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Model of Biomass Productivity under the Influence of Change in the Phytotoxicity of Podzol Soil Due to Reintroduction of Sewage Sludge under Energy Willow

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ABSTRACT
Utilization of sewage sludge during phytoremediation of territories and its introduction as fertilizer for energy crops requires testing for phytotoxicity of the soil cover, which will allow determining an ecologically safe dose of its use and minimizing the negative impact on agroecosystems. It will also contribute to the formation of optimal productivity of agrophytocenoses as well as optimize the nutrition conditions for intensive growth and development of cultivated plants. The research conducted an analysis of the impact of the increase in phytotoxicity of sod-podzolic soil from the introduction of fresh sewage sludge and its composts with various organic materials (sawdust of coniferous trees, straw of grain crops) on the formation of biomass productivity of energy willow during a repeated cycle of cultivation. Regression and correlation analyses were used to build a mathematical model of biomass productivity under the influence of changes in the phytotoxicity of podzol soil due to repeated introduction of sewage sludge under the energy willow. The obtained regression dependences show that the formation of phytotoxicity of sod-podzolic soil is most affected by the increase in the content of Pb and Cd. However, the introduction of the norm of fresh SS within 80 t/ha did not lead to an increase in the content of these heavy metals above the maximum allowable concentrations, although it contributed to an increase in phytotoxicity to an above average level. The maximum predicted productivity, depending on the content of mobile forms of heavy metals in the soil, is about 60 t/ha at a content of Cd = 0.25; Ni = 1.1 Pb = 4.6 mg/kg soil. As the phytotoxicity of the soil increases to an above-average level (phytotoxic effect 40–46%), the intensity of biomass accumulation of energy willow slows down somewhat. In general, after a repeated cycle of using the plantation during the 4-year growing season of energy willow in all options where fertilizers were applied, the productivity of wood biomass increased significantly compared to the control option by 7.7–17.4 t/ha and with the smallest significant difference between the indicators of the research options 4.23 t/ha.

Keywords: energy willow, sewage sludge, productivity, productivity model, phytotoxicity.

INTRODUCTION

Today, the culture of energy willow is considered not only as a means of obtaining biomass for energy purposes, but also as an important aspect in the stabilization of agroecosystems, in view of the preservation of biodiversity, the possibility of leachate purification, use as coastal mechanical and chemical buffers, as well as the purification of wetlands due to high evapotranspiration [Frédette Ch. et al., 2019].

The use of willow plantations can be a sustainable approach to the primary treatment of municipal wastewater, potentially reducing both the environmental and economic burdens on urboecosystems associated with conventional treatment, and is already successfully used in the practice of sewage sludge (SS) utilization, which accumulates in the cities of different countries in significant volumes [Sas E. et al., 2021].

Researchers note great prospects in the use of energy willow plantations for phytoremediation of soils as a safe mechanism for cleaning technogenically polluted areas and as a means of removing pollutants from ecosystems. Among the different types of plants, genus Salix spp. is considered a powerful tool for removing heavy metals using natural mechanisms from the most damaged places [Khursheed Ahmad Wani et al., 2020].

SS can be used as a fertilizer for soil and plants, positively influencing the regime of mineral nutrition and soil properties, which determines the formation of willow biomass yield and changes in metabolism [Lopushniak et al., 2016].

SS can be used either fresh (untreated waste), if allowed by the current legislation of the country where it is used, after biological decomposition processes (composting, biodegradation), or in combination with other substrates, for example, biochar, microbial vaccines, plant post-harvest residues etc. The use of SS promotes carbon absorption, as well as energy and substance recovery [Fijałkowski K., Kwarciak-Kozłowska A., 2021]. However, its introduction may lead to an increase in phytotoxicity of the soil [Urbaniak M. et al., 2017]. Some phytotoxicity is noted even during the introduction of biochar using SS [Godlewska P. et al., 2022].

Utilization of SS during phytoremediation of territories requires testing for phytotoxicity, which will allow determining a safe dose from the point of view of minimizing the negative impact on the formation of productivity of agrophytocenoses and optimizing nutrition conditions for intensive growth and development of cultivated plants.

The aim of the scientific work was to study and evaluate changes in the phytotoxicity of podzolic soil, which was repeatedly (after the first cycle of biomass removal) introduced with different doses of SS and its composts with straw of grain crops and sawdust of coniferous trees, as well as an analysis of the effect of the phytotoxic effect on the formation of energy willow productivity.

