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Bioecological Assessment of Arable Soil Pollution: A Case Study of Belgorod Region

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ABSTRACT

The Belgorod Region is one of the agricultural production leaders in the European part of Russia. The area is located in the forest-steppe and steppe zones, which differ in a significant level of arable soils pollution due to the long-lasting and intense agriculture. The work was aimed at a private (score by Cu, Cd, Pb, Zn and Cs) and integrated assessment of arable soil in view of 21 administrative units and individual agricultural commodity producers, identification of areas with high risk of contamination of agricultural products, which would allow us to recommend an adapted set of cultivated crops in crop rotations. A list of six agricultural crops was identified as a priority for agro-environmental monitoring of crop production quality. The elements of priority soil-ecological monitoring have been identified for steppe arable soils (Cu, Cd, Cs, Pb, Zn). The features of heavy metals translocation from soil to plants in specific soil and climatic conditions made it possible to recommend agronomic and technological methods aimed at obtaining environmentally friendly crop products.

KEY WORDS: HEAVY METALS, TRACE ELEMENTS, AGRICULTURAL SOIL, SOIL-PLANT SYSTEM, TRANSLOCATION

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INTRODUCTION

In order to search for agricultural solutions should remain technology-neutral it is necessary multiple paths to improving the production, food security and environmental performance of agriculture (Foley et al., 2011). A prolonged use of fertilizers has resulted in a change in the mineral composition of soils and plants by increasing the proportion of heavy metals (Protasova and Kopayeva, 1985). A number of studies have focused on the heavy metal content of arable soil (Fan et al., 2013; Briki et al., 2015; Wang et al., 2015; Baran et al., 2018; Volungevičius, et al., 2019). However, it should be borne in mind that even some of heavy metals are essential for humans and for them to apply term "trace elements" equal to "micronutrients" (Duffus, 2002).

The Russian Federation plans to lay down 80.5 mln. hectares with cultivated plants and get a grain yield of 110 mln. t. in 2019. Central Federal District (CFD) is an administrative unit that includes 18 regions of Russia with a total area of 650205 km² (3.8% of the country). This territory contains a significant part of the country's agricultural zone. The Belgorod Region (about 2 mln. ha agricultural land) is a part of CFD and it occupies 7% of the area under cultivation but provides 21% of agricultural production (2nd place on this indicator in CFD). There are 14 pig-growing companies, 9 poultry companies and 128 cattle breeding farms in the region.A tense environmental situation in the Belgorod Region is due to a range of problems related with the use of natural resources. A basic list of environmental resource issues includes the following: excess air emissions (Poletaev and Kornilov, 2017; Lisetskii and Borovlev, 2019), river degradation (Solov'eva et al., 2015; Grigoreva and Buryak, 2016; Marinina, 2018), reduction of forest areas (Chendev et al., 2016; Ukrainskij et al., 2016, 2017), dehumification of soil's plough layer (Lisetskii, 2012), soil erosion (Shtompel' et al., 1998), changes in soil biogeochemistry due to biological removal (Zelenskaya et al., 2018), deterioration of soil structure and erosion resistance (Lisetskii, 2008), increase in land areas disturbed by open pit mining (Lisetskii, 2018) and disproportion in land ratio (Lisetskii, 1998; Marinina, 2017; Martsinevskaya et al., 2018).

In addition, the Belgorod Region was exposed to radioactive contamination because of the accident at Chernobyl Nuclear Power Plant (1986). The eastern areas were most affected, where about 140 thous. ha of arable land was contaminated with Cs^{137} in the range from 1-5 Ku km^{-2}. Particularly significant changes have occurred with the fertility of arable soils and the development of erosion (60% of the territory). On wild land, the arrival of organic matter was 12 t ha^{-1}, and in agrocenoses (cereal crops), it decreased to 4 t ha^{-1} (Lisetskii, 1992). The monitoring soil organic matter (SOM) of soil organic matter in the arable layer under increasing anthropogenic stresses shows that this process is cyclical with SOM being decreased in general (Lisetskii, 2007). The soil cover on the slopes, which was relatively homogeneous before ploughing, has become to be deeply contrasting. Slope agricultural landscapes are distinguished by the fact that the masses of chemical elements, which are carried away from autonomous landscapes, are included in biogeochemical processes in subordinate ecogeosystems (Dobrovolskiy, 2003; Kalinitchenko, 2016).

