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AGRICULTURAL CHEMISTRY AND SOIL FERTILITY

Relationship of Land Use History and Chemical Properties of Soils with Their Allelotoxicity

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Abstract—The influence of land use history and chemical properties of soils on their allelotoxicity has been studied. Twelve soil samples collected on the Russian Plain and seeds of six cultivars of spring wheat, as well as seeds of barley, rye, and triticale have been used in the study. It was found that different grain crops are inhibited in the same manner by toxic substances in soils. The allelotoxicity of soils differed in dependence on the previous land use and was much higher in the soils from agricultural fields, irrespectively of grown crops, than in the soils of long-term fallow and forests. These data allow us to suppose that crop rotation systems are not always sufficient to reduce soil toxicosis. In this context, the assessment of real soil fatigue (soil allelotoxicity) in the course of crop rotation is necessary. Statistical processing of available data attested to the influence of chemical properties of soils on the inhibition of seed germination and the development of seedlings.

Keywords: allelopathy, soil allelotoxicity, deceleration of the development of seedlings, land use history, crop rotation, soil chemical properties

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INTRODUCTION

Agrophysical state of soil, its agrochemical and physicochemical properties are taken into account, when solving the problem of soil fertility improving. Consequently, practically all developed models of improvement the productivity of agrophytocenoses are based on optimization of these parameters [9]. However, soil should not be considered only as a substrate for moisture, air, and nutrients necessary for plants. Soil environment is one of most active components of biosphere; it is full of life, has high biochemical activity; and the living part of soil environment mostly determines soil fertility [10].

It should be taken into account that productivity of agroecosystems largely depends on the formation of biologically active substances, their accumulation in soil, and their effect on plants [9]. In particular, this concerns the synthesis and accumulation of allelotoxins in soils leading to soil toxicosis [1–3, 5, 18, 22, 24].

There was no profound interest to the phenomenon of soil toxicosis up to the 1950s. It is likely that this was connected to some extent with the success of chemicalization, against the background of which this problem seemed to be insignificant. It was supposed that with further advance in the application of chemicals, soil amelioration, and intense soil treatment, the role of crop rotation would be diminished and the problem of soil toxicosis would cease to exist [10]. This was one of the reasons why the problem of soil allelotoxicity was rather neglected despite wide distribution of this phenomenon [5] and the fact that it is an important additional factor of affecting soil fertility[1] [9].

The difficulty of studying soil allelotoxicity by the methods of chemical analysis was another reason. The method of soil extracts allowed determining the presence of allelotoxins in the soil, but their individual concentrations corresponded to the areas of stimulation rather than suppression[2].

Thus, the procedures of biotesting became the main method for studying soil allelotoxicity. The effects of soil extracts on seed germination and initial stage of development of seedlings are studied in most cases at the semiquantitative level. However, results concerning soil allelotoxicity obtained in such way agreed well with the fertility of these soils (correlation coefficient exceeded 0.9) and crop yields on them [6, 9].

The development of improved method allowed obtaining the quantitative information on soil allelo-

[1] According to FAO, crop loss from allelotoxicity (toxicosis) of soils in the world in some years reaches up to 25% of the potential yield, and this phenomenon is potentially one of greatest threats to world agriculture [10].

[2] This is attributed to the fact that allelotoxins act in the form of multicomponent mixture, the effect of which is not simply the sum of effects of its particular components.

toxicity [16]; therefore, it was of interest to study the effects of land use history and chemical properties of soil on soil allelotoxicity.

OBJECTS AND METHODS

The study was carried out with the seeds of spring wheat (*Triticum*) of Liza, Zlata, Ester, Agata, Lyubava, and RIMA cultivars, winter triticale (*Triticosecale*) of Nemchinovskii 56 cultivar, spring barley (*Hordeum*) of Nur cultivar, and winter rye (*Secale cereale*) of Tatiana cultivar.