MATERIALS AND METHODS

The soil of the experimental field is sod-podzolic medium-loamy, which before the establishment of the field experiment was characterized by the following agrochemical indicators in the 0–25 cm layer: hydrolytic acidity – 3.25 mmol/100 g of soil; cation absorption capacity – 11.73 mmol/100 g of soil; the amount of absorbed bases – 8.48 mmol/100 g of soil (according to Kappen); degree of saturation with bases – 73.1%; saline pH 5.0; humus content – 1.54% (according to Tyurin); total nitrogen – 0.07%; alkaline-hydrolyzed nitrogen – 66.40 mg/kg of soil (according to Kornfield); nitrogen of mineral compounds – 15.7 mg/kg of soil; mobile compounds of phosphorus and potassium (according to Kirsanov) are 120.0 and 48.0 mg/kg of soil, respectively.

An experimental plantation of energy willow was created in the second decade of March 2012 at the collection and research field of the Ivano-Frankivsk College of LNAU in the village of Chukalivka, Ivano-Frankivsk territorial community, Ivano-Frankivsk district, Ivano-Frankivsk region. The width of the experimental area is 4.0 m; length – 7.0 m; registered area – 28.0 m^2. The total area of the experimental site is 54 m^2. The experiment was repeated three times, whereas placement of plots was systematic.

After the establishment of plantations in the research, the four-year-old willow was cut in autumn so that 8–10 cm of the trunk remained above the soil surface. The following year, after the cutting of the vegetative mass in early spring, immediately after the cessation of persistent frosts before the germination of the willow cuttings, the soil was loosened between the rows with an improved milling cultivator, and sewage sludge and compost were re-introduced according to the experimental scheme [Frédette et al., 2019; Vasylʹyeva et al., 2006].

Processing was carried out in such a way that the loosened layer was not deep, but at the same time so that the fertilizers were covered with a layer of soil up with a thickness of 5–8 cm. During the first year of vegetation, after repeated application of SS, careful care and protection from weeds was provided up to the height of the willow shoots more than 1.0 m. In the first 1.5–2 months, weeds were periodically destroyed by hand. Later, when the willow outgrew the weeds, the process of destroying unwanted vegetation was no longer decisive in care, and during dry periods weeding was not carried out, thereby preventing excessive drying of the soil. The work carried out in the first year in an appropriate manner to ensure intensive vegetation of energy willow plants determines the level of accumulation of vegetative mass in the following years. In the first year after felling, 5–8 branches with a length of about 3–4 m sprout from one trunk. The length of the branches depends on the water regime and the level of mineral nutrition. After four years of vegetation, the willow was cut by hand, selectively weighed to determine the productivity and analyze the raw mass. Field and laboratory studies on the growth and development of plantations were carried out according to the appropriate methods [Frédette et al., 2019; DSTU 2007].

The research results were analyzed by methods of correlation and regression analysis [1] using the Mathcad computer algebra system. All experimental measurements were performed in 4 replicates, and results are presented as mean values based on correlation-regression analysis performed using STATISTICA 6.0.

The volume of the studied sample was about 0.5 cm^3. The paper presents the results of analyses of heavy metals that have the greatest impact on the pollution of agrophytocenoses, in particular Pb, Cd, Ni, Co, Zn, Fe, Cu.

To assess the level of soil toxicity in different variants of the experiment, seeds of sensitive test objects were germinated: common flax (*Linumustatissimum L.*), annual sunflower (*Helianthusannuus L.*), watercress (*Lepidiumsaivum L.*).

For the study, testing of soil samples in thermostat conditions at t = (+ 25) °C was chosen. Afterwards, 1 g of crushed soil was placed on filter paper in Petri dishes and 5–7 ml of settled boiled tap water was poured. Then 5 seeds of the test culture were laid out. The petri dishes were placed in a thermostat. The seeds were germinated for ten days at a temperature of 20 °C, after which the plants were removed from the soil and the length of the roots was measured.

The phytotoxic effect was determined as a percentage of plant weight, length of root or stem system, number of damaged plants or number of seedlings. On the basis of the amount of plant mass formed, the phytotoxic effect (PE) was calculated according to the formula:

$$\mathrm{PE} = \frac{M_0 - M_x}{M_0} \cdot 100$$

where: M_0 – the mass or growth indicators of plants in a Petri dish with control soil;
M_x – the mass or growth rate in a Petri dish with the soil under study.

Soil preparation for analysis was carried out according to DSTU 4287:2004 [DSTU 2004]. The content of mobile compounds of cadmium and zinc in soils was determined using a buffered ammonium acetate solution with a pH of 4.8 by the method of atomic absorption spectrophotometry on a C-115 PT spectrophotometer [DSTU 2007, 2004].