Soil, the living terrestrial skin of the Earth, plays a central role in supporting life (Tecon and Or, 2017). The physico-chemical properties of various types of soils largely determine the composition and quantity of microorganisms, which forms a certain biological balance which can change under the influence of anthropogenic effects (Polyanskaya et al., 2016; Borisov and Shishlina, 2017; Lisetskii and Vladimirov, 2019). Composition and activity of microorganisms have a positive effect on the bioavailability of the metal polluted soil, in particular Cd and Ni (Ahmed et al., 2017).

MATERIALS AND METHODS

Study area: The automorphic soils of the Belgorod Region are characterized in a number of integrating monographs (Solovichenko, 2005; Solovichenko et al., 2007). Chernozem is the most common soil in the Belgorod Region. They predominate on the plateau and cover significant areas of riverine and ravine slopes. The total area of Chernozem is 2090.8 thous. ha or 77.1% of the entire territory of the region (27100 km²), of which 327.6 thous. ha is located on the slopes. Among Chernozems subtypes typical (979.1 thous. ha) and leached (631 thous. ha) ones prevail, the third place in terms of area is occupied by ordinary ones (318.9 thous. ha). In addition, 97.6 thous. ha are occupied by specific residual-carbonate Chernozems on tight carbonate rocks (chalk, marl) and 64.2 thous. ha – by podzolized Chernozems. Grey forest soils (14.6%) are the second type by distribution.

The soil cover of the Belgorod Region steppe zone which, according to our measurements, occupies 12% of the region's territory is represented by ordinary Chernozems (208.2 thous. ha), ordinary carbonate Chernozems (74.5 thous. ha) and ordinary alkaline Chernozems (39.2 thous. ha) which in total occupy 11.8% of the total area of the region. These soil subtypes have been ploughed by 90% (Solovichenko, 2005). Ordinary back soils become dominant soils in the south-eastern part of the Belgorod Region (Rovensky, Veidelevsky districts and southern parts of Valuysky, Krasnogvardeisky and Alekseevsky districts).

In terms of nutrient-supplying capacity ordinary Chernozems do not significantly differ from typical Chernozems but the mobility of these elements is not high enough. In addition, ordinary Chernozems have insufficient phosphorus supply. It has been previously shown (Kiriluk, 2006) that Chernozems tend to differ by the average trace elements content at the subtype level: for example, in comparison with ordinary Chernozems, typical Chernozems are more enriched in Zn (81 vs 34 mg kg^{-1}) but somewhat depleted Cu (34 vs 37 mg kg^{-1}).

Data used: The field studies were carried out within the steppe part of the Belgorod Region in order to determine the regional standard for the content of the group of heavy metals including Pb, Cu, Zn, Cd, and Cs^{137}. An insight into the distribution of trace elements (micronutrients) and heavy metals over the arable land is provided by the results of five-year rounds of the agrochemical survey by Belgorodsky Agrochemical Service Centre (Lukin, 2004). The data on the content of gross forms of heavy metals were determined in the monitoring system of arable soils using samples taken from the wells. A concentrated HNO (1:1) extract with added HO was used by the laboratory. This is due to the fact that when determining the total content of heavy metals in the soil they use 1M HNO, 1M HCl and other extracts, but the obtained data make it impossible to determine the degree of territory contamination with heavy metals due to the lack of MAC. The total cadmium (extragent 5 MHNO3) was determined by atomic emission spectrometry. The total content of crop production element was determined using the methods generally accepted by the agrochemical service (Methodological guidelines ..., 1992; Sychev et al., 2006). Cs^{137} measurements were performed in soils and plants by gamma spectrometry. The energy resolution of the gamma-ray spectrometer with an energy of 662 keV is not less than 10%; the lower detection limit was at least 2 Bq kg^{-1}.

Methods: In ecogeochemistry any assessments of environmental contamination hazard in terms of landscape components are carried out using three main standards of comparison: hygiene standards (maximum allowable concentration – MAC), tentatively permissible concentrations (TPC) as well as background geochemical levels and chemical Clarks (Kasimov and Vlasov, 2015). Each of these standards has its own advantages and disadvantages. A cumulative pollution index (Z_c) used to characterize the effect of a group of elements is equal to the sum of concentration coefficients of selected chemical elements (K_{MAC}), and is calculated as per the formula

$$Z_c = K_{MAC1} + \dots + K_{MACn}, \quad (1)$$

Where n – the number of chemical elements.

