AGROLOGY

ISSN 2617-6106 (print)
ISSN 2617-6114 (online)
Agrology, 2022, 5(3), 87–91
doi: 10.32819/021113

Original researches

Received: 11.06.2022
Revised: 05.07.2022
Accepted: 08.07.2022

Optimization of the phytotoxic effect of herbicide mixtures in winter wheat crops of agrocenoses of the steppe ecotype

M. S. Shevchenko*, A. A. Mytsyk, S. M. Shevchenko**, V. V. Pozniak**, Y. I. Tkalich****

**Institute of Grain Crops of the National Academy of Agrarian Sciences of Ukraine, Dnipro, Ukraine*
***Dnipro State Agrarian and Economic University, Dnipro, Ukraine*

Institute of Grain Crops of NAAS,
Volodymyr Vernadskyi st., 14,
Dnipro, 49009, Ukraine.
Tel.: +38-067-960-51-72.
E-mail: m.s.shevchenko@ukr.net

Dnipro State Agrarian
and Economic University,
Serhii Efremov st., 25,
Dnipro, 49600, Ukraine.
Tel.: +38-097-381-54-40.
E-mail: s.m.shevchenko@ukr.net

Cite this article: Shevchenko, M. S., Mytsyk, A. A., Shevchenko, S. M., Pozniak, V. V., & Tkalich, Y. I., (2022). Optimization of the phytotoxic effect of herbicide mixtures in winter wheat crops of agrocenoses of the steppe ecotype. Agrology, 5(3), 87–91. doi: 10.32819/021113

Abstract. Grain productivity of winter wheat largely depends on the degree of weeds, the effectiveness of herbicide application, and soil and climatic conditions. We conducted field tests of new formulations of herbicides on winter wheat crops, aimed at optimizing the phytotoxic composition of tank mixtures consisting of multi-spectrum active substances. When performing the study, we used the general scientific and special research methods for studying the species composition of weeds, evaluating the technical effectiveness of herbicides, biometric indicators of plants and accounting for grain yield. Species identification of weed phytocenosis in winter wheat crops showed weed invasion by ragweed and sunflower. We studied the phytotoxic properties of tank mixtures of herbicides based on the active substance thifensulfuron-methyl, tribenuron-methyl, florasulam and combined preparations based on halauxifen-methyl, florasulam, cloquintocet acid and florasulam, aminopyralid, 2-ethylhexyl ether 2,4-D, their technical efficiency, dynamics of weed inhibition and death during the crop growing season, and individual resistance of the weed species. We carried out a biometric analysis (seeding density, linear growth, yield of grain from the ear) of winter wheat depending on the toxicity of herbicides. We concluded that the mixture of herbicides Granstar Gold 30 g/ha + Hammer 20 g/ha was the most effective. The relevance of the problems we considered in the article is enhanced by the broad potential of improving the weed control system in highly variable phytocenoses in crop rotations of modern adaptive agriculture and ensuring environmental safety.

Keywords: grain; weeds; control; active substance; pesticides; resistance; yield.

Introduction

The integration of national agricultural production into world markets is accompanied by significant changes in the structure of cultivated areas, the dominance of crops with high productivity, including winter wheat, and the strengthening of the role of chemical means of controlling weeds (Ramesh et al., 2017; Singh et al., 2017; Tsyliuryk et al., 2018).

As a result of the increase in the sown areas of winter wheat, which are placed in crop rotation with complex precursors such as sunflower, the risks of reducing the competitiveness of the crop and increasing grain yield losses due to weeds are noticeably increasing. The reason for this phenomenon is insufficient phytocenotic stability of winter crops as a result of their thinning, deterioration of moisture and nutrition conditions, opening of additional ecological space for weeds (Barberi et al., 2018; Beckie et al., 2020; Choudhary et al., 2021).

The transformation of the species structure of weeds leads to the establishment of the most resistant and harmful species in the phytocenosis, such as ragweed, catchweed bedstraw, field bindweed, Canada thistle, sunflower, etc. Traditional species of overwintering and biennial weeds are becoming somewhat rarer due to the expansion of wide-row plants (Bailly et al., 2012; Andert et al., 2018; Gaines et al., 2020).

The issue of selecting the phytotoxic effect of herbicides remains fundamental in a situation where a phytocenosis of weeds is dominated by species that have developed increased resistance and need to be controlled by more effective herbicides. The search of such herbicides is now underway. Therefore, one of the promising directions in the organization of weed control in winter wheat crops is the expansion of the phytotoxic spectrum using multicomponent herbicide compositions. At the same time, the issue of identifying a specific ratio of various active substances in the composition of the working solution remains important. This approach to suppress the relevant types of weeds would help to develop tank mixtures for the protection of crops with a different species structure of weeds. That is, we are talking about what would ensure a high level of adaptability of the winter wheat protection system against weeds depending on the ecotype, resistance, phase state and biometric model of weeds in crops.

