Minimizing the impact of long-lasting herbicides on the functioning of crop rotations

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Abstract. The studies aimed to identify the most responsive test plant species to the aftereffects of herbicides and to verify the actual signs of their phytotoxicity. Soil samples were collected in 2023 from plots treated with herbicides in 2022 on the experimental field of the research and production unit No. 2 of the Kursk FARC (Kursk region, Medvensky district, Panino village). This study proposes evaluating the responsiveness of test plants to the aftereffects of herbicides using the Harrington desirability function. The results show that the most pronounced sensitivity to phytotoxicity in terms of root growth intensity is "quite acceptable, good" on the desirability scale, with a value of $d_i = 0.68$. The sensitivity to phytotoxicity was more pronounced in dicotyledonous plants, particularly oilseed radish ($d_i = 0.69$), and in cereals, particularly spring barley ($d_i = 0.72$), based on the intensity of root growth.

1 Introduction

In modern agriculture, the use of herbicides allows us to solve the problem of crop weeds, which, on the one hand, helps to obtain an additional increase in yield, and on the other, causes certain environmental damage. The problem of soil pollution due to the aftereffect of herbicides on subsequent crops in crop rotation is becoming increasingly widespread [1-3]. Therefore, to achieve maximum biological effectiveness of herbicides and minimal phytotoxicity towards crops, regulated drug consumption rates are used and antidotes, growth stimulants, and nutritional correctors are used [4, 5].

The level of toxicity of soil contaminated with herbicides can be determined by three methods: chemical analysis, determination of the biological activity of the soil and its phytotesting. The most attractive method is phytotesting, the unique fundamental feature of which is the ability, in laboratory conditions, to carry out an integral assessment of the effect on living plant organisms of not only individual substances, but also the effects of their interaction. The length of roots and stems of seedlings, plant biomass, seed germination and germination energy are used as evaluated test parameters [6-8].

When conducting an agroecological assessment of the impact of crop rotation on the safety of grain crop production, as one of the factors of in-depth adaptation, it is important to take into account the accumulation and further manifestation of herbicide toxicity on a number of crops during the fruiting cycle [9, 10]. Part of the herbicide load can be reduced

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through agrotechnical measures, and it is also necessary to strive to select less toxic herbicides with special attention to doses and application technology, including for organic agriculture, which will reduce the risks of damage to human health and agroecosystems [11]. In this regard, the most relevant direction for improving modern crop rotations is to minimize the impact of herbicides with a long aftereffect on their functioning. Therefore, it is necessary to find a comprehensive, user-friendly and low-cost approach to assessing soil toxicity for herbicide residues [12-13].

The purpose of the research is to determine the test plant species that are most responsive to the aftereffects of herbicides and to substantiate the current signs of their phytotoxicity.

2 Materials and methods

Two dicotyledonous plants (white mustard, oilseed radish) and cereal crops (spring oats, barley) were used as test plants in accordance with standardized phytotesting methods used in the Russian Federation.

Laboratory studies were carried out in accordance with GOST R ISO 18763-2019 “Soil quality. Determination of the toxic effects of pollutants on germination and growth in the early stages of higher plants." Before the start of the experiment, the laboratory germination of test plant seeds was determined in accordance with GOST 12038-84 “Agricultural crop seeds. Methods for determining germination". A list of laboratory testing options is given in Table 1.

Table 1. Experimental options for assessing the aftereffects of herbicides.

Experiment variant	Soil samples for cultivation, 2023	Predecessor, 2022	Herbicide according to predecessor	Active ingredient [16]
1 (control)	Deposit	–	–	–
2	Barley	Corn for silage	Elumis	Mesotrione + nicosulfuron
3	Corn for silage	Sugar beet	Betanal 22 Betanal Progress OF Caribou Lonterr Panther	Desmedipham + phenmediphan Ethofumesate + phenmedipharm + desmedipham Triflusulfuron-methyl Clopyralid Quizalofop-P-tefuril
4	Buckwheat (plakor)	Barley	Camaro	2,4-D – (2-ethylhexyl ester + florasulam
5	Buckwheat (lower slope)	Barley	Camaro	2,4-D – (2-ethylhexyl ester) + florasulam
6	Buckwheat	Oats	Elumis	Mesotrione + nicosulfuron
7	Buckwheat variant with biological products	Oats	Elumis	Mesotrione + nicosulfuron
8	Lupine white	Corn for silage	Prima	2,4-D – (2-ethylhexyl ester) + florasulam
9	White lupine in the version with biological products	Corn for silage	Prima	2,4-D – (2-ethylhexyl ester) + florasulam