Samples of the following soils were used in the work: cultivated soddy-podzolic deeply podzolized deeply plowed light loamy soil on mantle loams underlain by glaciofluvial deposits after vetch and oats mix (1), after mustard (2), after potato (3), and after barley (4); soddy surface- podzolized deeply plowed light loamy soil on mantle loams underlain by moraine, fallow land from 2015 (5); soddy surface-podzolized deeply plowed light loamy soil on mantle loams underlain by moraine, fallow, illuvial horizon (6); soddy-podzolic deeply plowed strongly eroded soil on mantle loams underlain by glaciofluvial deposits after potatoes from 2015 (7); deeply podzolic weakly differentiated light loamy on mantle loams underlain by glaciofluvial deposits old-arable soil under forest, litter (8); agricultural soddy deeply podzolic sandy loamy soil on glaciofluvial (ancient lacustrine) deposits underlain from the depth of 92 cm by noncalcareous loesslike loams after wheat (9); typical medium-deep loamy chernozem on loesslike loams after potato (10); gray forest cultivated weakly eroded loamy soil on loess-like loams underlain by moraine after potato (11); and chestnut medium-deep light loamy on eluvial and colluvial loams, fallow (12). It was supposed that such a diversity of objects would make it possible to better understand the causes of soil allelotoxicity development.

Washed river sand with particles 0.5–0.8 mm was also used in the work, because the point of reference, i.e. the substrate, which did not contain toxins, was required for evaluating the soil allelotoxicity.

The influence of soil on the length of seedlings was studied[3] in 7.5 g of seeds (~200 seeds) germinated in different soils in comparison with sand. The length of seedlings was determined using the express method based on linear relationship between the bulk volume of germinated seeds and the length of their seedlings [16]. Germinated in soil or sand seeds were washed and placed by portions into the 100-mL measuring flask filled with water and located on vibrating table[4] with vibration frequency 50 Hz. After placing each portion of germinated seeds, which formed an openwork porous structure, into the cylinder, small load of 8 g weight in the form of rubber cork was placed above and caused the compaction of the structure. After the placement of all germinated seeds into the cylinder, the load was placed above, and additional compaction of the structure was made by tapping (30–40) of the cylinder with seeds on the table. These operations allowed forming the relatively homogeneous structure, and the lower boundary of the load allowed determining the bulk volume with the accuracy to 0.5 mL.

When carrying out the experiments, 30 g of soil or sand were placed on the bottom of 95-mm dish, then 7.5 g of seeds were placed in an even layer, and 30 g of soil or sand were placed above. After this, water was added evenly from the measuring pipette. The experiment was carried out in sixfold with subsequent statistical treatment of the results. In order to minimize the error connected with different quality of seeds 1000–1200 seeds were used in one experiment [14]. Hence, the error of experiment did not exceed 7% at 95% confidence probability. Most experiments were carried out at 23–26°C.

It is well known, that soil moisture is a significant factor affecting the rate of seed germination. It is evident that seed germination and development of seedlings would decelerate under insufficient moisture due to deficiency of water and due to oxygen deficiency under excessive moisture. So, the comparison of substrates with different affinity for moisture (sand and soils) should be correct only in the points, providing optimal water-air conditions and maximal rate of seed development. Optimal initial quantity of water for substrates was determined by maximal emission of carbon dioxide during seed germination depending on water content in the substrate [17].

Following chemical properties of soil were determined: pH_{KCl}, contents of exchangeable potassium, mobile phosphorus, exchangeable calcium, and total contents of carbon, nitrogen, and sulfur. Measuring of pH and determination of the contents of potassium (K_2O), phosphorus (P_2O_5), and mobile calcium in the soil were carried out according to commonly adopted methods [12, 15], using photoelectric colorimeter KFK-3 and flame photometer PFM. Soil concentrations of N, S, and C were determined in CHNS-analyzer Vario EL III, Elementar, Germany.

Correlation and regression analyses were used in order to determine the relationship between the inhibition of seeds of spring wheats and chemical properties of soils.

RESULTS AND DISCUSSION

Chemical analysis carried out before the study of soil allelotoxicity demonstrated (Table 1) that the availability of nutrients in soils was sufficient for testing, and chemical properties of soil cannot limit seed development.

[3] According to plant physiologists [11], plants use the stored substances up to the moment of germination.

[4] Small vibrating table was made of electrical starter by way of restriction the possibility of magnetic coil to fix the core in the downwardmost position, and this resulted in the core vibration.