RESULTS AND DISCUSSION

The role of micronutrients and their redistribution in the landscape

The "elements of life", i.e. those which are required for the normal life of plants and animals, includes Cu, Zn and Cd. Although their content in plants and soil generally does not exceed thousandths of a percent, in the process of feeding these trace elements are already very important as micronutrients, because they complement the action of the main components of fertilizers: N, P, K. Several functions are performed in plants by Cu and Zn: they are associated with proteins and organelles, fixed in large molecules, and Cd is involved in accumulation and transfer processes (Kiriluk, 2006). It should also be noted that the relative content of Pb tightly bound in soils is 80-90%, and more than half of the total mass of Zn in the soil is part of complexes with organic matter and is sorbed by Fe hydroxide films (Dobrovolskiy, 2003).

Assessment of environmental risk of pollution arable soil

Under the conditions of active manifestation of soil erosion by water and with a high proportion of eroded soils in the southeast of the Belgorod Region (Rovensky district – 63.9%, Veydelevsky district – 57.0%) which exceeds the 53.6% (Solovichenko, 2005) average erosion in the Belgorod Region, one should take into account the migration mobility in solid runoff fine silt and clay. It has been established (Tanasienko et al., 2011) that the particle size distribution of solid runoff products is heavier than that of the original soil: heaving is due to decreased content of coarse silt and fine silt (63-2 μm) fractions therein and increased amount of clay fraction (2 μm). As the data Table 1 has shown, for humus-accumulative horizon the geochemical accumulation coefficient (Kac), which was determined by the ratio of the concentrations of elements in the clay to the soil, had the highest values for Zn and Pb.

Based on the values of the geochemical accumulation coefficient, any soils with moderate erosion degree can become the most active solid runoff-related suppliers of such elements as Zn, Pb, Cr and Sr to accumulation zones (gully bottoms, floodplains, etc.). Such land in the steppe zone is often used for vegetable crops.The rationale for in-soil MAC is highly dependent on the specific soil and environmental situation. In different soils, the behavior of incoming heavy metals is largely determined by the genetic properties of soils (soil solution reaction, redox potential, humus composition and amount, buffering, etc.), modern dynamics of soil processes and chemical properties of pollutant metals (Obukhov et al., 1980). Therefore, in different countries, the MAC levels in soils (mg kg^{-1}) differ but they are Zn – 300; Pb – 100; Cu –

Table 1. Background content of heavy metals (mg kg^{-1}) and enrichment factor (EF) values in the soils of the steppe zone of the Belgorod region (Veydelevsky district. Chernozem ordinary loamy, virgin)

Elements	Horizon A, 0-36 cm		EF	Horizon AB, 36-48 cm		EF
	soil	< 0.001 mm		soil	< 0.001 mm	
Pb	17.69	38.06	2.2	11.81	46.96	4.0
Cu	50.18	71.65	1.4	49.04	62.06	1.3
Zn	51.29	199.77	3.9	52.49	343.14	6.5
Co	11.94	13.25	1.1	30.97	52.09	1.7
Ni	35.07	85.39	2.4	44.51	129.84	2.9
Cr	81.39	130.75	1.6	95.74	215.99	2.3
Sr	48.30	369.20	7.6	71.76	703.84	9.8
V	81.32	167.22	2.1	90.45	230.29	2.5
As	4.92	11.17	2.3	5.77	14.97	2.6

Note: EF is enrichment factor.

100; Cd – 3-5 on the average (Kiriluk, 2006). These limits are mainly higher than those standards, which were previously adopted in the USSR, and now used in Russia.

