Comparative Analysis of *Triticum aestivum* L. (Poaceae, Poales) and *Pisum sativum* L. (Fabaceae, Fabales) Resistance to Heavy Metals

E. A. Erofeeva*

Lobachevskii State University of Nizhny Novgorod, Nizhny Novgorod, 603950 Russia

*e-mail: ele77785674@yandex.ru

Received April 22, 2019; revised November 11, 2019; accepted December 14, 2019

Abstract—Heavy metals are widespread soil pollutants frequently identified in agricultural lands. In many cases, their pollution levels significantly exceed the maximum permissible concentrations. Pea (*Pisum sativum* L.) and wheat (*Triticum aestivum* L.) plants are among the most important agricultural crops. However, no comparative analyses of their resistance to high concentrations of heavy metals have been performed before. Therefore, an experiment was conducted with the purpose to assess the resistance of *T. aestivum* and *P. sativum* seedlings to chronic effects of lead and copper salts in concentrations lethal for *T. aestivum* (copper sulfate: 0.15, 0.30, and 0.60 g/L; lead nitrate: 0.5, 1.0, and 1.5 g/L). All studied toxicant concentrations reduce the germination capacity of *T. aestivum* seeds in comparison with the control variant: lead nitrate, by 19–38%; and copper sulfate, by 23–58%. The decrease in the germination capacity is a direct manifestation of the lethal effects exercised by these heavy metals. All studied toxicant concentrations reduce the root system length (from 69% to 25 times) and shoot height (by 25–76%) in *T. aestivum* seedlings in comparison with the control variant. In addition, heavy metals intensify lipid peroxidation in seedling shoots, which indicates the development of a stress reaction. By contrast, heavy metal salts in concentrations lethal for *T. aestivum* have virtually no effect on the parameters of *P. sativum* (except for the root system: exposure to lead nitrate reduces its length). Overall, *P. sativum* is significantly more resistant to effects caused by the concentrations of lead nitrate and copper sulfate studied than *T. aestivum*; this applies to parameters such as the seed germination capacity, growth processes in the root system and shoot, and peroxide homeostasis.

Keywords: *Triticum aestivum, Pisum sativum*, lead, copper, linear dimensions of seedlings, seed germination, lipid peroxidation

DOI: 10.1134/S1062359021100083

INTRODUCTION

Motor vehicles and industries (coal mining, metalurgical, chemical, energy, etc.) are the main sources of heavy metals contaminating the environment (Titov et al., 2014; Su et al., 2014). Strips of land along busy motorways 50–100 (sometimes up to 300) m in width are polluted with heavy metals. The main part of these contaminants settles on the land surface in the range of 10–15 m and concentrates in the 0- to 10-cm layer (Denisov and Rogalev, 2005). Heavy metals that enter soils even in small quantities can accumulate there, bind to humus components, and persist for a long time. Organophilic elements, such as copper and lead, are especially firmly fixed on the humus barrier (Vodyanitskii, 2008). The lead content in soil decreases by half in 740–5900 years; for copper, this period amounts to 310–1500 years (Kabata-Pendias and Pendias, 1989).

Agricultural lands located close to motorways are also exposed to heavy metal pollution. Aside from automotive emissions, heavy metals enter soils with mineral and organic fertilizers and crop protection agents (fungicides, herbicides, etc.) (Titov et al., 2011; Vodyanitskii, 2013; Xu et al., 2017). In addition, heavy metals contained in incompletely treated industrial and municipal waste waters are accumulated in reservoirs and subsequently enter irrigated soils (Vodyanitskii, 2013; Su et al., 2014). The concentrations of heavy metals in arable soils can significantly exceed their maximum permissible concentrations (MPC) (Micó et al., 2006). For instance, cadmium concentrations exceeding the MPC by 12 times were registered in Tyumen oblast, which is a consequence of application of large quantities of mineral fertilizers (Vodyanitskii, 2013).