To a large extent, the effectiveness of weed inhibition depends on the synchronicity of the most sensitive phase of certain types of weeds with the organogenesis of winter wheat and the timing of crop spraying. The problem of protecting winter wheat crops from weeds is complicated due to the fact that along with traditional weeds of the winter agrocenosis, such as annual dicotyledons, monocotyledonous weeds are becoming more and more noticeable. In this direction of species transformation of weeds, an obvious question arises regarding the inclusion of active substance components in the tank mixtures of herbicides, which are aimed at the inhibition of small legume species (Powles et al., 2001; Nandula et al., 2019; Pardo et al., 2019).

Currently, a relevant issue is reducing pesticide pressure on agrobiological objects by matching the phytotoxic effect of herbicides with the spectrum of weed resistance, and the targeted use of combined preparations in the case of mixed weed invasion of winter wheat crops (Harker et al., 2013; Alarcón et al., 2018; Dayan et al., 2019).

The objective of the research was conducting field tests of new formulations of herbicides on winter wheat crops and optimizing the phytotoxic composition of tank mixtures consisting of multi-spectrum active substances. The reaction of weeds to the herbicide treatment of crops was phytocenotically assessed by visual monitoring of the manifestation of their depression, as well as the level of biological indifference to the action of herbicides.

Materials and methods

The study was carried out at the research field of the educational and scientific center of the Dnipro State Agrarian and Economic University (DDAEU) on ordinary low-humus medium-strength silty-medium loam chernozems in the forest. The soils are characterized by high potential and effective fertility with 3.9% humus content.

The potential weed invasion of soil in places where the experiments were conducted on the vegetative organs of reproduction of perennial rhizome weeds was: 100–120 thousand units/m² (i.e. average) and the seeds of young plants: 700–800 million units/ha in the arable layer (high).

The hydrothermal conditions of the autumn period of 2018–2022 were characterized by favorable soil moisture of 22–27 mm in the 0–30 cm soil layer, a growing season with the overall effective temperatures measuring close to the perennial 257°C, which ensured the entry of plants into the state of winter dormancy during the phase of 2–3 shoots and a sufficiently developed root system.

Agricultural technology of winter wheat (Commercial variety) met the zonal recommendations. Precursor of wheat was sunflower, and N_{30} P_{30} fertilizers were applied for pre-sowing cultivation prior to sowing of the wheat. To study the effectiveness of herbicides, their mixtures and doses were selected according to the species composition of weeds and their resistance. Based on a preventive analysis, the group of herbicides used in the experiment included drugs such as Granstar Gold, the active substances of which are tribenuron-methyl (562.5 g/kg), thifensulfuron-methyl (187.5 g/kg); hummer – florasulam (250 g/kg); quelex – haloxifen-methyl (100g/kg), florasulam (100g/kg), cloquintocet acids (70.8 g/kg); prima forte – florasulam (5 g/L), aminopyralid (10 g/L), 2-ethylhexyl ether 2,4-D (180 g/L). Trend 90 adhesive agent was used as a surface-active substance. Herbicides in the experiment were applied using a small OM-4 sprayer, developed by the Department of General Agriculture and Soil Science of the Dnipro State Agrarian and Economic University and Agromodul LLC. Weed invasion of crops was determined by arranging 20 monitoring plots (0.25 m^2) along the largest diagonal, where we identified quantitative and species composition and further estimated the abundance per 1 m^2 of the field. At the last accounting, all weeds from the accounting framework were plucked, labeled and air-dried to determine their above-ground biomass (Trybel et al., 2001).

The data were analyzed using Statistica 10.0 software (StatSoft Inc., USA). The yield data are tabulated as x ± SD (x ± standard deviation). The differences between values in control and experimental variants were determined using the Tukey's test, where differences were considered significant at $P < 0.05$ (with Bonferroni correction).

Results

In the springing phase of winter wheat, before the application of herbicides, the degree of actual weed invasion of the crops was 19–22 ind/m^2, and 68.2% of the species structure of the phytocenosis was represented by such a dominant species as sunflower, grass fallow accounted for 30.7%, ragweed – 27.6%. Herbologically, overwintering weed species traditional for sowing winter crops (flixweed *Descurainia sophia*, tumble mustard *Sisymbrium altissimum*) were found at a minimum rate of 0.5–1.0 ind./m^2. At the same time, in the area of the field experiment during this growing season, the degree of weed invasion was fairly even, accounting for 19–22 ind./m^2. Weeds were in a sufficiently sensitive phase of growth and development to herbicides: sunflower – 6–12 cm (2–3 pairs of leaves), ragweed – 4–9 cm (cotyledons-3 leaves), catchweed bedstraw *Galium aparine* – 8–14 cm (1–5 internodes), perennial species – 8–16 cm (Table 1).