We have adopted the following MAC levels in soils (mg kg^{-1}): Zn – 70; Pb – 32; Cu – 50; Cd – 2. The cesium MAC level for soils cesium (Cs) has not been officially established, but regional studies (Lukin, 2004) indicate that cesium concentration of up to 1.5 Ku km^{-2} is allowed to be present in the soil and it is considered harmless. With Cs Clarke in soils 5.0 mg kg^{-1} its normal content is considered to be 1-14 (average 5) mg kg^{-1} (Kiriluk, 2006). Over the period that has passed since the accident at Chernobyl NPP about one third of artificial radionuclides have already decayed, (the half-life of Cs^{137} is 28.5 years). In the Belgorod Region the level of soil pollution in Cs^{137} is characterized as low (Geographical atlas...,

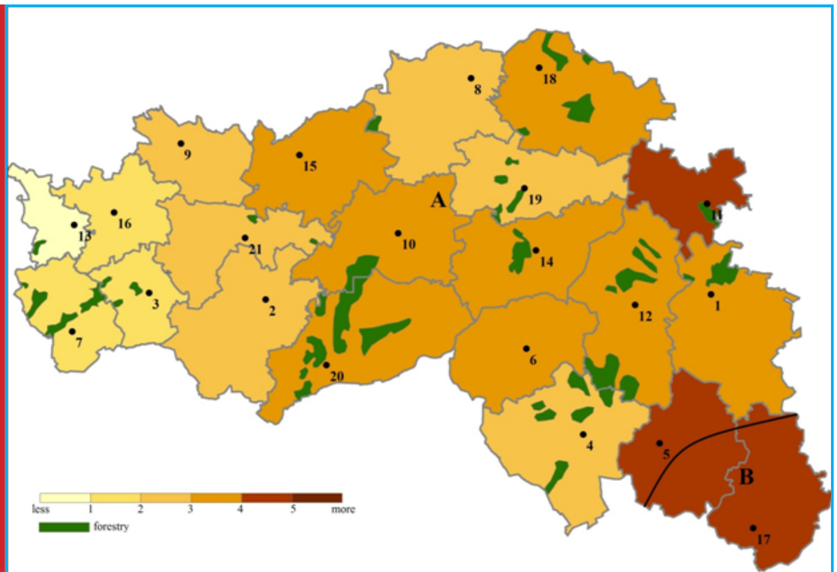

FIGURE 1. The distribution of the values of the total indicator of soil pollution (Zc) on the territory of the Belgorod region in the contours of agricultural enterprises: A – forest-steppe zone (88 % of the territory of the Belgorod region); B – steppe zone (12 % of the territory of the Belgorod region).
1 – Alekseevsky; 2 – Belgorodsky; 3 – Borisovsky; 4 – Valuysky; 5 – Veidelevsky; 6 – Volokonovsky; 7 – Graivoronsky; 8 – Gubkinsky; 9 – Ivnyansky; 10 – Korochansky; 11 – Krasnensky; 12 – Krasnogvardeisky; 13 – Krasnojaruzhsky; 14 – Novooskolsky; 15 – Prokhorovsky; 16 – Rakityansky; 17 – Rovensky; 18 – Starooskolsky; 19 – Chernyansky; 20 – Shebekinsky; 21 – Yakovlevsky

2018), and therefore normal technologies can be used in crop production.

We have conducted a soil pollution assessment in the Belgorod Region (Fig. 1) for the first time, and it showed that the north-western forest-steppe areas of the region (Krasnoyruzhsky, Grayvoronsky and Borisovsky) are least contaminated with heavy metals. In-oil concentrations of Cs and heavy metals, which exceed the MAC level, can be observed in the Rovensky (by Cu), Veidelevsky (by Zn) and Krasnensky regions.

The weighted average content of four heavy metals and cesium in the arable land of the Belgorod Region is shown in the Table 2. This is more generalized data, which was obtained using GIS-technologies in the context of municipal districts, which can contribute to the development of managerial decisions when introducing agroecological measures.

The steppe areas of the Belgorod Region (Rovensky and Veidelevsky) are characterized by excess average regional concentrations of all five elements (Table 2) under evaluation, and the total soil pollution index (Z_c) is consequently at 1.8 and 1.5 times higher than in the region on the average. The Krasnensky and Alekseevsky municipal districts are characterized by noticeably increased average regional concentrations of cesium – 2.3 and 2.2 times, respectively. The value of the total index of arable soils contamination (Z_c) exceeds the regional average level (2.7) for only 11 municipal districts (out of 21), and an excess of $Z_c > 3.5$ is observed in four districts only (Rovensky, Veidelevsky, Krasnensky and Alekseevsky). All these districts are located in the southeast of the Belgorod Region, i.e. in the steppe zone.