Peas (*Pisum sativum* Linnaeus, 1753) and wheat (*Triticum aestivum* Linnaeus, 1753) are among the...
most important agricultural crops. Numerous studies address the resistance of these cultures to various heavy metals (Petrova and Raikhert, 2013; Pukhal'skii et al., 2017; Belimov et al., 2018; Fagorzi et al., 2018; etc.). However, comparative analyses of species-specific resistance of *T. aestivum* and *P. sativum* to effects caused by heavy metals were never performed before. It has been shown that some wild leguminous species growing along motorways are significantly more resistant to impacts of these pollutants in comparison with nonleguminous plants (Savinov et al., 2007). By contrast, other authors note that gramineous plants are more resistant to heavy metals, including cadmium, than legumes (Seregin and Ivanov, 2001). Earlier, it was established that the impacts of sublethal and lethal pollutant concentrations provide a better insight into the species-specific resistance of plants to these pollutants because, under such conditions, the plant defense systems are activated to the maximum (Erofeeva, 2012, 2014, 2018).

Therefore, an experiment involving a high degree of control over the heavy metal concentrations available to the plants was conducted with the purpose to perform a comparative analysis of the resistance of *T. aestivum* and *P. sativum* seedlings to effects caused by heavy metal salts (copper sulfate and lead nitrate) in concentrations lethal for *T. aestivum*. These two heavy metals were selected because their concentrations in the vicinity of motorways often exceed the MPC values set for soils (Gelashvili et al., 2007) and because their degrees of significance for plants are different. Unlike lead, copper is a plant microelement forming a part of enzymes such as superoxide dismutase, polyphenol oxidase, ascorbate oxidase, and cytochrome oxidase, as well as the plastocyanin protein that transfers electrons between the photosystems I and II (Yruela, 2005; Polesskaya, 2007).

**MATERIALS AND METHODS**

Two series of experiments were conducted. In the first series, the effects of lead nitrate on the state of *P. sativum*, Stabel variety and *T. aestivum*, Moskovskaya 59 variety were studied. In the second series, the effects of copper sulfate on the same plant species were studied. The toxicant concentrations were selected in the course of preliminary studies carried out to make sure that they fall within the lethal range (i.e., reduce the germination capacity of *P. sativum* seeds) because some data indicate that nonleguminous herbaceous species in roadside phytocoenoses are more sensitive to the effects of heavy metals in comparison with the family Fabaceae (Savinov et al., 2007).

Each experimental series involved four groups of plants for each of the studied species: three experimental and one control group. In each group, 50 seeds were placed on one layer of filter paper in five 500-mL transparent plastic containers. In the experimental groups, 10 mL of heavy metal salt solutions (copper sulfate 0.15, 0.30, and 0.60 g/L or lead nitrate 0.5, 1.0, and 1.5 g/L) were poured into the containers. In the control group, 10 mL of distilled water were poured into the containers. The containers were closed with transparent lids and placed on a rack with phytolamps at a temperature of 20–22°C with a daylight duration of 17 hours. Every two days, salt solutions were added in the same volume to the containers in the experimental groups, while distilled water was added to the control group. After eight days, the seedlings’ parameters were measured. The germination capacity of seeds in the laboratory environment was determined as the share of germinated seeds in the total number of seeds in the group (*n* = 250). The maximum root system length and shoot height (i.e., the length of the seedling’s above-ground part) were measured to an accuracy of 1 mm (*n* = 30). The maximum root system length was measured as the seminal root length for *P. sativum* and as the linear dimensions of the longest roots for *T. aestivum*. The length of the above-ground part and roots in seedlings are commonly used parameters reflecting the development of grain crop seedlings (Aleksiechuk, 2009). Earlier, it was shown that the linear dimensions of seedlings at this age strongly correlate with the dry biomass of their roots and shoot (Erofeeva, 2014).