Studies have established certain regularities of changes in the content of mobile forms of heavy metals during repeated application of SS under the energy willow (Table 1). The content of mobile forms of heavy metals in the podzolic soil

Table 1. The content of mobile forms of heavy metals in turf-podzolic soil after repeated (after four years of cultivation) application of sewage sludge under energy willow, mg/kg of soil

No.	Options	Pb	Cd	Ni	Co	Zn	Fe	Cu
1	No fertilizers (control)	3.76	0.19	1.09	2.08	2.95	7.35	6,75
2	$N_{100}P_{100}K_{100}$	3.99	0.22	1.27	2.27	3.13	14.85	6,93
3	SS 40 t/ha	4.44	0.28	1.29	2.31	5.06	15.07	6,82
4	SS 60 t/ha	4.58	0.29	1.39	2.60	5.37	15.88	7,00
5	SS 80 t/ha	4.77	0.32	1.48	2.69	9.34	16.34	7,13
6	Compost (SS + sawdust (3:1)) – 60 t/ha	4.49	0.30	1.35	2.58	5.67	15.85	6,81
7	Compost (SS + straw (3:1)) – 20 t/ha	4.29	0.22	1.28	2.29	4.66	15.46	6,81
8	Compost (SS + straw (3:1)) – 40 t/ha	4.36	0.24	1.17	2.29	5.16	15.80	6,70
9	Compost (SS + straw (3:1)) – 60 t/ha	4.44	0.29	1.19	2.37	5.33	16.06	6,69
10	Compost (SS + straw (3:1) + cement dust 10%) – 40 t/ha	4.58	0.25	1.26	2.33	5.06	15.96	6,60
LSD 05		0.14	0.02	0.2	0.04	0.4	0.9	0.3
MPC maximum permissible concentration		6.0	0.7	4.0	5.0	23.0	-	3.0

after re-introduction of SS under energy willow after a four-year growing cycle reflects a slight effect on increasing the content of mobile forms of Pb, Fe, Co, Ni; however, the content of mobile forms of Cd, Zn, Cu varies within significant limits. The content of mobile forms of heavy metals is also influenced ambiguously by the form of application of SS. Application of SS in fresh form in the highest doses - 60–80 t/ha (options 4 and 5) leads to the highest indicators of the content of mobile forms of heavy metals in the soil.

The accumulation of mobile forms of each element in the soil has its own characteristics. The increase in the content of mobile Pb compounds slightly depends on the dose and form of SS application. A reliable tendency to decrease this indicator is observed in the variants where SS compost with straw and the appropriate amount of mineral fertilizers were applied. However, in the version where SS compost with sawdust of coniferous trees was applied, the decrease in content was unreliable. The highest values of Pb content (4.58 mg/kg of soil) were recorded in variants with a dose of 60 t/ha of SS and 40 t/ha of compost (SS + straw (3:1) + cement dust 10%). The content of mobile forms of Co and Ni varies between 2.1–2.7 and 1.1–1.5 mg/kg of soil, respectively. The content of mobile forms of Fe increases twice in all options where fertilizers were applied compared to the control option. However, the dose and form the application of SS has a negligible effect on this indicator. The content of mobile forms of Zn and Cu in the variant with the highest dose of SS application (option 5) increases almost twice compared to other variants of the experiment, and the application of composts with SS reduces the content of mobile forms of these elements in the soil almost to the indicators of the control option.

It should be noted that the content of all heavy metals did not exceed the maximum allowable concentrations of heavy metals, except for Cu [Bilous et al., 2012, Lopushniak et al., 2022]. However, as can be seen later in the text, this element had a minor effect on increasing the phytotoxicity of sod-podzolic soil.

Plants are the primary links of trophic chains, perform an important role in absorbing various pollutants and are constantly affected by them due to their fixation on the substrate. That is why plants are considered the most convenient objects for soil biomonitoring. Soil toxicity was determined by the method of Grodzinsky [Lopushniak et al., 2026., 2020]. Radishes were used as test crops *(Raphanus sativus*), white cabbage (*Brassica oleracea var. capitata*) and watercress (*Lepidium sativum L.*).

On the basis of the conducted research, the ambiguity of different types of plants on the test reaction was revealed.

A high sensitivity to the effect of SS as a soil pollutant was established: the root length and shoot height of common radish under the cultivation of willow energy was 0.58–0.60 cm and 0.28–0.31 cm, respectively. The coefficient of variation of morphological indicators was about 1.36% for root length and 0.7% for shoot height. The root length and shoot height of white cabbage were 4.90–5.41 cm and 2.49–2.65 cm, respectively. The coefficient of variation of morphological indicators for cabbage plants was about 9.83% for root length and 3.61% for shoot height (Table 2).