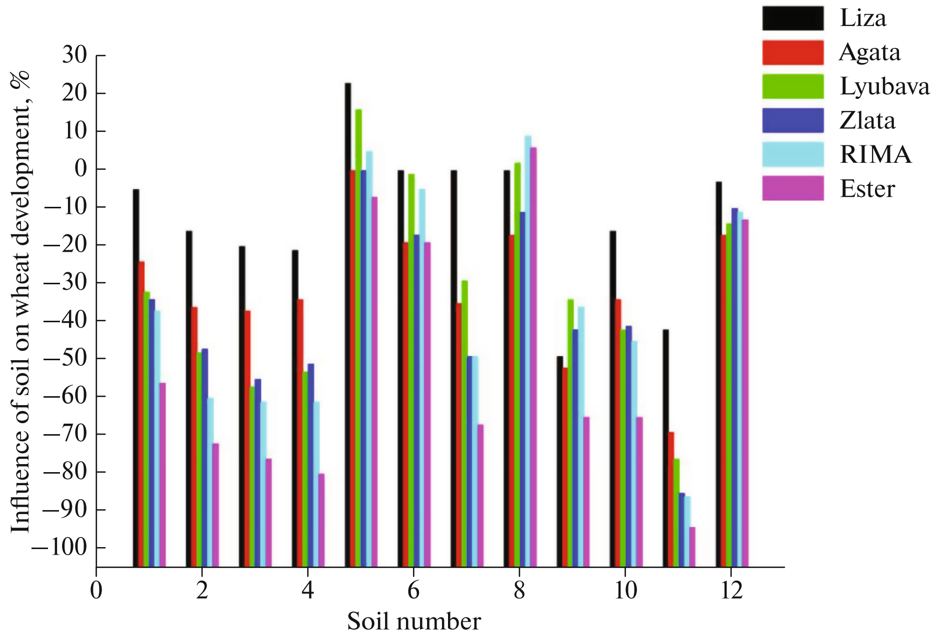

Fig. 1. Soil influence on seed germination and development of seedlings of different wheat cultivars. Soil numbers are given in Table 1.

The results of the study of soil influence on germination of wheat seeds and development of seedlings are presented in Table 2. The curves of inhibition of different wheat cultivars by soils under the study were built on the basis of these data (Fig. 1). It is well seen that cultivars differed in their response to allelotoxins. Some of them demonstrated higher resistance to the complex of allelotoxins in all soils (Liza cultivar), while other cultivars are more intensely inhibited by allelotoxins in all soils (Ester). Other wheat cultivars were found to respond in between.

The absence of randomness in the response of cultivars to the complexes of allelotoxins in different soils calls attention. There were practically no cases, when one cultivar was more resistant to allelotoxins on one soil, but was inhibited more intensely than other cultivars on the other soil.

It was seen that the order of inhibition of cultivars by allelotoxins was approximately the same for each soil, though the ratio between the inhibition values for different cultivars could differ. The uniformity of inhibition of different wheat cultivars was apparent, and this was confirmed by close correlation between them. Correlation coefficients were close to one (Table 3). This fact allows using in the following research not all cultivars, but only the most typical ones.

For example, Ester correlated with Zlata, RIMA, and Lyubava with correlation coefficient 0.940–0.977. The correlation was smaller with Liza and Agata cultivars. So, it would be sufficient to use cultivars Ester, Liza, and Agata for studying the influence of soil allelotoxicity on seed germination and development of seedlings.

The data obtained for barley, triticale, rye, and wheat on zonal soils (Fig. 2), suggested that the regularity of effects of allelotoxins complexes observed for spring wheat were typical for these grain crops either. Such results allow assuming the existence of the same nature of response of the studied grain crops to the complexes of allelotoxins.

It follows from the observed regularity that the crop (cultivar) more resistant to allelotoxins of one soil will

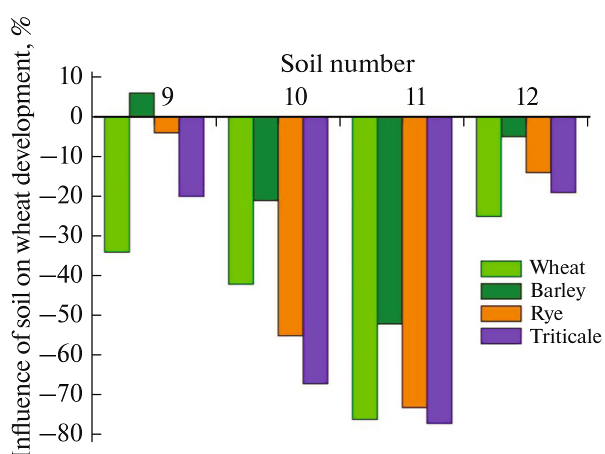

Fig. 2. Influence of soil on seed germination and development of seedlings of wheat cultivar Lyubava, barley cultivar Nur, rye cultivar Tatiana, and triticale cultivar Nemchinovskii 56.