To assess the intensity of lipid peroxidation (LPO), shoots of 3–4 plants (0.3 g) were put together and homogenized in 2 mL of 3 mM Trilon B solution in a porcelain mortar frozen in ice. In each group, there were ten biological replications (*n* = 10; two biological replications per container). The LPO intensity was assessed based on the content of TBA-reactive lipid peroxidation products. The prime such product is malondialdehyde (MDA) (Kamyshnikov, 2002); its concentration was expressed in relative optical density units.

The statistical analysis of the results was performed in STATISTICA 10 and Biostatistika 4.03 using single-factor analysis of variance (ANOVA) and Student’s test with the Bonferroni correction for quantitative parameters with a normal distribution (LPO intensity). If the sample distribution was not normal (maximum length of the root system and shoot height), the Kruskal–Wallis test and the nonparametric variant of Dunn’s test for multiple pairwise comparisons were used. The chi-square test (*χ²*) with the Bonferroni correction for multiple pairwise comparisons was used for the qualitative parameter (germination capacity of seeds). For the quantitative parameters, the diagrams provide mean values and their errors (*M ± SE*) (LPO intensity) or median values and their errors (*Me ± sMe*) (linear dimensions of seedlings); for
and T. aestivum Seedlings Caused by Chronic Effects of Lead Nitrate and Copper Sulfate

The Shapiro–Wilk test has shown that the distribution in some samples significantly differs from normal ($p < 0.05$); therefore, the data were analyzed using nonparametric tests. The impacts of the “lead nitrate” and “copper sulfate” factors on the linear dimensions of $T.\ aestivum$ seedlings have been determined using the Kruskal–Wallis test ($Pb$ (shoot): $H = 93.9, p = 0.001$; $Pb$ (root system): $H = 91.0, p = 0.001$; $Cu$ (shoot): $H = 104.8, p = 0.001$; and $Cu$ (root system): $H = 85.5, p = 0.001$). Dunn’s test, which takes into account the error of multiple pairwise comparisons, has shown that copper sulfate and lead nitrate in all concentrations statistically significantly ($p < 0.05$) reduce the maximal root system length ($Pb$: $Q_{0.5/c} = 8.9, Q_{1.0/c} = 6.6$, and $Q_{1.5/c} = 3.2$; $Cu$: $Q_{0.15/c} = 4.9, Q_{0.30/c} = 6.3$, and $Q_{0.60/c} = 9.1$) and shoot height ($Pb$: $Q_{0.5/c} = 3.2, Q_{1.0/c} = 6.8$, and $Q_{1.5/c} = 9.0$; $Cu$: $Q_{0.15/c} = 3.4, Q_{0.30/c} = 6.2$, and $Q_{0.60/c} = 9.9$) in $T.\ aestivum$ seedlings in comparison with the control (Figs. 1, 2). The adverse effect on the linear dimensions of the $T.\ aestivum$ root system is especially strong. In the experimental groups, exposure to lead nitrate reduces this parameter in the range from 69% to 25 times in comparison with the control (Fig. 1a), while exposure to copper sulfate, by 8–24 times in comparison with the control (Fig. 1b). The reduction of the shoot height is manifested not as strongly in $T.\ aestivum$: this parameter decreases by 35–65% in comparison with the control for copper sulfate and by 25–76% for lead nitrate (Fig. 2). Other researchers also note that various heavy metals suppress the root system growth stronger than growth processes in the shoot (Titov et al., 2014).

Concurrently, the Kruskal–Wallis test has shown that copper sulfate does not affect the linear dimensions of the root system ($H = 2.1, p = 0.770$) and shoot ($H = 7.5, p = 0.072$) in $P.\ sativum$ seedlings (Figs. 1b, 2b). The adverse effect of lead nitrate in all concentrations is statistically significant ($p < 0.05$) only for the maximum root system length of $P.\ sativum$ ($H = 84.9, p = 0.001$; $Q_{0.5/c} = 4.3, Q_{1.0/c} = 6.7$, and $Q_{1.5/c} = 8.8$).
Fig. 3. Germination capacity of T. aestivum and P. sativum seeds chronically exposed to various concentrations of (a) lead nitrate and (b) copper sulfate (share ± error; n = 250). * Statistically significant differences in the parameter from the control group at $p < 0.05$.

