astrakhan Region for one year. Salsola tragus was in 2017 before POST spraying in the phase BBCH 12-14, up to 9 cm (3 weeds / m^2). Diclosulam efficiency 22.5 g ha^{-1} a.i. (POST) was 50.0-66.7% (30-45 DAT) and 100% (before harvest). Polygonum aviculare was in 2017 in the phase BBCH 12-16, up to 15 cm (5 weeds / m^2). Efficiency 37.5 g ha^{-1} a.i. (PRE) was 40-100%. Efficiency 22.5 g ha^{-1} a.i. (POST) was от 25.0-33.0%. Abutilon theophrasti was found in 2018. During PRE treatment weed was in the cotyledon phase. Before POST treatment it was in the phase BBCH 12-14, up to 11 cm. The total amount of this species in the untreated control during the experiment was 3-9 weeds / m^2. Efficiency 37.5 g ha^{-1} a.i. (PRE) was 55.6-80.0%. Efficiency 22.5 g ha^{-1} a.i. (POST) was 68.8-78.1%.

Two weed species (POLCO, SOLNI) were found rarely and in small quantities. Fallopia convolvulus was only in Altai Region for two years. Before POST treatment it was in the phase BBCH 14-16, up to 10-15 cm. The total amount of this species in the untreated control did not exceed 8 weeds / m^2. Solanum nigrum was (up 3 weeds / m^2) in

Altai Region (two years) and in Astrakhan Region (in 2018). In Altai Region, the weed was in the germination phase before treatment; in Astrakhan Region - BBCH 12-14, up to 14 cm. POLCO and SOLNI were completely destroyed by the herbicide, even at the minimum application rate at PRE and POST.

Based on the data presented above, we supposed that diclosulam would effectively suppress monocotyledonous weeds, but received other data.

ECHCG was found in Altai and Krasnodar Regions. Before POST treatment the weed was in the phase from germination to tillering (35 weeds / m^2 in Krasnodar Region and 134 weeds / m^2 in Altai Region). In Altai Region, the low efficiency was at low application rates: 52% (30 DAT) when used 11.25 g ha^{-1} a.i. (POST) and 65% (30 DAT) when used 18.75 g ha^{-1} a.i. (PRE). In Krasnodar Region, even the maximum rates were ineffective for both periods of application (Fig. 1).

Diclosulam was significantly inferior to the standard imazethapyr (especially at a low rate and POST application).

It should be noted that the next year (when the effectiveness of adding surfactants was studied) in contrast to other weeds (information below) there were also no improvements. Even the PRE application of the standard clomazone was more efficient.

A similar situation was with Panicum miliaceum ssp. ruderale, which was noted only in the Altai Region. Before POST treatment the weed was in tillering phase (20 weeds / m^2 - in 2017; 147 weeds / m^2 - in 2018). In 2017 application of 50 g i.a. ha^{-1} standard imazethapyr (POST) resulted 100% efficiency. Diclosulam efficiency 11,25 g i.a. ha^{-1} (POST) was 44-55% (30-45 DAT). In 2018 an attempt to enhance activity by adding surfactants was unsuccessful: 19-31% (30-45 DAT) at diclosulam - 18,75 g i.a. ha^{-1} (PRE) and 20-37% - at diclosulam - 18,75 g i.a. ha^{-1} + EIAb (PRE). Clomazone efficiency 336 g i.a. ha^{-1} (PRE) was 74-78%.

Since low diclosulam activity against monocotyledonous weeds was detected the following year background treatments were made against this group of weeds. For this purpose, we used clethodim (72 g i.a. ha^{-1}) or haloxyfop-P-methyl (52 g i.a. ha^{-1}). In this regard, in 2018 we did not use the standard imazethapyr. For experiment with POST application, we used standard thifensulfuron-methyl (4.5/6.0 g ha^{-1} a.i.), for experiment with PRE - standard clomazone (336/480g ha^{-1} a.i.).