Table 1
Dynamics of the degree of weed invasion of winter wheat against the background of the use of herbicides (average for 2019–2022, units/m^2, x ± SD, n=20)

Variants	Periods of measuring weed invasion			
	before applying herbicides	10 days after applying herbicides	30 days after applying herbicides	before harvesting
Control	19.9 ± 2.1^a	19.9 ± 2.5^a	19.9 ± 2.1^a	25.9 ± 2.5^a
Granstar gold 20 g/ha + Hammer 15 g/ha + trend 300 mL/ha	20.6 ± 2.0^a	3.9 ± 0.4^b	2.4 ± 0.2^b	5.2 ± 0.4^b
Granstar gold 20 g/ha + Hammer 20 g/ha + trend 300 mL/ha	21.1 ± 1.9^a	3.6 ± 0.3^b	2.2 ± 0.3^b	4.8 ± 0.5^b
Granstar gold 25 g/ha + Hammer 15 g/ha + trend 300 mL/ha	19.2 ± 2.2^a	3.4 ± 0.4^b	1.8 ± 0.3^b	4.3 ± 0.4^b
Granstar gold 25 g/ha + Hammer 20 g/ha + trend 300 mL/ha	19.6 ± 2.3^a	3.3 ± 0.3^b	1.7 ± 0.2^b	3.9 ± 0.5^b
Granstar gold 30 g/ha + Hammer 15 g/ha + trend 300 mL/ha	18.8 ± 2.5^a	3.2 ± 0.4^{bc}	1.5 ± 0.3^{bc}	3.7 ± 0.5^{bc}
Granstar gold 30 g/ha + Hammer 20 g/ha + trend 300 mL/ha	20.1 ± 2.5^a	2.7 ± 0.3^{bc}	1.3 ± 0.2^{bc}	3.3 ± 0.4^{bc}
Granstar gold 35 g/ha + trend 300 mL/ha	21.4 ± 1.9^a	3.5 ± 0.4^c	2.1 ± 0.3^b	4.6 ± 0.5^b
Hammer 25 g/ha + trend 300 mL/ha	20.6 ± 2.1^a	3.7 ± 0.3^c	2.2 ± 0.3^b	4.9 ± 0.4^b
Quelex 60 g/ha + trend 300 mL/ha	18.5 ± 2.0^a	3.4 ± 0.4^c	1.8 ± 0.2^b	4.3 ± 0.4^b
Prima forte 0.7 L/ha	20.5 ± 2.3^a	3.2 ± 0.3^c	1.6 ± 0.3^b	3.8 ± 0.2^b

Note: different letters indicate values that are significantly different from each other in Table 1 according to the Tukey test ($P < 0.05$) with the Bonferroni correction.

According to the scheme of experiments on the phytotoxic potential of various combinations of the active substances florasulam, thifensulforon-methyl, tribenuron-methyl, a sufficiently transparent pattern of weed sensitivity or resistance was determined on the 10th day after the application of the herbicides.

According to the degree of damage, the following types of weeds were found to be the most resistant to the action of herbicides: field bindweed *Convolvulus arvensis* – 96.4% (resistance), ragweed – 32.1%, catchweed bedstraw – 28.2%, sunflower – 14.3%, barnyardgrass – 100.0%, Canada thistle – 16.1%. The rest of the weed species almost completely lost their regeneration ability as a result of contact with the herbicide.

The main signs of phytotoxic damage to weeds and sunflower (loss of turgor and intensity of chlorophyll color, dehydration and drying, inhibited growth, complete death) appeared on the 10th day after the treatment of crops with herbicides. The aridity of the climate and the sharp drying of the top layer of the soil contributed to a significant increase in the depressive effect. Regarding the mixtures of herbicides Granstar Gold (20–25 g/ha) and Hammer (15–20 g/ha), the maximum efficiency was seen when herbicides Granstar Gold 25–30 g/ha + Hammer 20 g/ha were applied, which was 89–92%. A further increase in the dose of these drugs to 93% was impractical. Biometric and phase changes of winter wheat and weeds were observed within 30 days after the application of herbicides in the flag leaf phase. Both the crop and the weeds were in the zone of deep moisture deficit, when only 18–25 mm of rain fell, and the reserves of productive moisture at the time of grain milk maturity (65%) in the 0–30 cm soil layer were only 14–23 mm. The height of winter crops increased slightly to 83.0–89.8 cm, and 3–4 upper leaves remained functional.

At the same time, the trend regarding the technical efficiency indicators of various combinations of the active substance in mixtures and combined preparations remained. At the minimum applied doses of the mixture of the herbicides Granstar Gold 20 g/ha + Hammer 15 g/ha, 2.4 weeds/m^2 with signs of viability remained in the crops, and after the maximum dosage of herbicides Granstar Gold 30 g/ha + Hammer 20 g/ha, the degree of weed invasion decreased to 1.3 ind./m^2.