This parameter decreases by 2–6 times in comparison with the control variant (Fig. 1a).

Overall, the growth processes in P. sativum are significantly more resistant to effects caused by the studied heavy metal salts in comparison with T. aestivum. Unlike copper, lead can disturb the growth processes in the P. sativum root system; apparently, this is due to the lead accumulation patterns in P. sativum organs. It was shown that copper enters the P. sativum root system and shoot from the contaminated soil in similar quantities, while lead is mostly accumulated in the root (Trots et al., 2012). This is likely the reason behind the inhibitory effect of lead on the linear dimensions of the root system.

Changes in the Germination Capacity of P. sativum and T. aestivum Seeds Caused by Chronic Effects of Lead Nitrate and Copper Sulfate

The $\chi^2$ test with the Bonferroni correction that takes into account the error of multiple pairwise comparisons has shown that all studied toxicant concentrations statistically significantly reduce the germination capacity of T. aestivum seeds in comparison with the control: lead nitrate, by 19–38% ($\chi^2_{0.5/c} = 23.5, p = 0.001$; $\chi^2_{1.0/c} = 11.7, p = 0.001$; and $\chi^2_{1.5/c} = 44.3, p = 0.001; df = 3$) and copper sulfate, by 23–58% ($\chi^2_{0.15/c} = 28.0, p = 0.001$; $\chi^2_{0.30/c} = 78.3, p = 0.001$; and $\chi^2_{0.60/c} = 168.4, p = 0.001; df = 3$). The adverse effect significantly increases at higher concentrations of the pollutants in the solution (Fig. 3).

By contrast, the germination capacity of P. sativum seeds does not change ($\chi^2 = 6.5, p = 0.117, df = 3$) or even increases statistically significantly (by 14–19% in comparison with the control) as a result of exposure to the two higher copper sulfate concentrations (Fig. 3b) ($\chi^2_{0.15/c} = 2.9, p = 0.087$; $\chi^2_{0.30/c} = 14.4, p = 0.001$; and $\chi^2_{0.60/c} = 8.6, p = 0.006; df = 3$). Apparently, the stimulating effect is observed because, unlike lead, copper is a plant microelement. Research data indicate that presowing seed treatments with salts of microelements, including copper, can increase the germination capacity of cultivated crops (Bulygin et al., 2007).

Therefore, the seed germination process in P. sativum is more resistant to the effects of copper sulfate and lead nitrate in comparison with T. aestivum.

Changes in the Lipid Peroxidation Intensity in P. sativum and T. aestivum Shoots Caused by Chronic Effects of Lead Nitrate and Copper Sulfate

The Shapiro–Wilk test has shown that the distribution in all samples does not statistically significantly differ from normal ($p > 0.05$); therefore, the data were analyzed using parametric tests. The single-factor analysis of variance performed using Student’s test with the Bonferroni correction that takes into account the error of multiple pairwise comparisons has shown that all studied lead nitrate concentrations ($F = 9.6, p = 0.001$; $t_{0.5/c} = 6.3, t_{1.0/c} = 5.7$, and $t_{1.5/c} = 6.8$) and the two higher copper sulfate concentrations ($F = 8.3, p = 0.001$; $t_{0.15/c} = 0.6, t_{0.30/c} = 2.7$, and $t_{0.60/c} = 4.2$) statistically significantly ($p < 0.05$) intensify lipid peroxidation in the leaves of T. aestivum seedlings in the range from 22% to two times in comparison with the control variant (Fig. 4), which indicates the development of a stress reaction in the seedlings because the lipid peroxidation intensity increases in plants affected by environmental stress factors (Baraboi, 2006; Polesskaya, 2007).