Table 1. Chemical properties of studied soils

Soil no.	Soil name (according to classification of soils of the USSR 1977)	History of use	pH_{KCl}	Ca_{exch}	$P_2O_{5mobile}$	K_2O_{exch}	N_{tot}	S_{tot}	C_{tot}
				mg/100 g			%		
1	Soddy-podzolic deeply podzolized deeply plowed light loamy on mantle loams underlain by glaciofluvial deposits	Vetch and oat mix	6.2	208	31.5	36.9	0.29	0.09	3.33
2	″	Mustard	6.3	216	32.5	25.9	0.35	0.10	3.91
3	″	Potato	5.9	167	31.5	29.8	0.23	0.07	2.57
4	″	Barley	6.1	117	31.0	22.0	0.20	0.06	2.23
5	Soddy surface-podzolized deeply plowed light loamy soil on mantle loams underlain by moraine, humus horizon	Fallow from 2015	5.5	83	14.5	6.48	0.17	0.05	1.82
6	Illuvial horizon of soil 5	Fallow from 2015	5.1	67	3.0	3.25	0.04	0.02	0.26
7	Soddy-podzolic deeply plowed strongly eroded soil on mantle loams underlain by glaciofluvial deposits	After potato from 2015	5.1	67	17.5	7.15	0.17	0.04	1.71
8	Deeply podzolic weakly differentiated light loamy on mantle loams underlain by glaciofluvial deposits (forest litter)	Old arable soil under the forest	3.6	117	6.0	11.0	1.18	0.39	35.1
9	Agrosoddy deeply podzolic sandy loamy soil on glaciofluvial (ancient lacustrine) deposits underlain from the depth of 92 cm by noncalcareous loesslike loams	Wheat	6.6	133	29.0	19.4	0.14	0.05	1.65
10	Typical medium medium-loamy chernozem on loesslike loams	Potato	5.3	316	4.0	–	0.24	0.08	3.58
11	Gray forest cultivated weakly eroded loamy soil on loesslike loams underlain by moraine	Wheat	5.0	100	18.5	15.5	0.12	0.05	1.07
12	Chestnut medium-deep light loamy soil on eluvial and colluvial loams	Fallow	6.2	150	5.5	11	0.09	0.05	0.80

Table 2. Influence of biologically active soil substances on seeds of spring wheat as judged from changes in the total length of seedlings appearing in two days in the soil in comparison with the sand, %

Soil no.	Cultivar					
	Liza	Agata	Lyubava	Zlata	RIMA	Ester
1	−5 ± 5	−24 ± 5	−32 ± 5	−34 ± 5	−37 ± 5	−56 ± 6
2	−16 ± 5	−36 ± 6	−48 ± 6	−47 ± 6	−60 ± 6	−72 ± 7
3	−20 ± 6	−37 ± 5	−57 ± 7	−55 ± 7	−61 ± 6	−76 ± 7
4	−21 ± 5	−34 ± 5	−53 ± 7	−51 ± 6	−61 ± 7	−80 ± 6
5	23 ± 6	0 ± 6	16 ± 5	0 ± 5	5 ± 5	−7 ± 5
6	0 ± 5	−19 ± 5	−1 ± 5	−17 ± 5	−5 ± 5	−19 ± 5
7	0 ± 5	−35 ± 6	−29 ± 6	−49 ± 6	−49 ± 6	−67 ± 6
8	0 ± 5	−17 ± 6	2 ± 5	−11 ± 5	9 ± 5	6 ± 5
9	−49 ± 7	−52 ± 7	−34 ± 6	−42 ± 6	−36 ± 5	−65 ± 6
10	−16 ± 6	−34 ± 6	−42 ± 6	−41 ± 7	−45 ± 6	−65 ± 7
11	−42 ± 6	−69 ± 6	−76 ± 7	−85 ± 7	−86 ± 7	−94 ± 7
12	−3 ± 5	−17 ± 5	−14 ± 5	−10 ± 5	−11 ± 5	−13 ± 5