At 25.9 units/m^2 degree of weed invasion of the crops in the control without herbicides, the most effective mixtures of herbicides Granstar Gold + Hammer with doses of 25–20 g/ha, 30+15 g/ha, 30+15 g/ha and 30+20 g /ha before harvesting, the minimum number of weeds remained – 3.3–4.0 ind./m^2.The overall technical efficiency against the background of the full species complex of weeds ranged high level of 85.7% when applying the mixture of Granstar Gold 20 g/ha + Hammer 15 g/ha to 93.5% at the maximum dose of Granstar Gold 30 g/ha + Hammer 20 g/ha (Table 2). Weed counts with simultaneous uprooting of weeds after reaching full ripeness of winter wheat grain showed that their air-dry mass in the control reached 43.4 g/m^2, and with the best formulations of herbicides in terms of doses and properties of the active substance, it decreased to 6.6–8.8 g/m^2. Compared with the control, the highest difference in the density of the productive stem was 362.6–388.5 ind./m^2. At the same time, the linear growth of winter wheat had a stable dependence on the effectiveness of herbicides and the degree of weed invasion of the crops (Table 3).

Table 2
Technical efficiency (%) of mixtures and combined herbicides on winter wheat (average for 2019–2022, x ± SD, n=20)

Variants	Terms of determining weed invasion				Total
	sunflower	catchweed bedstraw	regweed	others	
Control	91.8 ± 3.2[a]	90.5 ± 2.9[a]	85.5 ± 3.2[a]	85.7 ± 2.5[a]	87.9 ± 2.8[a]
Granstar gold 20 g/ha + Hammer 15 g/ha + trend 300 mL/ha	91.8 ± 3.1[a]	90.5 ± 3.2[a]	87.2 ± 2.9[a]	87.3 ± 2.7[a]	88.9± 2.5[a]
Granstar gold 20 g/ha + Hammer 20 g/ha + trend 300 mL/ha	93.4 ± 3.0[a]	95.2 ± 2.7[a]	89.1 ± 3.2[a]	88.8 ± 2.8[a]	91.0± 2.9[a]
Granstar gold 25 g/ha + Hammer 15 g/ha + trend 300 mL/ha	93.4 ± 2.9[a]	95.2 ± 3.1[a]	90.9 ± 2.5[a]	88.8 ± 3.1[a]	91.4± 2.5[a]
Granstar gold 25 g/ha + Hammer 20 g/ha + trend 300 mL/ha	95.0 ± 3.2[ab]	95.2 ± 2.9[ab]	90.9 ± 2.8[ab]	90.5 ± 2.5[ab]	92.5± 3.0[ab]
Granstar gold 30 g/ha + Hammer 15 g/ha + trend 300 mL/ha	96.7 ± 3.0[ab]	100.0 ± 2.7[ab]	92.7 ± 2.4[ab]	90.5 ± 2.1[ab]	93.5± 2.8[ab]
Granstar gold 30 g/ha + Hammer 20 g/ha + trend 300 mL/ha	91.8 ± 2.8[a]	90.5 ± 3.0[a]	87.2 ± 3.1[a]	88.8 ± 2.8[a]	89.4± 3.1[a]
Granstar gold 35 g/ha + trend 300 mL/ha	88.5 ± 3.1[a]	90.5 ± 3.1[a]	89.1 ± 3.0[a]	88.8 ± 2.6[a]	88.9± 2.6[a]
Hammer 25 g/ha + trend 300 mL/ha	91.8 ± 2.9[a]	95.2 ± 2.8[a]	89.1 ± 2.7[a]	90.5 ± 3.0[a]	91.0 ± 3.1[a]
Quelex 60 g/ha + trend 300 mL/ha	93.4 ± 3.2[a]	90.5 ± 2.9[a]	90.9 ± 2.9[a]	92.1 ± 2.7[a]	92.0 ± 3.0[a]

Note: see Table 1.

Table 3
Bioproductive parameters of winter wheat when using the herbicides (x ± SD, average for 2019–2022)

Options	Plant height, cm	Productive stems, ind./m^2	Mass of grain in an ear, g	Productivity, t/ha
n	40	20	40	8
Control	83.0± 2.4[a]	362.6± 12.4[a]	0.99± 0.04[a]	3.56 ± 0.12[a]
Granstar gold 20 g/ha + Hammer 15 g/ha + trend 300 mL/ha	87.0± 3.0[b]	378.1± 13.3[b]	1.05± 0.03[b]	3.71± 0.11[b]
Granstar gold 20 g/ha + Hammer 20 g/ha + trend 300 mL/ha	87.5± 3.8[b]	380.4± 14.0[b]	1.06± 0.03[b]	3.73±0.09[b]
Granstar gold 25 g/ha + Hammer 15 g/ha + trend 300 mL/ha	87.8± 3.1[b]	382.5± 14.7[bc]	1.06± 0.03[b]	3.79±0.10[bc]
Granstar gold 25 g/ha + Hammer 20 g/ha + trend 300 mL/ha	88.1± 3.3[b]	385.0± 14.8[bc]	1.08± 0.04[b]	3.86±0.08[bc]
Granstar gold 30 g/ha + Hammer 15 g/ha + trend 300 mL/ha	89.0± 2.8[bc]	387.9± 15.1[c]	1.11± 0.02[bc]	3.89±0.09[c]
Granstar gold 30 g/ha + Hammer 20 g/ha + trend 300 mL/ha	89.8± 2.8[bc]	388.5± 14.3[c]	1.12± 0.02[bc]	3.90±0.09[c]
Granstar gold 35 g/ha + trend 300 mL/ha	87.1± 3.2[b]	379.7± 15.0[bc]	1.05± 0.03[b]	3.75±0.08[bc]
Hammer 25 g/ha + trend 300 mL/ha	86.8± 2.7[b]	378.0± 14.8[bc]	1.06± 0.04[b]	3.72±0.10[b]
Quelex 60 g/ha + trend 300 mL/ha	87.6± 3.0[b]	381.1± 14.9[bc]	1.06± 0.03[b]	3.77±0.11[bc]
Control	88.0± 3.1[b]	385.0± 13.4[bc]	1.08± 0.02[b]	3.85±0.10[bc]