By contrast, all copper sulfate concentrations studied do not intensify lipid peroxidation in P. sativum in comparison with the control (Fig. 4b) ($F = 0.68, p = 0.560$). Lead nitrate either does not affect this parameter in P. sativum ($t_{1.0/c} = 0.9$ and $t_{1.5/c} = 1.6; p > 0.05$) or reduces it in comparison with the control (0.5 g/L: $F = 7.96, p = 0.001$; $t_{0.5/c} = 6.3, p < 0.05$) (Fig. 4a). Apparently, this is due to the significant activation of the antioxidant system in P. sativum seedlings (Polesskaya, 2007) able to overcompensate for the changes in...
the peroxide homeostasis caused by the pollutants (Erofeeva, 2014, 2015). Overall, the data obtained indicate that, unlike *T. aestivum*, the concentrations of copper sulfate and lead nitrate studied do not cause a stress reaction in *P. sativum*.

**CONCLUSIONS**

By a number of parameters, including the seed germination capacity, growth processes in the root system and shoot, and peroxide homeostasis, *P. sativum* is significantly more resistant to effects caused by the concentrations of lead nitrate and copper sulfate studied in comparison with *T. aestivum*. The resistance levels in the two species differ so much that heavy metal salts in concentrations lethal for *T. aestivum* virtually do not cause disturbances in the parameters of *P. sativum* (except for the root system in which exposure to lead nitrate reduces its maximum length). Perhaps the main reason behind the phenomenon identified is that leguminous plants, including *P. sativum*, contain more protective peptides (phytochelatins and metallothioneins) that form complexes with heavy metals in the cytoplasm and transport the heavy metals to the vacuole than gramineous plants (Seregin and Ivanov, 2001). In addition, legumes contain more proteins enhancing their resistance to environmental stress factors, including antioxidant system enzymes (Polemov, Malkov, Puhalsky, Tsyganov, and Tikhonovich, 2006. Belimov, K.B., Safronova, V.I., Dietz, K.-J., and Tikhonovich, I.A., The crucial role of roots in increased cadmium-tolerance and Cd-accumulation in the pea mutant SGECd, *Biol. Plant.*, 2015, vol. 62, no. 3, pp. 543–550. Bulygin, S.Yu., Demishev, L.F., Doronin, V.A., Zapishnyak, A.S., Paschenko, Ya.V., Turovskii, Yu.E., Fateev, A.I., Yakovenko, M.M., and Kordin, A.I., *Mikroelementi v sel’skom hozyaistve* (Trace Elements in Agriculture), Dnepropetrovsk: Sich, 2007. Denisov, V.N. and Rogalev, V.A., *Problemy ekologizatsii avtomobil’nogo transporta* (Problems of Road Transport Ecologization), St. Petersburg: MANEB, 2005. Erofeeva, E.A., Developmental stability of a leaf of *Pisum sativum* L. under the influence of formaldehyde in a wide range of doses, *Russ. J. Dev. Biol.*, 2012, vol. 42, no. 5, pp. 259–263. Erofeeva, E.A., Hormesis and paradoxical effects of wheat seedling (*Triticum aestivum* L.) parameters upon exposure to different pollutants in a wide range of doses, *Dose Response*, 2014, vol. 12, no. 1, pp. 121–135. Erofeeva, E.A., Dependence of guaiacol peroxidase activity and lipid peroxidation rate in drooping birch (*Betula pendula* Roth) and tillet (*Tilia cordata* Mill.) L.leaf on motor traffic pollution intensity, *Dose Response*, 2015, vol. 13, no. 2, pp. 1–6. Erofeeva, E.A., Hormesis and paradoxical effects of pea (*Pisum sativum* L.) parameters upon exposure to formaldehyde in a wide range of doses, *Ecotoxicology*, 2018, vol. 27, pp. 569–577.