Table 3. Coefficients of correlation between different cultivars of spring wheat

Cultivar	Liza	Agata	Lyubava	Zlata	RIMA	Ester
Liza	1	0.918	0.778	0.759	0.690	0.718
Agata	0.918	1	0.866	0.921	0.837	0.832
Lyubava	0.778	0.866	1	0.954	0.974	0.940
Zlata	0.759	0.921	0.954	1	0.967	0.944
RIMA	0.690	0.837	0.974	0.967	1	0.977
Ester	0.718	0.832	0.940	0.944	0.977	1

be more resistant to allelotoxins of another soil. Hence, when selecting the crops and cultivars for sowing on particular soils in the cases of existence the order in their positions in the row of resistance to allelotoxins, it will be worthwhile estimating the significance of difference in their response to the complex of allelotoxins specific for studied soil. This significantly simplifies the choice of cultivars (crops) in the presence of the data on the order of their positions in the sequence of resistance obtained on any soil.

It is well seen from the presented data that minimal value of inhibiting among the fields, where the four-course rotation was used, was observed in the field 1, where vetch and oat mix were used as a preceding crop. However, wheat was planned to be sown according to the crop rotation after potato on field 3, where the value of inhibiting was much higher for all six cultivars. These data suggest that crop rotation without control of allelotoxicity of fields cannot give positive result in yield increase. Only combination of crop rotations with control of field allelotoxicity will allow selecting crop rotations most suitable for particular conditions.

Conspicuous is the fact that soil allelotoxicity was much higher in the territories of agricultural use irrespectively of crops grown there. This was typical for all studied wheat cultivars and for triticale, rye, and barley. Minimal values of allelotoxicity were observed for fallow plots (soil samples 5 and 12) and for litter under forest (soil sample 8). Stimulation, but not inhibiting, by soils of seed germination and seedling development was observed on such soils for the crops most resistant to allelotoxins.

Obtained data confirm the opinion that allelotoxicity phenomenon is not typical for natural climax plant communities. The relationships between plants and soil environment were formed in natural phytocenoses in the processes of evolution. As a result, they are well functioning, adjusted, and relatively stable. The energy and substance formed owing to photosynthesis are redistributed sequentially and consumed by components of phytocenosis [10]. Soil is a component of biosphere full of life and has specific matter exchange, in which plants play an important part [13]. This exchange is disturbed in the case of one-way influence on soil. Hence, general cause of soil toxicosis shows up as the disturbance of the processes of substance and energy exchange in the soil–plant system [10]. Adverse influence on soils of any agricultural use was connected with these disturbances of substance and energy exchange because the productivity of agrocenoses is several times higher than that of natural phytocenoses (Table 4). This shifts the balance in an ecosystem, and the production of allelotoxins is a defensive reaction of ecosystems, which begin to limit productivity of agrocenoses, decreasing soil quality [9].

Table 4. Production of plant biomass in the steppe and arable fields of the Central Chernozemic Reserve [9]

Field and crop	Production	Yield		Yield of elements, kg/ha	
		c/ha	crude protein, c/ha	nitrogen	phosphorus
Mown steppe	Dry matter	23.7	2.0	31	7
Unmown steppe	Dry matter	29.7	2.6	42	9
Winter wheat	Total yield	109.1	9.0	143	54
Sugar beat	Total yield	619.0	10.0	167	44
Corn	Herbage	341.0	5.1	81	33

Table 5. Correlation coefficients between inhibition of spring wheat of different cultivars and the chemical properties of soils

Cultivar	pH_{KCl}	Ca	P_2O_5	K_2O	N	S	C
Liza	–0.323	–0.190	–0.430	–0.395	0.184	0.164	0.193
Agata	–0.164	–0.096	–0.394	–0.306	0.226	0.223	0.244
Lyubava	–0.326	–0.335	**–0.564**	**–0.592**	0.264	0.286	0.339
Zlata	–0.166	–0.130	**–0.514**	–0.425	0.261	0.288	0.315
RIMA	–0.342	–0.249	**–0.599**	**–0.525**	0.354	0.391	0.437
Ester	–0.423	–0.271	**–0.651**	**–0.555**	0.409	0.449	0.493

The level of significance of correlation coefficient was calculated using tabulated Pearson's critical values. For line $K = n - 2 = 10$, it should be 0.58 at $p = 0.5$ and 0.71 at $p = 0.01$. In our case, almost all correlation coefficients were no higher than 0.58. Consequently, the significance of difference could not not determined, except for the relationship between the Ester and RIMA cultivars and P_2O_5 and the Lyubava cultivar and K_2O. Here, the empirical value was intermediate between columns $p = 0.05$ and $p = 0.01$ in Pearson's table, so $0.05 \geq p \geq 0.01$. Hence, these values are significant at $p < 0.05$ (the level of statistical significance).