Table 2. Sensitivity of test cultures after re-introduction of sewage sludge in sod-podzolic soil for growing energy willow

Options	*Raphanus sativus*			
	root length		shoot height	
	min-max, sm	Coefficient of variation, %	min-max, sm	Coefficient of variation, %
No fertilizers (control)	0.58–0.60	1.36	0.28–0.31	0.7
$N_{100}P_{100}K_{100}$	0.50–0.55	1.25	0.25–0.28	0.63
SS 40 t/ha	0.43–0.48	1.10	0.21–0.23	0.53
SS 60 t/ha	0.40–0.43	0.98	0.20-0.24	0.54
SS 80 t/ha	0.39–0.42	0.95	0.19–0.20	0.45
Compost (SS + sawdust (3:1)) – 60 t/ha	0.44–0.45	1.03	0.22–0.23	0.53
Compost (SS + straw (3:1)) – 20 t/ha	0.47–0.49	1.11	0.23–0.25	0.57
Compost (SS + straw (3:1)) – 40 t/ha	0.45–0.47	1.02	0.22–0.24	0.55
Compost (SS + straw (3:1)) – 60 t/ha	0.41–0.43	0.98	0.20–0.23	0.53
Compost (SS + straw (3:1) + cement dust 10%) – 40 t/ha	0.43–0.45	1.02	0.22–0.23	0.53

Table 3. Levels of toxicity of sod-podzolic soil with re-introduction of sewage sludge during the cultivation of energy willow, in percent

Options	Phytotoxic effect			Level of toxicity
	Raphanus sativus	*Brassica oleracea var. capitata*	*Lepidium sativum L*	
1. Без добрив (контроль)	20	18	21	Weak
No fertilizers (control)	27	25	30	Average
$N_{100}P_{100}K_{100}$	44	40	44	Above average
SS 40 t/ha	45	41	45	Above average
SS 60 t/ha	46	42	45	Above average
SS 80 t/ha	37	38	38	Average
Compost (SS + sawdust (3:1)) – 60 t/ha	36	34	34	Average
Compost (SS + straw (3:1)) – 20 t/ha	37	36	37	Average
Compost (SS + straw (3:1)) – 40 t/ha	38	39	37	Average
Compost (SS + straw (3:1)) – 60 t/ha	37	38	39	Average
least significant difference 0,5	1.6	1.2	1.7	

The conducted soil analysis shows that the levels of inhibition of the growth processes of phytoindicators in the test options with repeated application of composts (options 6–10); although they range from 37 to 40% for radish, white cabbage and watercress, they determine the toxicity of the samples soil at the "average" level (Table 3). In the soil samples with the introduction of SS in a dose of 40–80 t/ha, the toxicity of the soil was noted in the range from 41 to 45%, the toxicity of the soil samples was at the "above average" level.

Studying the complex effect of the content of all heavy metals on phytotoxicity and productivity due to its multifactorial nature and the different degree of influence of each factor is a difficult task. From the point of view of the efficiency of processing experimental data and obtaining the results that would meet the conditions of adequacy, optimality and quality, the solution of such a problem requires the use of a combination of regression and factor analysis methods. The only difference is that Mathcad Equations and Graphs recalculate mathematical expressions and change graphs.

The results of the conducted research can be visualized with the help of functions and data with the help of three-dimensional graphs.

Grouping of factors (Table 4) into groups of three factors place was carried out taking into account the significance of each factor (index of metal content and phytotoxicity) and correlations between these factors.

Table 4. Parameters of the equations of the influence of the content of heavy metals in the soil on its phytotoxicity and the value of the productivity of the energy willow with the application of SS

Basic functions b_i	Model parameters	The value of the model parameter $\hat{B}ij$				The value of the model parameter $\hat{B}ij$			
		Phytotoxicity				Productivity			
		NiPbCu	NiPbCd	NiPbZn	NiPbFe	NiPbCu	NiPbCd	NiPbZn	NiPbFe
1	B_{i1}	-15.97	129.226	129.226	129.226	129.226	12.165	-7.38	13.935
c_c	B_{i2}	-1.998	-39.882	-39.882	-39.882	-39.882	5.137	2.956	-4.819
c_s	B_{i3}	21.723	47.948	47.948	47.948	47.948	23.367	7.375	-0.688
c_n	B_{i4}	1.292	-20.018	-20.018	-20.018	-20.018	88.087	-0.253	0.055
$c_s c_n$	B_{i5}	–	–	–	–	–	–	–	–
$c_n c_c$	B_{i6}	–	4.492	4.492	4.492	4.492	19.819	–	–
$c_s c_c$	B_{i7}	2.493	-11.019	-11.019	-11.019	-11.019	-7.357	-1.824	
c_n^2	B_{i8}		–	–	–	–	–	0.02	–
c_s^2	B_{i9}	-13.54	–	–	–	–	3.22	–	–
c_c^2	B_{i10}	–	2.721	2.721	2.721	2.721	–	–	0.583
$c_c c_n c_s$	B_{i11}	–	–	–	–	–	–	–	–