**REFERENCES**

Alekseichuk, G.N., *Sila rosta semyan zernovykh kul’tur i ee otsenka metodom uskorennogo stareniya* (Seed Vigor of Cereal Crops and Its Evaluation by Accelerated Aging Method), Minsk: Pravo i ekonomika, 2009. Baraboii, V.A., *Stress: priroda, biologicheskaia rol’, mekhaniizmy, iskhody* (Stress: Nature, Biological Role, Mechanisms, and Outcomes), Kiev: Phytosociocenter, 2006. Belimov, A.A., Malkov, N.V., Puhalsky, J.V., Tsyganov, V.E., Bodyagina, K.B., Safronova, V.I., Dietz, K.-J., and Tikhonovich, I.A., The crucial role of roots in increased cadmium-tolerance and Cd-accumulation in the pea mutant SGECd, *Biol. Plant.*, 2018, vol. 62, no. 3, pp. 543–550. Bulygin, S.Yu., Demishev, L.F., Doronin, V.A., Zapishnyak, A.S., Paschenko, Ya.V., Turovskii, Yu.E., Fateev, A.I., Yakovenko, M.M., and Kordin, A.I., *Mikroelementi v sel’skom hozyaistve* (Trace Elements in Agriculture), Dnepropetrovsk: Sich, 2007. Denisov, V.N. and Rogalev, V.A., *Problemy ekologizatsii avtomobil’nogo transporta* (Problems of Road Transport Ecologization), St. Petersburg: MANEB, 2005. Erofeeva, E.A., Developmental stability of a leaf of *Pisum sativum* L. under the influence of formaldehyde in a wide range of doses, *Russ. J. Dev. Biol.*, 2012, vol. 42, no. 5, pp. 259–263. Erofeeva, E.A., Hormesis and paradoxical effects of wheat seedling (*Triticum aestivum* L.) parameters upon exposure to different pollutants in a wide range of doses, *Dose Response*, 2014, vol. 12, no. 1, pp. 121–135. Erofeeva, E.A., Dependence of guaiacol peroxidase activity and lipid peroxidation rate in drooping birch (*Betula pendula* Roth) and tillet (*Tilia cordata* Mill.) L.leaf on motor traffic pollution intensity, *Dose Response*, 2015, vol. 13, no. 2, pp. 1–6. Erofeeva, E.A., Hormesis and paradoxical effects of pea (*Pisum sativum* L.) parameters upon exposure to formaldehyde in a wide range of doses, *Ecotoxicology*, 2018, vol. 27, pp. 569–577.
Fagorzi, C., Checucci, A., DiCenzo, G.C., Debiec-Anrdejewska, K., Dziewit, L., Pini, F., and Mengoni, A., Harnessing rhizobia to improve heavy-metal phytoremediation by legumes, *Genes*, 2018, vol. 9, no. 11, pp. 1–16.

Gelashvili, D.B., Koposov, E.V., and Laplev, L.A., *Ekologiya Nizhnego Novgoroda* (Ecology of Nizhny Novgorod), Nizhny Novgorod: Nizhegorod. Gos. Arkhitekt.-Stroit. Univ., 2007.

Kabata-Pendias, A. and Pendias, H., *Mikroelementy v pochvakh i rasteniakh* (Trace Elements in Soils and Plants), Moscow: Mir, 1989.

Kamyshnikov, V.S., *Spravochnik po kliniko-biokhimicheskoi laboratornoi diagnostike* (Reference Book on Clinical and Biochemical Laboratory Diagnostics), Minsk: Belarus’, 2002, vol. 2.

Kozeko, L.Ye., *Alterations in a soluble protein pattern and a quantity of stress proteins HSP90 and HSP70 in pea seedlings in response to clinorotation*, *Biopolym. Cell*, 2006, vol. 22, no. 2, pp. 136–142.