10	Soybeans for grain (non-eroded chernozems)	Soybeans for grain	Bazagran Harmony	Bentazon Thifensulfuron-methyl
11	Soybeans for grain (eroded chernozems)	Soybeans for grain	Bazagran Harmony	Bentazon Thifensulfuron-methyl
12	Soybeans for grain (alluvial chernozems)	Soybeans for grain	Bazagran Harmony	Bentazon Thifensulfuron-methyl

To quantitatively assess the signs of phytotoxicity of test plants, in the spring of 2023, during the sowing period of crops, soil samples were taken from plots of the experimental field of the Federal State Budgetary Scientific Institution "Kursk FARC", treated with herbicides in 2022.

The soil of option 1 is a natural deposit, where no treatment with plant protection agents has ever been carried out (control). Options 2 and 3 were selected from the plots of the experiment “Develop effective combinations of biological and anthropogenic means of increasing the productivity of arable land.”

The soil of options 4 and 5 represents the grain shortened crop rotation of the experiment in contour-reclamation agriculture (northern exposure of the control catchment). In this case, option 4 – non-eroded soil, 5 – bottom of the slope (slightly eroded soil). Soil samples 6-9 from an experimental plot for the study of biological products for grain crop rotation. In options 7 and 9, according to predecessors in 2022, seeds and soil were treated with biological preparations before sowing, as well as crops and crushed by-products, followed by their incorporation into the soil. Samples of 10-12 options from an experimental site with a dome-shaped relief. The soil was taken from non-eroded chernozem (option 10), eroded (11) and alluvial alluvial soil (12). Crop rotation is grain crop rotation.

100 white mustard seeds, 50 oil radish seeds (dicot test plants) and 15 grains of spring barley and oats (cereal test) were sown in soil samples prepared for analysis according to the sampling method to determine the amount of pesticides. -plants).

3 Results and discussion

Seed shoots of test plants appeared evenly, without sharp differences between variants and within each replicate. On the 5th, 14th and 21st days of the experiment, phytotoxicity was determined by the intensity of growth of the roots of the test plants and by the change in the length of the seedlings. It was classified into four groups: 1) <20% - no phytotoxicity, 2) 20-40% - weak, 3) 40-60% - medium, 4) > 60% - strong.

Analysis of options for the development of the root system showed that the examined soil samples have a weak and medium degree of toxicity. Phytotoxicity did not appear in variants 4 and 5 of the experiment. In option 5, on the fifth day of research, it reached 22%, and then began to decrease. On the 14th day, these options have minimal phytotoxicity - 12 and 14%, respectively. In general, according to the degree of negative impact on dicotyledonous test plants, the variants of the studied samples can be ranked in ascending order: 4, 5, 9, 8, 6, 3, 10, 12, 2. Accordingly, for cereal test plants: 4, 10, 5, 11, 12, 7, 9, 6, 3, 2.

Thus, according to the intensity of root growth, phytotoxicity increased from 5 to 14 days. Its decrease was noted on day 21 within each experimental variant. It was also found that among the test plants, white mustard and spring oats react more responsively to the aftereffect. In them, phytotoxicity was 1.1 times stronger than in oilseed radish and spring barley, respectively.

Differences in the degree of toxicity on the development of roots of test plants and their seedlings appear not only between variants taken from different experimental sites, but also on variants within the same experiment. This is strongly expressed in options 10, 11 and 12, selected from three experimental points with varying degrees of soil erosion. Thus, an increase in toxicity occurred from option 10 from non-eroded soil to eroded option 11 and reached its maximum on reclaimed soils of option 12.

Analysis of the aftereffect of herbicides on the development of the test plant as a whole showed that it had a significant effect on the growth of root hairs, which ensure the growth and development of plants as a whole. The best results were shown by options 4, 5 and 11, which ensured the development of a more branched and powerful root system among dicotyledons and options 4, 5 and 10 among cereal test plants.

The maximum values of the assessed traits corresponded to the control and were obtained on soil without the use of herbicides, and the minimum values were obtained on soil experiencing the aftereffect of herbicides (Table 2).

Table 2. Dimensionless desirability scale.