The processing of research results for indicators of the influence of metal content on phytotoxicity was performed in the class of polynomials of the third order, since increasing the order of the polynomial reduces the adequacy of the model:

$$g(c_c, c_s, c_n) = Bb(c_c, c_s, c_n) \quad (1)$$

where: $b(c_c, c_s, c_n) = (1, c_c, c_s, c_n, \ldots, c_n^3)^T$ – vector of basis functions;

– concentrations of the corresponding metals (according to Table 4). The parameters of the polynomial model (1) are determined in a class of various combinations of basis functions from the condition of minimizing the variance σ_ε^2 adequacy

$$min\left\{\sigma_\varepsilon^2 = \frac{1}{N - r_\varepsilon}\sum_{i=1}^{N}\left[\begin{matrix} B_j^\varepsilon b(c_{ci}, c_{si}, c_{ni}) - \\ -g_{ji} \end{matrix}\right]^2\right\} \Rightarrow \quad (2)$$

$$\Rightarrow \{\hat{B}_j^\varepsilon, \hat{\varepsilon}\}, \varepsilon \in E$$

where: r_ε – the number of estimated parameters in the models (9);

B_j^ε–j-a row of the matrix Bε parameters of the model (1);

c_{ci}, c_{si}, c_{ni} – experimental data according to the research plan;

g_{ji} – results of measurements of the i-th indicator of metal content in the i-th experiment of the research plan.

The class E is formed from polynomials that contain various combinations of products, squares, and cubes of the initial factors (the content of mobile forms of various heavy metals in the soil) and consisted of 1,300 models. Of all the models, 4 were chosen, which best visually reflect the correlation-regression relationship between these indicators (Fig. 1).

Figure 1 shows a section of a three-dimensional surface, an image on the surface (in x, y coordinates) of the digital value of phytotoxicity as a