Note: see Table 1.

The use of combined or monotoxic herbicides such as Hammer, Granstar Gold, quelex, prima forte was inferior to spraying with the Granstar Gold + Hammer tank mixtures in optimal doses in terms of linear growth of wheat plants. As can be seen, the maximum height of winter wheat plants of 89.8 cm was achieved when the Granstar Gold 30 g/ha + Hammer 20 g/ha mixture was applied or with the active ingredient thifensulfuron-methyl + tribenuron-methyl + florasulam.

According to the type and degree of active weeding that developed in the experiment, the regulatory value of tank mixtures and combined preparations was that they contributed to the growth of winter wheat grain yield with minimal technical efficiency (Granstar Gold 20 g/ha + Hammer 15 g/ha) from 3.56 to 3.71 t/ha, and at the maximum (Granstar Gold 30 g/ha + Hammer 20 g/ha) to 3.90 t/ha.

The Prima forte herbicides 0.7 L/ha allowed for the production of 3.85 t/ha of grain, approaching the maximum indicators of the level of protection of winter wheat crops. The herbicides Granstar Gold 35 g/ha, Hammer 25 g/ha, quelex 60 g/ha made it possible to obtain grain yield at the level of 3.71–3.77 t/ha, which was equivalent to applying the mixture of Granstar Gold 20 g/ha + Hammer 15–20 g/ha.

Discussion

The formation of the type and degree of weed invasion in the experiment took place under the influence of agrotechnical measures, hydrothermal conditions and potential soil weed invasion. The objective prerequisites for the formation of limited weed invasion were a short autumn vegetation, a protracted stage of winter dormancy, a sharp transition to high temperatures and a long dry period in the interphase interval of bush-flag leaf (Sonderskov et al., 2015; Tsyliuryk et al., 2017; Andert et al., 2018).The application of Quelex 60 g/ha and Prima Forte herbicides was inferior to the optimal doses of Granstar Gold and Hammer herbicides in terms of the depth of impact on ragweed, sticky ragwort and sunflower stubble. Weeds that germinated in winter wheat crops after the application of herbicides were under the phytotoxic effect of the active substance, the competitive pressure of the crop and weather conditions with a hydrothermal coefficient of 0.35–0.48, as a result of which the degree of weed invasion was constantly decreasing during 30 days compared with the previous record (10 days after spraying). On the 10[th] day after the introduction of herbicides, the depth of phytotoxic depression was not complete and the residual degree of weed invasion was 2.7–3.9 units/m^2, whereas after 20 days, the prolonged toxic pressing contributed to its reduction to 1.3–2.4 units/m^2 (Jabran et al., 2017; Verma et al., 2017; Storkey et al., 2018).

Due to the expansion of the spectrum of phytotoxic action, the mixtures exceeded the effectiveness of individual herbicides applied in the maximum doses of Granstar Gold 35 g/ha and Hammer 25 g/ha by 3–5%. The Granstar gold and Hammer herbicide mixtures significantly controlled not only the general weed invasion, but also individual weeds with specific resistance, which ensured the following level of technical efficiency: sunflower stubble – 97.2%, catchweed bedstraw – 95.4%, ragweed – 91.1%.

Starting from the 30th day after spraying the crops with herbicides before the harvest of winter wheat, a certain increase in the degree of weed invasion was observed due to the new generation of barnyardgrass. However, it practically did not affect the formation of grain yield, since wheat formed the main biological mass and the plants became less dependent on competition in the agrocenosis and soil conditions. There was no mass threat of an emergence of the second "wave" of weeds due to the long-term dehydration of the upper soil layer, in which the germination of seeds of annual species had been activated. When the grain of winter wheat reached the complete maturity, the technical effectiveness of herbicides was similar to the records made on the 10th and 30th day after spraying the crops. That is, during the growing season of winter wheat in the spring-summer period, the dynamics of weed invasion did not have a radical transformation and was formed under the action of the most powerful factor – herbicides.