Base marks	**Estimation of properties of the desirability function**
1,00	Best value
0,80-1,00	Most acceptable
0,63-0,80	Quite acceptable, good
0,37-0,63	Acceptable, satisfactory
0,20-0,37	Unacceptable, bad
0-0,20	Completely unacceptable

Laboratory experiments have established that the responsiveness of bioindicators to the aftereffects of herbicides can be assessed by three signs of phytotoxicity:

- decreased seed germination,
- reducing the intensity of root growth,
- changing the length of the seedlings.

Thus, the responsiveness of test plants to the aftereffect of herbicides is a multi-criteria problem, the solution of which can be achieved using the Harrington desirability function [14-16].

The desirability function allows several characteristics (i=1, 2, ..., n) to be converted into a dimensionless scale that generalizes particular desirabilities. A scale was constructed using the method of quantitative assessments in the range of function values from 0 to 1, where the unacceptable value of the optimization parameter corresponds to zero, and the best value corresponds to one. Basic intermediate scale marks within the designated interval are given in Table 3.

Table 3. Signs of phytotoxicity of test plants.

Culture	**Seed germination, %**		**Number of days after sowing**	**Intensity of root growth, %**		**Change in seedling length, %**	
	min	**max**		**min**	**max**	**min**	**max**
White mustard	83	90	5	18	42	26	46
			21	12	46	16	58
Oilseed radish	85	92	5	16	41	20	42
			21	9	45	13	47
Spring oats	81	90	5	16	39	23	37
			21	10	51	13	60
Spring barley	80	90	5	14	30	12	34
			21	10	50	6	43

The problem under consideration assumes a scale with one-sided restriction, when the signs of phytotoxicity y_i are converted into a desirability function d_i using an exponential dependence:

$$d_i = \exp[-\exp(-y_i')]\,; \qquad (1)$$

where

$$y_i' = b_0 + b_1 y_i. \qquad (2)$$

Coefficients b_0 and b_1 of equation (2) determined on the basis of experimental data for values y_i, corresponding to the value of the desirability function d_i within the preferred interval $(a_i;\ c_i)$ within the dimensionless scale range (0; 1):

$$a_i \le d_i \le c_i.$$

Unfavorable value for the processes under study $d_i \ge 0{,}2$ in the field of the desirability scale smoothly turns into favorable when $d_i \le 0{,}8$:

$$0{,}2 \le d_i \le 0{,}8.$$

Signs of phytotoxicity y_i were converted to a desirability function d_i in the following way. From the preferred interval $(a_i;\ c_i)$ the largest c_{imax} and the smallest a_{imin} was substituted to (1) and the system of two equations was got:

$$\begin{aligned} a_{imin} &= \exp[-\exp(-y_i')]\,; \\ c_{imax} &= \exp[-\exp(-y_i')]. \end{aligned} \qquad (3)$$

Having taken the logarithm of system (3) twice, we determined two valuesy_i', which, together with the corresponding values of y_i, were successively substituted into equation (2). By solving a new system of equations, the coefficients b_0 and b_1 were determined and the partial desirability function di was calculated using equation (1) (Table 4).

Table 4. Indicators of desirability of phytotoxicity traits of test plants.

Culture	**Particular desirability of seed germination**			**Number of days after sowing growth**	**Particular desirability of the intensity of root**			**Particular desirability of changing the length of seedlings**			**Generalized desirability**	
	max	**min**	**Average**		**max**	**min**	**average**	**max**	**min**	**average**	**seed germination + root growth + change in seedling length**	**growth of roots+ change in seedling length**
White mustard	0.27	0.21	0.24	5	0.75	0.6	0.675	0.7	0.57	0.635	0.47	0.65
				21	0.77	0.57	0.67	0.76	0.48	0.62	0.47	0.64
Oilseed radish	0.25	0.2	0.225	5	0.76	0.61	0.685	0.74	0.6	0.67	0.47	0.68
				21	0.79	0.58	0.685	0.77	0.56	0.665	0.47	0.67
Spring oats	0.29	0.21	0.25	5	0.76	0.62	0.69	0.72	0.63	0.675	0.49	0.68
				21	0.78	0.53	0.655	0.77	0.46	0.615	0.47	0.63
Spring barley	0.29	0.21	0.25	5	0.76	0.68	0.72	0.77	0.65	0.71	0.51	0.71
				21	0.78	0.54	0.66	0.8	0.59	0.695	0.49	0.68
Average			0.24				0.68			0.66	0,48	0,67
Average for the 5th day							0.69			0.67	0.49	0.68
Average for the 21st day							0.67			0.65	0.47	0.66

After converting the phytotoxicity signs yi into partial desirability di, they were combined into a generalized desirability D, representing the geometric mean of the partial values:

$$D = \sqrt[m]{\prod_{i=1}^{m} d_i}\,. \qquad (4)$$

The mathematical model (1)-(5) allows one to determine specific and generalized desirabilities for specific signs of plant phytotoxicity, falling within the range from minimum to maximum values.