The two species (CHEAL, AMRE) were ubiquitous and the most common weeds.

Before POST treatment Chenopodium album was in the phase BBCH 14-16, 10-16 cm (10-12 weeds / m^2). In Altai Region PRE treatment diclosulam efficiency against

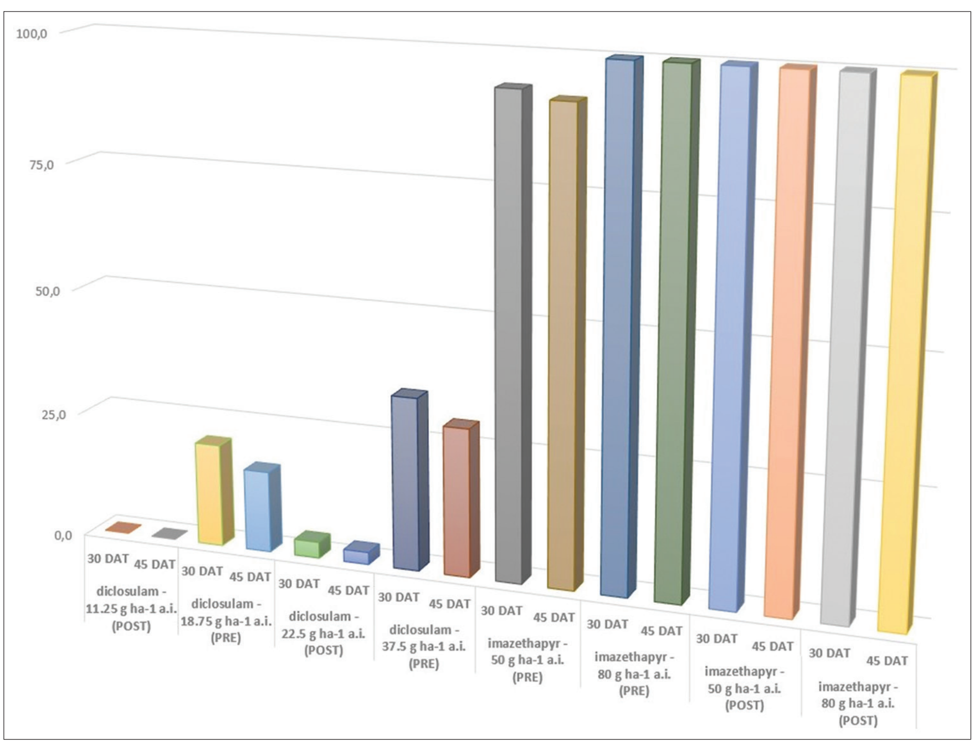

Fig 1. Diclosulam efficiency against Echinochloa crusgalli in 2017 (Krasnodar Region, % to untreated control).

Chenopodium album was 100% in both rates of application, but in 2017 diclosulam efficiency 11.25 g i.a. ha^{-1} (POST) was 33% (30 DAT) and 50% (45 DAT); in 2018 - did not exceed 40%. A similar trend was noted in Krasnodar and Astrakhan Regions. PRE treatment diclosulam efficiency reached 100% at maximum application rate, but diclosulam efficiency 11,25 g i.a. ha^{-1} (POST) was lower. In Krasnodar Region: 67.1% (30 DAT) и 65.4% (45 DAT). In Astrakhan Region: 83.3% (30 DAT) и 71.4% (45 DAT). Thus, PRE treatment diclosulam efficiency against Chenopodium album was sufficient, but for post-emergence application it was necessary to find ways to increase it (see application with surfactants below).