Soil contamination with heavy metals and assessment of their toxicity for cultivated crops

The phytotoxicity of the metals examined by us can be represented as a ranked series of toxicity (Kloke, 1980): Pb>Cu>Cd>Zn. The fact that there are significant ter-

Table 2. The weighted average content of heavy metals and cesium in the arable land of the Belgorod region

No	Municipal districts	Arable land, km²	Zn	Pb	Cu	Cd	Cs	Zc
			mg kg^{-1}				Bq km^{-2}*	
1	Alekseevsky	1765	59.3	18.5	15.3	0.9	83.0	3.9
2	Belgorodsky	1628	57.3	14.1	13.8	0.8	21.2	2.2
3	Borisovsky	650	35.7	13.0	11.3	0.2	16.8	1.4
4	Valuysky	1709	48.7	14.5	13.7	0.6	43.5	2.1
5	Veidelevsky	1353	74.2	22.4	27.6	1.1	57.1	4.1
6	Volokonovsky	1288	52.9	17.2	55.5	0.6	42.7	3.1
7	Graivoronsky	854	35.0	12.6	10.8	0.2	17.1	1.5
8	Gubkinsky	1527	50.0	12.9	12.6	0.7	18.3	2.2
9	Ivnyansky	871	48.9	14.1	11.6	0.7	17.5	2.1
10	Korochansky	1455	63.6	15.6	15.4	0.9	44.7	3.1
11	Krasnensky	867	68.4	19.4	15.7	1.3	85.8	4.3
12	Krasnogvardeisky	1763	70.8	15.8	14.5	0.8	45.8	3.4
13	Krasnojaruzhsky	479	19.8	8.9	6.9	0.1	7.7	0.9
14	Novooskolsky	1401	54.6	16.9	15.8	0.8	38.2	3.3
15	Prokhorovsky	1380	56.2	15.4	34.4	0.9	31.4	3.2
16	Rakityansky	901	35.1	11.2	11.6	0.1	16.9	1.6
17	Rovensky	1369	67.7	22.3	65.7	1.1	57.3	4.8
18	Starooskolsky	1693	63.5	14.8	64.2	0.7	32.1	3.5
19	Chernyansky	1192	53.7	15.1	14.7	0.9	37.1	2.4
20	Shebekinsky	1866	61.3	16.4	15.0	0.9	46.2	3.4
21	Yakovlevsky	1089	60.1	14.8	13.9	0.8	17.6	2.3
	By region	27100	56.7	16.1	14.1	0.7	37.9	2.7
MAC**		–	70	32	50	2	–	–

Note: * 1 Ku km^{-2} = 37 Bq km^{-2}. ** MAC is maximum allowable concentration.