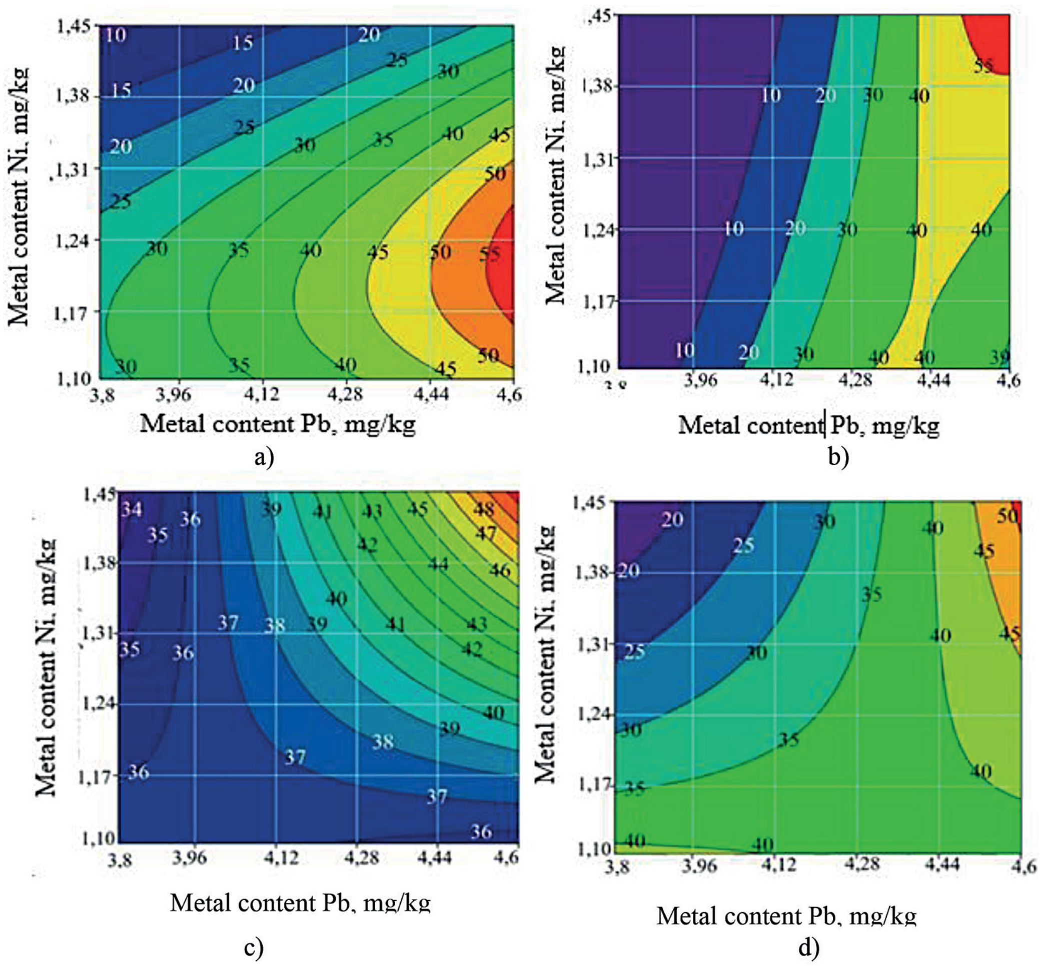

Figure 1. Dependence of phytotoxicity on the content of mobile forms of heavy metals in the soil, (a) fixed value of Cu – 6.95 mg/kg of soil, (b) fixed value of Zn – 5 mg/kg of soil, (c) fixed value of Cd – 0.25 mg/kg of soil, (d) fixed value of Fe – 15.5 mg/kg of soil

variable from the content of mobile forms of heavy metals, which depends on three values (x, y, z).

Figure 1a shows a plane cross-section of the dependence of the level of phytotoxicity of the soil, with a fixed value of Cu - 6.95 mg/kg of soil, which changes according to the change in the indicators of the content of lead and nickel in the soil. Figure 1b shows a plane cross-section of the dependence of soil phytotoxicity content at a fixed value of Zn - 5 mg/kg of soil, which varies within 21-45% according to the value of lead and nickel in the soil in different variants of the experiment.

Figure 1c shows a plane cross-section of the dependence of the level of soil phytotoxicity, at a fixed value of Cd – 0.25 mg/kg of soil, which varies from 21% in the control version to 45% in the version with the introduction of SS of 80 t/ha according to the value of the lead content of 4.77 mg/kg soil (option 5) and nickel 1.48 mg/kg soil (option 5).

Figure 1g shows a plane section of the dependence of the level of phytotoxicity, at a fixed value of Fe – 15.5 mg/kg of soil, which varies from 21% in the control variant to 44–45% in the variants with the introduction of SS – 40–80 t/ha, according to the value of the content lead 4.44 – 4.77 mg/kg soil (options 3 – 5) and nickel 1.29 – 1.48 mg/kg soil (option 5).

On the basis of the presented results (Fig. 1), it can be stated that the greatest increase in the level of phytotoxicity of the soil is facilitated by the application of SS with an increased content of Pb, Cu, and Cd. At the same time, such heavy metals as Ni, Zn and Fe do not cause sharp increases in the phytotoxicity index.

The dependence of the productivity of the energy willow on the content of mobile forms of heavy metals in the soil (Fig. 2) is displayed on a section of a three-dimensional surface, the image on the surface (in coordinates x, y) of the value (productivity of the energy willow), which depends on three values (x, y, z). Figure 2a shows the changes in the productivity of willow energy with the changes in the content of mobile forms of Ni in the range of 1.1–1.45 mg/kg of