Amaranthus retroflexus was the most common weed in experiments. The amount of this weed in the fields reached 43 weeds / m^2 (in the Altai Territory). Before POST treatment Amaranthus retroflexus was from BBCH 11-12 (in Astrakhan) to BBCH 14-16 (in other regions) and reached from 7 to 15 cm. In 2017 at Altai Region PRE treatment 18,75 g i.a. ha^{-1} diclosulam efficiency against AMRE was 56% (30 DAT) and 52% (45 DAT); PRE treatment 37.5 g i.a. ha-1 diclosulam efficiency was 88 and 81% according to accounting dates. In 2018, the efficiency of diclosulam application was slightly higher, but the trend continued. In Krasnodar Region efficiency of dicosulam ranged within a very wide range from 34.8-37.3% (after application 11.25 g i.a. ha^{-1} (POST)) to 100% after application 37.5 g i.a. ha^{-1} (PRE). In Astrakhan Region similar trend was observed - the efficiency varied from 50 to 100%.

Ambrosia artemisiifolia was found only in Krasnodar Region. Before POST treatment this weed was BBCH 14-17 (16 weeds / m^2). According to early studies, this species is highly sensitive to diclosulam when used in Peanut (Grey et al., 2001; Everman et al., 2006). However, in our experiments, the dicosulam efficiency against Ambrosia artemisiifolia was not always high and varied widely: from 16.7-21.3% (18,75 g i.a. ha^{-1} (PRE)) to 100% (37.5 g i.a. ha^{-1} (PRE)).

Persicaria maculosa was found only in the Astrakhan Region in 2018. Before POST treatment Persicaria maculosa was BBCH 12-14, up to 13 cm (7 weeds / m^2). POST treatment 22.5 g i.a. ha^{-1} dicosulam efficiency was 42.9% (30 DAT) and 50% (45 DAT); PRE treatment 37.5 g i.a. ha^{-1} dicosulam efficiency was 71.4%.

The results obtained in our experiments confirm the data available in the literature, according to which the sensitivity of the above species can vary widely depending on the period of use, application rate and external conditions (Lancaster et al., 2007a). Therefore, for a long time, to control these species, diclosulam have been applied together with other herbicides (Price and Wilcut, 2002). In 2018 to increase diclosulam efficiency we add a surfactant to the tank mixture, using adjuvant “Adieu” - 900 g/l ethoxylated isodecyl alcohol (EIAb) at 0.1% of the total spray volume.

EIA adding to diclosulam to enhance efficacy against weed species, showed clearly distinguishable trend: the greatest increase in efficiency was observed when using the minimum rate diclosulam at POST treatment (Fig. 2).

In Altai Region diclosulam efficiency increase against Chenopodium album after applying 11.25 g i.a. ha^{-1} diclosulam + EIAb (POST) reached 78% on average by count dates. The least significant increase efficiency treatment (up to 13%) was observed after applying 18.75-37.5 g i.a. ha^{-1} diclosulam + EIAb (PRE) in Astrakhan and Krasnodar Regions.

Similar trends were in relation Ambrosia artemisiifolia in Krasnodar Region. Efficiency increase at POST applying 11.25 g i.a. ha^{-1} diclosulam + EIAb averaged 23%, while the gain at PRE applying 18.75-37.5 g i.a. ha^{-1} diclosulam + EIAb did not exceed 2%.

POST applying 11.25 and 22.5 g i.a. ha^{-1} + EIAb against Persicaria maculosa in Astrakhan Region increased the effect by 50-52%; while 18.75 g i.a. ha^{-1} (PRE) + EIAb - by 26%, and 37.5 g i.a. ha^{-1} + EIAb (PRE) - only by 11%.

The efficiency gain against Amaranthus retroflexus was maximum (24%) in Krasnodar Region at 11.25 g i.a. ha^{-1} + EIAb (POST); and the minimum (1%) - when PRE applying 18.75 g i.a. ha^{-1} + EIAb in the same region.

Thus, using of diclosulam with the EIA is advisable when applying 11.25 g i.a. ha^{-1} (POST) for all 4 weed species.

Regular monitoring of the state of soybean crops showed that the use of diclosulam did not cause phytotoxicity in any of the experiments.