It should be noted that even the minimum dosages of herbicides Granstar Gold and Hammer 20+15 g/ha and 20+20 g/ha provided a high protective effect during the growing season and at the time of its completion kept the degree of weed invasion of the crops at the minimum level of harmfulness – 4.8–5.2 ind./m^2. According to the phytotoxic characteristics, the results produced by the herbicides Granstar

Gold 35 g/ha, Hammer 25 g/ha and Quelex 60 g/ha, measuring 4.3–4.9 ind./m^2, were equivalent to the treatment of crops with mixtures of the herbicides Granstar Gold and Hammer in the minimum doses of 20–15 and 25+15 g/ha.

In terms of the effectiveness against the most resistant and harmful types of weeds and sunflower stubble, we determined that the mixtures of herbicides Granstar Gold + Hammer also caused deep depression and destruction of the main part of those weeds. For example, the introduction of the mixture of herbicides Granstar Gold 30 g/ha + Hammer 20 g/ha before harvesting winter crops – compared with the control - decreased the amount of sunflower from 6.1 to 0.1 ind./m^2, catchweed bedstraw from 2.1 to 0 ind./m^2, ragweed from 6.7 to 0.6 ind./m^2. The spectrum of phytotoxic action narrowed when the hericides were applied individually. For example, applications of the herbicides Granstar Gold 35 g/ha and Hammer 25 g/ha alone were less effective than the mixtures, leaving more residual amount of sunflower and ragweed, equaling 0.7 ind/m^2 and 1 ind/m^2, respectively. Starting with the dose of the Granstar Gold mixture of 25 g/ha + Hammer 15 g/ha, the technical efficiency of the three-component mixture (tribenuron-methyl + tifensulfuron-methyl + florasulam) reached an acceptable level for any herbicide – 91.1. The combined herbicides Quelex and Prima Forte provided the same level of technical efficiency. The effectiveness of herbicides against reached 90.5–100% when using a mixture of Granstar Gold 30 g/ha + Hammer 20 g/ha. At the same time, this mixture caused the greatest, 100%, inhibition of tenacious catchweed bedstraw and 96.7% inhibition of sunflower. The phytotoxic resistance of ragweed was slightly higher, which accordingly reduced the technical efficiency of the mixture of herbicides to 92.7%, and the group of other weeds to 90.5% (Kaundun et al., 2014; Sonderskov et al., 2015; Zargar et al., 2020).

Pre-harvest air-dry weed biomass is believed to be a more objective measure of weed damage. Characterizations of the agrocenosis in generale and individual plants of winter wheat provided more reliable and convincing results of the effect the herbicides took on the formation of the grain yield of this crop. Such constituent elements of the growth and development of winter wheat as plant height, ear length, grain yield from the ear and the density of the productive stem opened up additional opportunities for assessing the impact of weeds and herbicides on grain yield and competitive relations in agrocenosis (Petit et al., 2011; Hicks et al., 2018; Vijay et al., 2020).

Despite the insufficient bushiness and productivity coefficient of winter wheat plants, the indicators of grain yield from the ear, due to the redistribution of nutrition in favor of the productive part, turned out to be high enough, as well as all biometric components of the plants sensitively reacted to the harmful effects of weeds. Therefore, in the control, the mass of grain in the ear was 0.99 g, while at the minimum residual weed invasion of 1.2 ind./m^2, it reached the maximum of 1.12 g. The growth dynamics of grain mass in the ear paralleled other biometric data such as plant height and ear length.

Thanks to the high level of controllability of resource factors and the biological response of the crop, it was possible to obtain objective yield indicators in the experiments with full disclosure of its dependence on the effectiveness of herbicides with a complex phytospectrum. It is important to note that increasing of doses of those herbicides lead up to a point when a further increase in the level of an active substance is inadequate from the standpoint of the yield increase. Thus, at the doses of the Granstar Gold + Hammer mixture accounting for 25 + 20 g/ha, 30 + 15 g/ha, 30 + 20 g/ha, the winter wheat yields of 3.86–3.90 t/ha can be considered equivalent.

Similar patterns and trends in the efficiency are confirmed by the studies of both domestic (Tsyliuryk et al., 2017) and foreign scientists (Janka et al., 2015; Singh et al., 2017; Alarcón et al., 2018). According to the cited researches, expansion of the spectrum of the phytotoxic effect of the chemical method of weed control at the expense of tank mixtures of such agents as Granstar Gold, Quelex, and Prima forte efficiently suppress weeds in agrocenoses of winter wheat at the level of technical efficiency indicators of 89–95%. Spraying of winter wheat crops in the tillering-emergence phase made it possible to significantly increase the competitiveness of the cultivated plants, improve morphobiometric parameters and ensure high grain yield. The ecological parameters of the agrocenosis of winter wheat were ensured at a high level, as evidenced by the absence of external damage to the leaf apparatus and reproductive organs of the plant, the absence of deformation and necrotic damage (Chauhan et al., 2012; Huang et al., 2019).