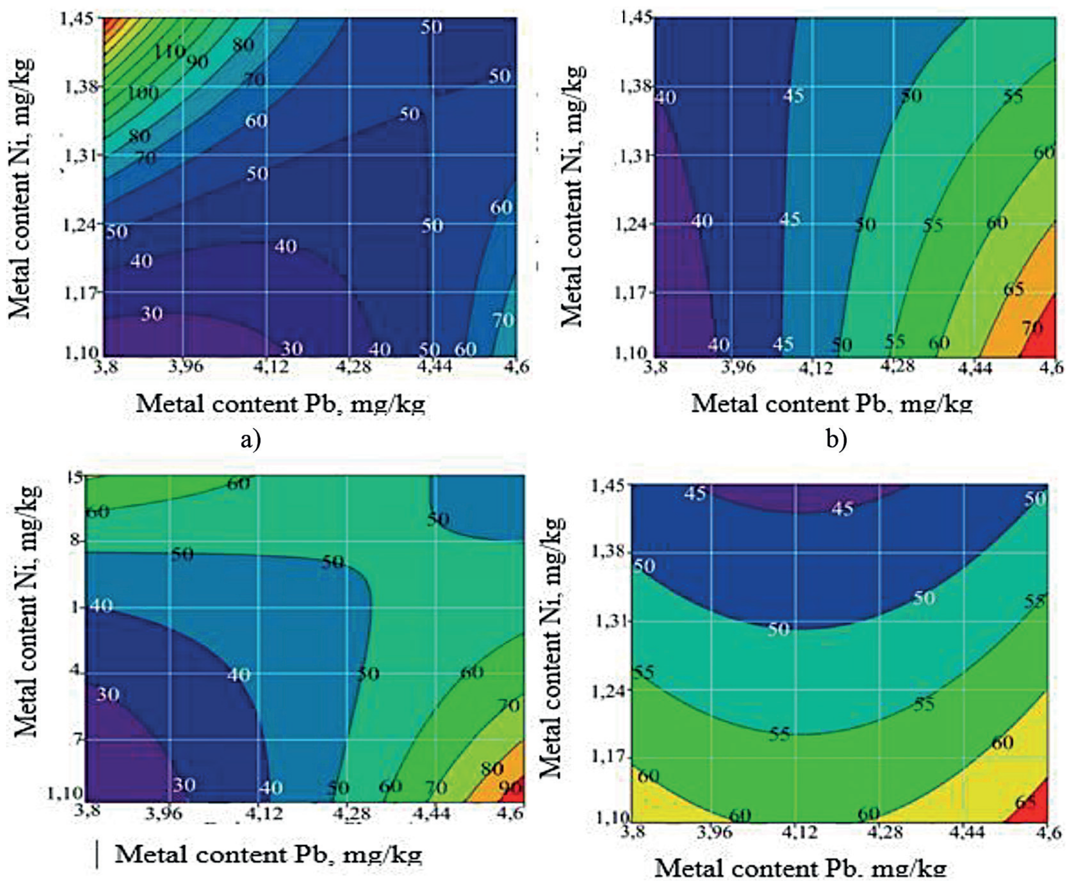

Figure 2. The dependence of energy willow productivity on the content of mobile forms of metals in the soil, (a) fixed value of Cu – 6.95 mg/kg of soil, (b) fixed value of Zn – 5 mg/kg of soil, (c) fixed value of Cd – 0.25 mg/kg of soil, (d) fixed value of Fe – 14.5 mg/kg of soil

soil according to the research options, and mobile forms of Pb from 3.8 to 4.6 mg/kg of soil for the corresponding value Cu (6.95 mg/kg soil).

Figure 2b graphically displays the mathematical model of the productivity of willow energy under the condition of applying SS at the rate of 40–80 t/ha. The content of mobile forms of the chemical element Ni varies in the range of 1.1–1.45 mg/kg of soil according to the variant of research, and Pb from 3.8 to 4.6 mg/kg of soil with the corresponding fixed value of the content of mobile forms of Zn (5 mg/ kg of soil). Figure 2c shows how the productivity of willow energy varies with changes in the content of mobile forms of Ni in the range from 1.1 to 1.45 mg/kg of soil, and Pb – from 3.8 to 4.6 mg/kg of soil at the corresponding fixed value of Cd (0.25 mg/kg of soil). Figure 2d shows the change in the productivity of willow energy, depending on the content of mobile forms of Ni in the soil in the range from 1.1 to 1.45 mg/kg of soil, and Pb - from 3.8 to 4.6 mg/kg of soil for the corresponding value of Fe (14.5 mg/kg soil).

As a result of observations, it was established that the yield of wood biomass in research options after a repeated cycle of energy willow use during 4 years of vegetation was distinguished by the following features. In the control version, without fertilizer, productivity was 43.5 t/ha. With the introduction of mineral fertilizers, productivity increased to 51.2 t/ha, which significantly exceeded the biomass yield in the control variant. In general, in all the options where fertilizers were applied, productivity increased significantly compared to the control option by 7.7–17.4 t/ha. The smallest significant difference between the indicators of research options was 4.23 t/ha of energy willow plant biomass (Fig. 3).

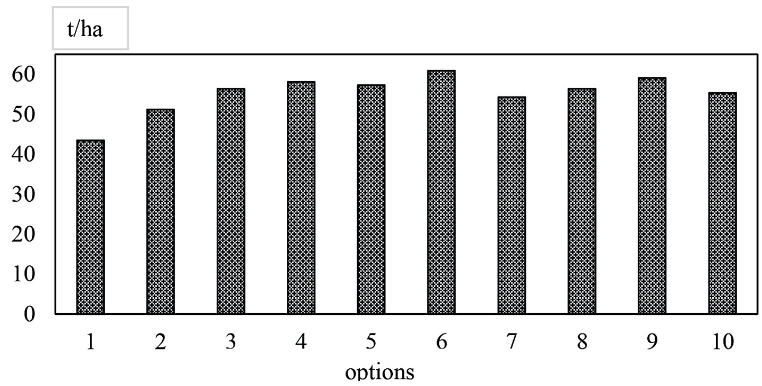

Figure 3. Productivity of wood biomass of energy willow depending on repeated application of SS and composts based on it on sod-podzolic soil, for 2018–2021, t/ha