Soybean yields depended on the varieties and research regions (Table 1). The lowest yield (6.3 centners per hectare) was obtained in untreated control at cultivar Altom in the Altai Region in 2018. The highest yield in the untreated control (19.2 centners per hectare) was noted in Krasnodar Region at cultivar Bara in 2017. Despite such a significant range of values, in all variants with diclosulam applying (except for 11.25 g ha^{-1} a.i. (POST) in the Altai Region in 2017), significant increases yield was obtained.

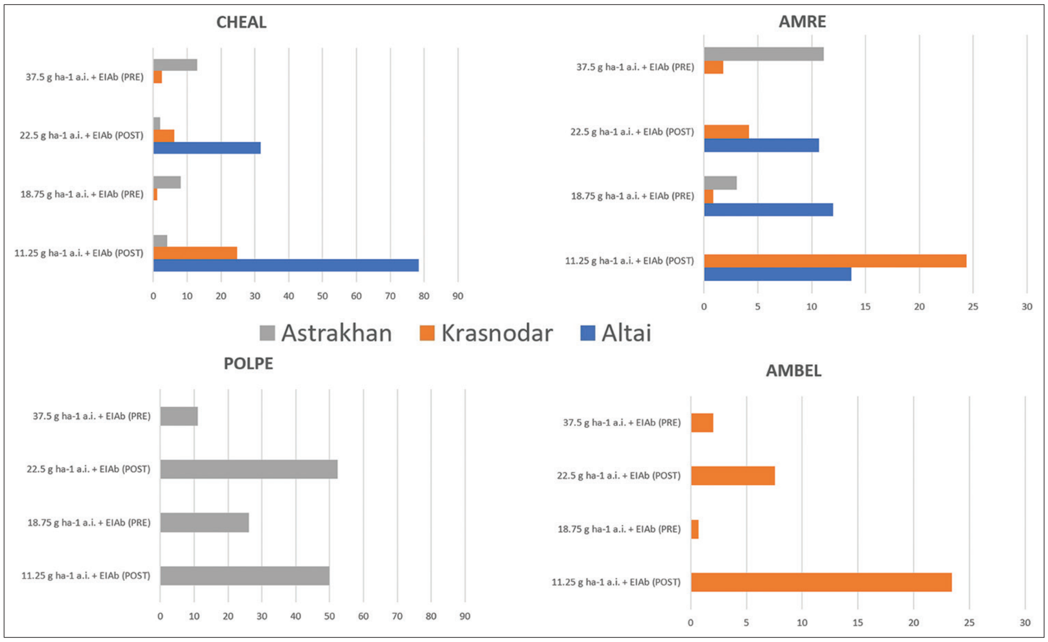

Fig 2. Increasing diclosulam efficiency by add EIA - ethoxylated isodecyl alcohol (2018).

Table 1: Soybean yield after diclosulam application (2017-2018).