Micó, C., Peris, M., Sánchez, J., and Recatalá, L., Heavy metal content of agricultural soils in a Mediterranean semi-arid area: the Segura River valley (Alicante, Spain), *Spanish J. Agricult. Res.*, 2006, vol. 4, no. 4, pp. 363–372.

Petrova, E.E. and Reikhert, E.V., *Effect of vehicles on the accumulation of lead and zinc in soils and their biological absorption by soft wheat (Triticum aestivum)* in roadside agricultural lands (Alei Zone, Altai Territory), *Izv. Altaisk. Gos. Univ.*, 2013, no. 3-1, pp. 44–48.

Poleskaya, O.G., *Rastitel’naia kletka i aktivnye formy kisloroda* (Plant Cell and Reactive Oxygen Species), Moscow: Knizhn. Dom Universitet, 2007.

Pukhalsky, Ya.V., Vishniyakova, M.A., Loskutov, S.I., Sementova, E.V., Sekste, E.A., Shaposhnikov, A.I., Sfafrova, V.I., Belimov, A.A., and Tikhonovich, I.A., *Pea (Pisum sativum L.) cultivars with low accumulation of heavy metals from contaminated soil*, *S.-Kh. Biol.*, 2017, vol. 52, no. 3, pp. 597–606.

Savinov, A.B., Kurganova, L.N., and Shekunov, Yu.I., Intensity of lipid peroxidation in *Taraxacum officinale* Wigg. and *Vicia cracca* L. in biotopes with different levels of heavy metals pollution in soil, *Russ. J. Ecol.*, 2007, vol. 38, no. 3, pp. 174–180.

Seregin, I.V. and Ivanov, V.G., Physiological aspects of cadmium and lead toxic effects in higher plants, *Russ. J. Plant Physiol.*, 2001, vol. 48, no. 4, pp. 523–544.

Su, C., Jiang, L.Q., and Zhang, W.J., A review on heavy metal contamination in the soil worldwide: situation, impact and remediation techniques, *Environ. Skept. Crit.*, 2014, vol. 3, no. 2, pp. 24–38.

Titov, A.F., Talanova, V.V., and Kaznina, N.M., *Fiziotekhicheskie osnovy ustoichivosti rastenii k tiashelym metallam* (Physiological Bases of Plant Resistance to Heavy Metals), Petrozavodsk: Karel. Nauchn. Tsentr Ross. Akad. Nauk, 2011.

Titov, A.F., Kaznina, N.M., and Talanova, V.V., *Tiazhelye metally i rasteniiia* (Heavy Metals and Plants), Petrozavodsk: Karel. Nauchn. Tsentr Ross. Akad. Nauk, 2014.

Trots, N.M., Trots, V.B., and Obuschenko, S.V., Accumulation of heavy metals grain legumes in agricultural landscapes of Samara Trans-Volga Region, *Dostizh. Nauki Tekhn. Agroprom. Kompl.*, 2012, no. 2, pp. 50–51.

Vodyanitskii, Yu.N., *Tiazhelye metally i metalloidy v pochvakh* (Heavy Metals and Metalloids in Soils), Moscow: Pochv. Inst. im. V.V. Dokuchaeva Russ. Akad. S.-Kh. Nauk, 2008.

Vodyanitskii, Yu.N., *Contamination of soils with heavy metals and metalloids and its ecological hazard* (analytic review), *Eurasian Soil Sci.*, 2013, vol. 46, no. 7, pp. 793–801.

Xu, Y., Liang, X., Xu, Y., Qin, X., Huang, Q., Wang, L., and Sun, Y., Remediation of heavy metal–polluted agricultural soils using clay minerals, *Pedosphere*, 2017, vol. 27, no. 2, pp. 193–204.

Yruela, I., Copper in plants, *Braz. J. Plant Physiol.*, 2005, vol. 17, no. 1, pp. 145–156.

*Translated by L. Emeliyanov*