Conclusions

The degree of weed invasion and species structure of weeds in winter wheat crops before the introduction of herbicides during the flag leaf phase were formed in the conditions of acute moisture deficit in the upper soil layer, which significantly limited the realization of potential weed invasion. The crops were dominated by perennial dicotyledonous weeds, which accounted for 70% of the species structure, while 20% were perennial rhizomes and Poaceae species.

Spraying of winter wheat crops during the flag leaf phase at the weed height of 4–12 cm with multi-spectrum herbicides gradually increased inhibition, deformation, necrosis and complete death of weeds, which ensured high technical efficiency in the range of 82–94%. The maximum effectiveness was provided by the introduction of the tank mixture of Granstar Gold 30 g/ha + Hammer 15–20 g/ha, which contributed to the reduction to the minimum of 1.3–1.5 ind/m^2 of the degree of weed invasion in the phase of milk ripeness of winter wheat grain. At the same time, the weeds had the least harmfulness and competitiveness according to air-dry mass, which was 6.6–7.4 g/m^2.

Winter wheat responded positively to the decrease in weed invasion by improving biometric and productive indicators. With the lowest weed competitiveness, when the herbicide mixtures Granstar Gold 30 g/ha + Hammer 20 g/ha were applied, the winter wheat reached the maximum parameters of height – 75.8 cm, ear length – 8.3 cm, weight of grain from the ear – 1.12 g, and the density of spikelets stem – 308.5 ind./m^2.

The yield of winter wheat grain was naturally dependent on the degree of weed invasion of the crops and phytotoxic effectiveness against weeds. The maximum increase in grain yield equaled 0.34 t/ha, compared with the control when winter wheat crops were treated with the mixture of herbicides Granstar Gold 30 g/ha + Hammer 20 g/ha. From the point of view of the ecological and economic expediency of using herbicides for production, the mixtures of Granstar Gold and Hammer may be recommended, depending on the species composition of weeds and the degree of weed invasion in the dose ratios of 25+20 g/ha, 30+15 g/ha and 30+ 20 g/ha.

The analysis of the results of studies on the effectiveness of combined herbicides against the background of significant weed invasion revealed the perspectives and main directions of scientific research in the field of herbology regarding the transformation of the species composition of weeds, improving the technology of herbicide application and overcoming resistance using combinatorial drugs based on active substance. First of all, improving the adaptation of the phytotoxic action of herbicides in the conditions of the transformation of the species composition of weeds, the search for sensitive phase zones of weed phytocenoses, and the selection of technologically reliable methods of herbicide application have not been fully studied. It is necessary to pay special attention to the problem of increasing the harmfulness of the group of Poaceae weeds in winter wheat crops after widerow precursors, as well as to monitor the after-effect of herbicides on the growth and development of winter wheat.

The authors declare no official obligations or financial responsibility for the use and promotion of research results in the interests of third parties.

References

Alarcon, R., Hernández-Plaza, E., Navarrete, L., Sanchez, M.J., Escudero, A., Hernanz, J. L., Sanchez-Giron, V., & Sanchez, A. M. (2018). Effects of no-tillage and non-inversion tillage on weed community diversity and crop yield over nine years in a Mediterranean cereal-legume cropland. Soil and Tillage Research, 179, 54–62.

Andert, S., Bürger, J., Mutz, J. E., & Gerowitt, B. (2018). Patterns of pre-crop glyphosate use and in-crop selective herbicide intensities in Northern. Germany European Journal of Agronomy, 97, 20–27.

Bailly, G. C., Dale, R. P., Archer, S. A., Wright, D. J., & Kaundun, S. S. (2012). Role of residual herbicides for the management of multiple herbicide resistance to ACCase and ALS inhibitors in a black-grass population. Crop Protection, 34, 96–103.

Barberi, P., Bocci, G., Carlesi, S., Armengot, L., Blanco-Moreno, J. M., & Sans, F. X. (2018). Linking species traits to agroecosystem services: A functional analysis of weed communities. Weed Research, 58(2), 76–88.

Beckie, H. J. (2020). Herbicide resistance in plants. Plants, 9(4), 435.

Chauhan, B. S., & Mahajan, G. (2012). Role of integrated weed management strategies in sustaining conservation agriculture systems. Current Science, 103(2), 135–136.

Choudhary, A. K., Yadav, D. S., Sood, P., Rahi, S., Arya, K., Thakur, S. K., Lal, R., & Singh, R. (2021). Post-emergence herbicides for effective weed management, enhanced wheat productivity, profitability and quality in North-Western Himalayas: A ‘participatory-mode’ technology development and dissemination. Sustainability, 13(10), 5425.

Dayan, F. E. (2019). Current status and future prospects in herbicide discovery. Plants, 8(9), 341.