There are several mechanisms of counteraction of ecosystems. First, the composition of soil microorganisms changes in the case of monoculture with an increase in the fraction of phytopathogens. Second, growing of virtually any crop with the high density enhances plant competition for the resources; in particular, plant produce and release allelotoxins into the soil, which was noted in many studies on allelopathy [3, 9]. Similar phenomena in natural ecosystems are observed in the case of fluctuation changes (well studied in meadow phytocenoses), when the domination of one species is replaced by domination of another species in the next year [4]. It is likely that, along with climatic factors, this is related to the accumulation of allelotoxins in the soils.

The study of allelotoxicity of different soil horizons (Table 2, samples 5 and 6) confirmed the formerly known data that soil allelotoxicity increased with the depth [3, 8, 10]. This is attributed to migration of allelotoxins into lower horizons with soil water [3] and to the fact that population density of microorganisms, which use allelotoxins as a source of carbon [3, 18–21, 23, 25] and, hence, decrease their content, go down with depth. The decrease of concentration of microorganisms results in accumulation of allelotoxins brought from the upper soil layers. It is noted that population density of phytotoxic forms of bacteria and fungi increased down soil profile [7].

Mathematical treatment of data on inhibition and chemical properties of soil demonstrated that linear relationship between these parameters was relatively weak for different cultivars of spring wheat (Table 5). Correlation coefficients exceeding in absolute magnitude 0.5, were obtained only for phosphorus and potassium compounds and some wheat cultivars.

The curve of linear regression of inhibiting for spring wheat cultivar Ester had the relationship with determination coefficient $R^2 > 0.5$. It is conventional that the higher is determination coefficient the better is model (it is good >0.8). In our case the relationship had $R^2 = 0.42$ for P_2O_5 and $R^2 = 0.31$ for K_2O. Correlation coefficients were $r = –0.651$ and $–0.555$ respectively.

The assumption was put forward that combination of factors could affect inhibition of spring wheat. So, multiple regression analysis was carried out. Good correlation was obtained with such chemical properties as pH and concentrations of mobile calcium, phosphorus, and potassium. Multiple correlation coefficient equaled 0.901, $R^2 = 0.811$.

The values of coefficient of multiple determination $R^2 = 0.811$ demonstrated that 81.1% of total variation of effective feature was explained by variations of factorial features X_1, X_2, X_3, X_4, and 18.9% were attributed to the other unaccounted factors. Consequently, selected factors had significant influence on inhibition, and this confirmed the truthfulness of their including into developed model. The calculated confidence level (0.0112 < 0.05) confirmed the significance of R^2.

Hence, statistical treatment of data suggested the influence of chemical soil properties on inhibition. However, we cannot say anything about the nature of this effect at this stage of research. Chemical properties of soils can affect accumulation of allelotoxins in soil. However, their influence on the availability of allelotoxins to plants, the strength of bonding between allelotoxins and soil, cannot be ruled out.

CONCLUSIONS

(1) The changes in inhibition of different cultivars of spring wheat and other cereal crops by the studied soils have similar patterns. This is confirmed by close correlation between cultivars of spring wheat. Correlation coefficients are close to 1.0. Wheat cultivars Zlata, RIMA, Lyubava, and Ester are most subjected to inhibition and strongly correlate with one another. The Liza cultivar is most resistant to allelotoxins, and the Agata cultivar occupied an intermediate position.

(2) Allelotoxic effect of cultivated soils on seed germination and development of seedlings of spring wheat is much stronger in comparison with that of the soils that were not used for crop growing.

(3) The obtained data suggest that crop rotation is not always an efficient measure to decrease soil toxicosis. In this context, special assessments of soil allelotoxicity should be performed for different crop rotation systems.

(4) Statistical treatment of data attests to the influence of a combination of soil chemical properties on the inhibition of seed germination and development of seedlings. However, we cannot say anything about the nature of this effect at this stage of research.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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