To analyze the data obtained, the average values of Table 3 was presented in a graphical version (Figure 1).

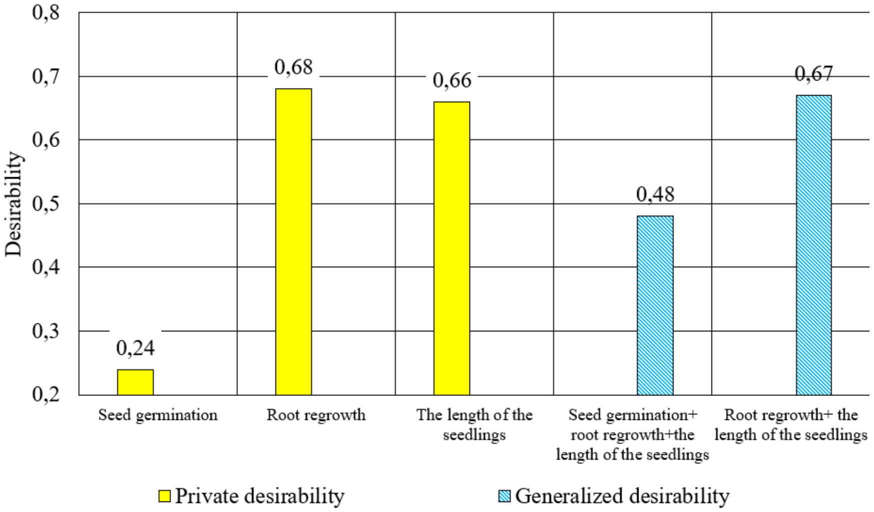

Fig. 1. Indicators of desirability of phytotoxicity traits of test plants.

The germination of seeds of the test plants under consideration according to the value of private desirability cannot be accepted as a criterion for assessing sensitivity to phytotoxicity, since d_i = 0.24 corresponds to the base mark of the desirability scale “unacceptable, poor”. Therefore, of scientific interest are the particular desirabilities of the intensity of growth of plant roots and changes in the length of seedlings, as well as the generalized desirabilities of the studied traits, where $d_i \geq 0.48$.

The most pronounced sensitivity to phytotoxicity of test plants in terms of the intensity of root growth d_i = 0.68 - “quite acceptable, good” on the desirability scale. The sensitivity of test plants based on changes in the length of seedlings is not much, but lower, d_i = 0.66. Based on the intensity of root growth in test plants of dicotyledonous crops, sensitivity to phytotoxicity is more evident in oilseed radish - the same d_i = 0.69 when observed both on the 5th and 21st days after sowing. The particular desirability of changing the length of seedlings is somewhat lower, d_i =0.67.

The generalized average desirability of plant sensitivity to the phytotoxicity of the aftereffect of herbicides according to the three characteristics studied (seed germination + root growth + change in the length of seedlings) with a value of d_i = 0.48 falls within the range of the scale marked “acceptable, satisfactory.” But this is significantly lower than the private desirability in terms of the intensity of growth of roots and changes in the length of seedlings, where d_i = 0.66-0.68.

When excluding seed germination in the generalized desirability, it takes the value d_i =0.67 and approaches the particular desirability of the traits under study, d_i =0.66-0.68, but at the same time the complexity of obtaining generalized desirability data increases. Therefore, in order to save labor costs, it is most appropriate to assess the sensitivity of test plants to the phytotoxicity of the aftereffects of herbicides based on the particular desirability of changing the length of seedlings when observed on the 5th day after sowing.

4 Conclusion

The most responsive test plant species to the aftereffects of herbicides were determined and the current signs of their phytotoxicity were substantiated. For test plants of cereal crops, spring barley has an advantage in the intensity of root growth when observed on the 5th day after sowing, $d_i = 0.72$. The sensitivity of the culture in terms of the level of partial desirability of seedling length is approximately the same when observed both on the 5th and 21st days after sowing, $d_i = 0.70$-0.71. The best indicators of responsiveness to the aftereffect of herbicides among dicotyledonous crops were obtained for oilseed radish $d_i = 0.69$.

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