Treatments (Application time[a])	Productivity of soybeans cultivars (in regions), centners per hectare		
2017	**Altom (Altai)**	**Bara (Krasnodar)**	**Bara (Astrakhan)**
1. Diclosulam - 18.75 g ha^{-1} a.i. (PRE)	11.7	24.6	20.0
2. Diclosulam - 37.5 g ha^{-1} a.i. (PRE)	14.4	25.5	21.4
3. Imazethapyr - 50 g ha^{-1} a.i. (PRE)	12.6	27.1	19.5
4. Imazethapyr - 80 g ha^{-1} a.i. (PRE)	15.1	27.8	21.9
5. Nontreated check	7.0	19.2	16.3
LSD (P=0.05)	1.6	0.9	2.3
1. Diclosulam - 11.25 g ha^{-1} a.i. (POST)	8.0	23.4	17.8
2. Diclosulam - 22.5 g ha^{-1} a.i. (POST)	11.1	24.1	19.3
3. Imazethapyr - 50 g ha^{-1} a.i. (POST)	19.8	28.9	18.8
4. Imazethapyr - 80 g ha^{-1} a.i. (POST)	19.3	29.1	20.0
5. Nontreated check	6.4	19.2	15.2
LSD (P=0.05)	1.7	1.1	1.7
2018	**Altom (Altai)**	**Bara (Krasnodar)**	**Vilana (Astrakhan)**
1. Diclosulam - 18.75 g ha^{-1} a.i. (PRE)	10.0	20.2	22.0
2. Diclosulam - 37.5 g ha^{-1} a.i. (PRE)	10.4	22.5	23.1
3. Diclosulam - 18.75 g ha^{-1} a.i.+ EIA[b] (PRE)	10.8	20.3	22.6
4. Diclosulam - 37.5 g ha^{-1} a.i.+ EIA[b] (PRE)	11.0	22.7	24.1
5. Clomazone - 336 g ha^{-1} a.i. (PRE)	10.9	20.5	21.5
6. Clomazone - 480 g ha^{-1} a.i. (PRE)	11.5	22.6	22.2
7. Nontreated check	6.3	17.5	18.1
LSD (P=0.05)	1.6	1.2	2.3
1. Diclosulam - 11.25 g ha^{-1} a.i. (POST)	10.2	23.8	21.5
2. Diclosulam - 22.5 g ha^{-1} a.i. (POST)	10.5	26.4	22.7
3. Diclosulam - 11.25 g ha^{-1} a.i. + EIA[b] (POST)	11.3	26.1	22.5
4. Diclosulam - 22.5 g ha^{-1} a.i. + EIA[b] (POST)	10.8	27.0	23.6
5. Thifensulfuron-methyl - 4,5 g ha^{-1} a.i. + EIA[b] (POST)	11.1	26.0	22.2
6. Thifensulfuron-methyl - 6,0 g ha^{-1} a.i. + EIA[b] (POST)	10.1	26.9	23.1
7. Nontreated check	8.4	17.8	18.4
LSD (P=0.05)	1.6	1.4	2.4

[a]Abbreviations: PRE - preemergence; POST - post emergence
[b]Abbreviations: EIA - ethoxylated isodecyl alcohol (90%) - surfactant (0.1% v/v)

In absolute terms the high increase yield after herbicide treatment was obtained in Krasnodar Region in 2018 on the Bara. It was 9.2 centners per hectare with an application of 22.5 g ha^{-1} a.i. + EIAb (POST) with untreated control yields of 17.8 centners per hectare.

In relative terms yield increase in the experiments ranged from 17% (11.25 g ha^{-1} ai (POST) in Astrakhan Region in 2017 with a yield of cultivar Bara (in untreated control - 15.2 centners per hectare) to 106% (37.5 g ha^{-1} ai (PRE) in Altai Region in 2017 with a yield of cultivar Altom (in untreated control 7 centners per hectare).

CONCLUSION

Monocotyledonous weeds (Echinochloa crusgalli and Panicum miliaceum ssp. ruderale had low sensitivity to diclosulam. This can be compensated for by using diclosulam in tank mixture with graminicides (Lancaster et al., 2007b).

Dicotyledonous weeds react differently to diclosulam treatment. Diclosulam efficacy at the minimum application rate (11,25 g i.a. ha^{-1} (POST)) against Fallopia convolvulus (L.) A. Love and Solanum nigrum L. was 100%. Diclosulam efficiency against Chenopodium album L., Amaranthus retroflexus L., Ambrosia artemisiifolia L., Persicaria maculosa S.F. Gray can be improved by adding adjuvant ethoxylated isodecyl alcohol (EIAb) to diclosulam. The maximum effect of it was observed when using EIAb with diclosulam - 11,25 g i.a. ha^{-1} (POST).

The use of diclosulam does not cause phytotoxicity in soybean cultivars Altom, Bara and Vilana. The maximum yield increase of soybean cultivar Bara (9.2 centners per hectare) was observed in Krasnodar Region in 2018 when applying 22.5 g ha-1 a.i. + EIAb (POST); in untreated control - 17.8 centners per hectare.

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Author contributions

The author designed the experiment, analyzed the data and wrote the manuscript.

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