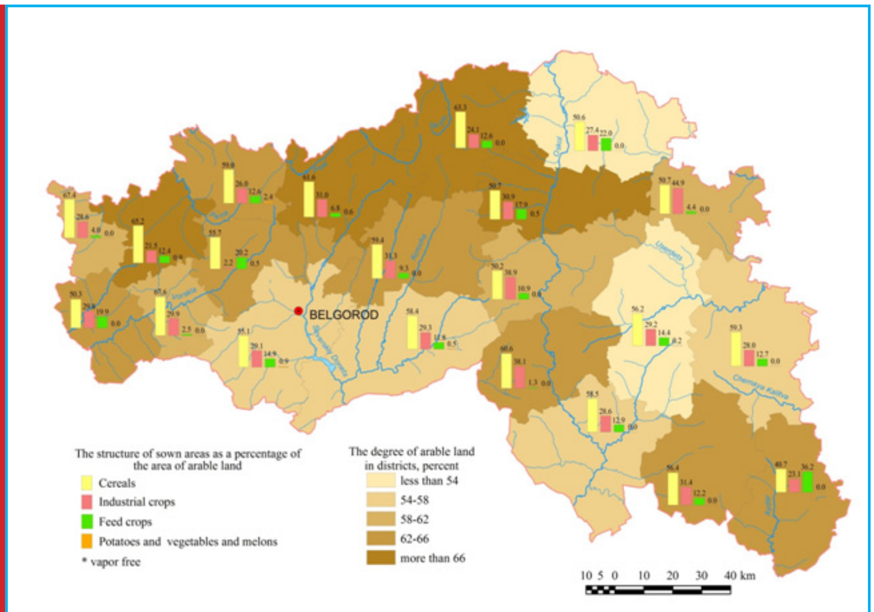

FIGURE 2. Plowing of land in the Belgorod region

ritorial differences observed in the Belgorod region for the formation of dangerous zones for agriculture and livestock breeding (on pastures) in terms of heavy metals concentration in soils makes it necessary to have cultivated areas agroecologically differentiated subject to a set of rotation crops, and in the future, possibly also with regard to their varietal characteristics. For example, it is shown that differences in cadmium uptake in various maize hybrids can be up to 13–18 times (Chernikov et al., 2000).

In the Belgorod region the sown areas are structurally dominated by (in thousand ha): spring grain crops (3552.2), fodder crops (3251.0), winter crops (2601.3), industrial crops (1944.5), legumes (302.4) (Fig. 2). Among industrial crops, large areas are occupied by sugar beet, which is inferior to other crops in resistance to the accumulation of heavy metals.

When considering the soil-plant block in agroecosystems it is important to note that the features of soil-to-plants translocation of heavy metals depend on the genetic properties of the soil, the behaviour of heavy metals and the biological characteristics of cultivated plants. Plants have certain mechanisms that prevent the accumulation of heavy metals in the reproductive organs and assimilate storage organs. The highest content of heavy metals is generally found in the roots, followed by stems and leaves, and finally by the following: seeds, tubers. As experiments with wheat (Il'in, 2007) from heavily contaminated soil have showed, only 0.5% of the heavy metal reserve was supplied to the whole phytomass at the end of the vegetation period. Thanks to the protective (barrier) capabilities of plants the following occurred: 90% of the metals turned to be trapped in the roots and about 10% of them were present in stems and leaves, and only 0.1% penetrated into the grain, which does not exceed the established limits (Il'in, 2007). Due to the translocation of trace elements from the soil, their content in grain crops can be as follows: Pb – 34-69%; Cd – 45-83%.

The content of heavy metals in root crops is comparable to their content in leaves and stems (Lukin, 2004). When growing food crops on soils with a high content of heavy metals, you should avoid provide them with plants the leaves (lettuce, spinach, onions, sorrel, etc.), stems and roots of which are used for food (Lukin, 2004). The data Table 2 show that in the steppe regions of the Belgorod Region (Rovensky, Veidelevsky) there is a ranked series of those heavy metals and Cs whose concentrations in steppe soils are higher than in the region on the average has the form: Cu, Cd, Cs, Pb, Zn. To reduce the risk of soil contamination by these heavy metals, you should apply agronomic and technological protective arrangements – the selection of less sensitive (tolerant) agricultural crops, the use of different plant parts with due account for their different ability to accumulate metals, etc. The plants can be arranged in descending order subject to their resistance to the toxic effects produced by heavy metals: herbs – cereals – industrial crops – potatoes – sugar beets (Chernikov et al., 2000).

Special environmental requirements are also needed for grass-arable rotations the share of which has significantly increased in the Belgorod Region with the implementation of the arable land biologization program. You may not use contaminated soils for feed growing because livestock are fed with the parts of plants being in the phase when they accumulate very many metals (Chernikov et al., 2000).

CONCLUSION

The Belgorod Region is one of the leading Russian regions in the production of crop and livestock products. The specific soil and climatic conditions in the steppe part of the region (12% of the territory) have led to increased concentrations of a number of heavy metals (Cu, Cd, Pb, Zn) and Cs in arable soils. A large-scale regional program for arable land biologization has resulted in increased share of grass-arable rotations and tilled land the products of which are used in animal husbandry.Given the current structure of cultivated areas in the Belgorod Region, the following list of agricultural crops should be considered as a priority for agro-environmental monitoring of the quality of the main products: winter wheat, barley, sunflower, sugar beets, corn, and peas.With due regard for the multicriteria approach to the determination of the phytotoxicity of heavy metals and radionuclides (Kiriluk, 2006) for hazardous territorial areas in crop production, it is necessary to take into account different sensitivity of cultivated plants to metals as well as the influence of soil properties subject to the practice in the application of fertilizers and ameliorants.

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