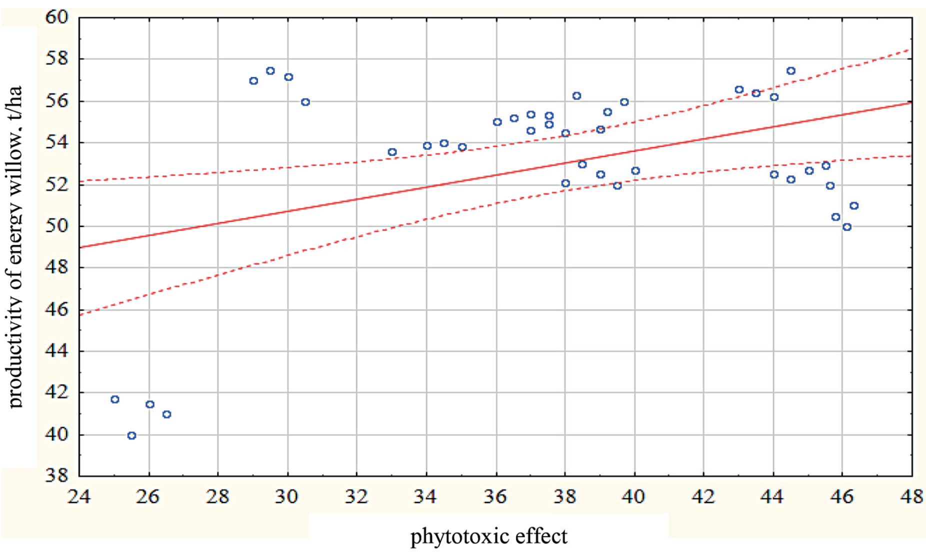

Figure 4. Dependence of energy willow productivity after a repeated cycle of use on the phytotoxic effect due to the use of fresh SS (options 1, 3, 4, 5)

The highest productivity indicators were recorded in the variant where compost (SS + sawdust (3:1)) was applied at the rate of 60 t/ha, which ensured a wood biomass yield of 61 t/ha. Application of SS composts with straw of grain crops led to an increase in the productivity of willow energy to the level of 54–59 t/ha, which was almost at the level of application of fresh SS (56.4–58.1 t/ha). It should be emphasized that the increase in the dose of applying fresh SS from 40 to 80 t/ha did not lead to a directly proportional increase in biomass productivity. In the variant with the application of 80 t/ha, the productivity of biomass even decreased, compared to the application of 60 t/ha of fresh wood. This may be related to the change in phytotoxicity of the soil, which increases in the options with the introduction of SS without prior biodegradation through composting, which is confirmed by the multiple regression equations of the dependence of these indicators in the options (Fig. 4).

This dependence can be described by the following multiple regression equation:

$$y = 41.9849 + 0.2907 \cdot x$$

where: y – productivity of energy willow, t/ha; x – phytotoxic effect, %

For this dependence, the multiple coefficient of determination is $R^2 = 0.81$, and the correlation coefficient is $r = 0.786$, which indicates a close dependence of energy willow productivity on the growth of phytotoxicity of sod-podzolic soil.

CONCLUSIONS

The obtained regression dependences show that the formation of phytotoxicity of sod-podzolic soil is most affected by an increase in the content of Pb, Cd. However, the introduction of the norm of fresh organic matter within 80 t/ha did not lead to an increase in the content of these heavy metals above the maximum permissible concentrations. The maximum predicted productivity, depending on the content of mobile forms of heavy metals in the soil, is about 60 t/ha at a content of Cd = 0.25; Ni = 1.1 Pb = 4.6 mg/kg soil.

As the phytotoxicity of the soil increases to an above-average level (phytotoxic effect 40–46%), the intensity of biomass accumulation of energy willow slows down somewhat. The dependence of energy willow productivity after a repeated cycle of use on the phytotoxic effect due to the use of fresh SS (options 1, 3, 4, 5) is characterized by a multiple coefficient of determination $R^2 = 0.81$, and a correlation coefficient $r = 0.786$, which indicates a close dependence of energy willow productivity from phytotoxicity of sod-podzolic soil.

Thus, during the planning and implementation of phytoremediation measures to increase the bioproductivity of sod-podzolic soils through the application of SS as a fertilizer for energy crops, it is advisable to monitor the phytotoxicity of the soil cover, since the growth of the phytotoxic effect to an above-average level causes a slowdown in the intensity of the accumulation of phytomass of energy crops, in particular willow energy

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