Gaines, T. A., Duke, S. O., Morran, S. C., Rigon, A. G., Tranel, P. J., Küpper, A., & Dayan, F. E. (2020). Mechanisms of evolved herbicide resistance. Journal of Biological Chemistry, 295(30), 10307–10330.

Harker, K. N., & O’Donovan, J. T. (2013). Recent weed control, weed management, and integrated weed management. Weed Technology, 27, 1–11.

Hicks, H. L., Comont, D., Coutts, S. R., Crook, L., Hull, R., Norris, K., Neve, P., Childs, D. Z., &Freckleton, R.P. (2018). The factors driving evolved herbicide resistance at a national scale. Nature Ecology and Evolution, 2(3), 529–536.

Huang, Z., Huang, H., Chen, J., Chen, J., Wei, S., & Zhang, C. (2019). Nicosulfuron-resistant *Amaranthus retroflexus* L. in Northeast China. Crop Protection, 122, 79–83.

Jabran, K., Mahmood, K., Melander, B., Bajwa, A. A., & Kudsk, P. (2017). Weed dynamics and management in wheat. Advances in Agronomy, 145, 97–166.

Kaundun, S. S. (2014). Resistance to acetyl-CoA carboxylase-inhibiting herbicides. Pest Management Science, 70(9), 1405–1417.

Nandula, V. K., Riechers, D. E., Ferhatoglu, Y., Barrett, M., Duke, S. O., Dayan, F. E., Goldberg-Cavalleri, A., & Ma, R. (2019). Herbicide metabolism: Crop selectivity, bioactivation, weed resistance, and regulation. Weed Science, 67(2), 149–175.

Pardo, G., Cirujeda, A., Perea, F., Verdú, A. M., Mas, M.T., & Urbano, J. M. (2019). Effects of reduced and conventional tillage on weed communities: Results of a long-term experiment in Southwestern Spain. Planta Daninha, 37, e019201336.

Petit, S., Boursault, A., Le Guilloux, M., Munier-Jolain, N., & Reboud, X. (2011). Weeds in agricultural landscapes. A review. Agronomy for Sustainable Development, 31(2), 309–317.

Powles, S.B., & Shaner, D.L. (Eds.). (2001). Herbicide resistance and world grains. CRC Press.

Ramesh, K., Matloob, A., Aslam, F., Florentine, S. K., & Chauhan, B. S. (2017). Weeds in a changing climate: Vulnerabilities, consequences, and implications for future weed management. Frontiers in Plant Science, 8, 95.

Singh, R. P., Verma, S. K., & Kumar, S. (2020). Weed management for enhancing yield and economics of wheat (*Triticum aestivum*) in Eastern India. Indian Journal of Agricultural Sciences, 90(7), 1352–1355.

Verma, S. K., Singh, R. P., & Kumar, S. (2017). Effects of irrigation and herbicides on the growth, yield and yield attributes of wheat (*Triticum aestivum* L.). Bangladesh Journal of Botany, 46(3), 839–845.

Singh, R. P., Verma, S. K., Kumar, S., & Lakara, K. (2017). Impact of tillage and herbicides on the dynamics of broad leaf weeds in wheat. International Journal of Agriculture, Environment and Biotechnology, 10, 643–652.

Sønderskov, M., Fritzsche, R., de Mol, F., Gerowitt, B., Goltermann, S., Kierzek, R., Krawczyk, R., & Rydahl, P. (2015). DSSHerbicide: Weed control in winter wheat with a decision support system in three South Baltic regions – Field experimental results. Crop Protection, 76, 15–23.

Storkey, J., & Neve, P. (2018). What good is weed diversity? Weed Research, 58 (4), 239–243.

Tribel, S. O., Sigareva, D. D., & Sekun, M. P. (2001). Metody testuvannia ta zastosuvannia pestycydiv [Methods of testing and application of pesticides]. Svit, Kyiv (in Ukrainian).

Tsyliuryk, O. I., Shevchenko, S. M., Shevchenko, O. M., Shvec, N. V., Nikulin, V. O., & Ostapchuk, Y.V. (2017). Effect of the soil cultivation and fertilization on the abundance and species diversity of weeds in corn farmed ecosystems. Ukrainian Journal of Ecology, 7(3), 154–159.

Vijay, K.,& Nandula, F. (2019). Herbicide resistance traits in maize and soybean: Current status and future outlook. Plants, 8, 337.

Yu, Q., & Powles, S. (2014). Metabolism-based herbicide resistance and cross-resistance in crop weeds: A threat to herbicide sustainability and global crop production. Plant Physiology, 166(3), 1106–1118.

Yu, Q., & Powles, S. B. (2014). Resistance to AHAS inhibitor herbicides: Current understanding. Pest Management Science, 70(9), 1340–1350.

Zargar, M., Bayat, M., & Astarkhanova, T. (2020). Study of postemergence-directed herbicides for redroot pigweed (*Amaranthus retroflexus* L.) control in winter wheat in Southern Russia. Journal of Plant Protection Research, 60(1), 7–13.