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Assessment of the micronutrient status of arable land in Rivne region for the establishment of special raw material zones

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Abstract. Soil contamination by heavy metals and micronutrient deficiency in agricultural land reduce product quality and limit its suitability for infant and dietary nutrition, which necessitates a comprehensive study of micronutrient content in soils. The aim of the study was to assess the micronutrient status of arable land in Rivne region for the establishment of special raw material zones. The research was conducted on the basis of agrochemical monitoring data for 2015-2020 using correlation and regression

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analyses. It was established that in the Polissia zone the micronutrient content was as follows: manganese levels ranged from 4.6 to 17.1 mg/kg, copper from 0.1 to 0.75 mg/kg, cobalt from 0.18 to 2.57 mg/kg, and cadmium from 0.08 to 0.5 mg/kg; in the Forest-Steppe zone, manganese ranged from 10.08 to 21 mg/kg, copper from 0.08 to 0.23 mg/kg, cobalt from 0.24 to 0.42 mg/kg, and cadmium from 0.05 to 0.14 mg/kg. Correlation and regression analyses showed that the dynamics of changes in these elements exhibited significant fluctuations described by stochastic models with weak and strong correlation relationships. It was determined that most districts within the studied zones are unsuitable or only marginally suitable for the establishment of special raw material zones due to low copper and cadmium content; in the Forest-Steppe zone, nine districts were assessed as unsuitable. To ensure the production of raw materials suitable for infant and dietary nutrition, it is necessary to maintain high levels of manganese, copper, and cadmium availability. The obtained data make it possible to substantiate measures aimed at optimising soil micronutrient status and forming special raw material zones for the production of safe infant and dietary products

Keywords: soil quality; assessment of soil suitability; soil contamination; infant nutrition; product quality; raw material production

INTRODUCTION

The issue of establishing special raw material zones (SRMZs) in Ukraine stems from insufficient production volumes of raw materials for the manufacture of infant food products, which currently fail to satisfy even half of the existing demand. At the same time, due to the difficult socio-economic situation caused by the full-scale invasion of Ukraine by the Russian Federation in 2022, the process of granting SRMZ status to agricultural producers cultivating raw materials suitable for infant and dietary food production has slowed considerably. Addressing this issue should be facilitated through the implementation of strategic national priorities, in particular the organisational, social, and economic foundations of state policy in the field of providing children with adequate, high-quality, and safe nutrition in accordance with Law of Ukraine No. 142-V (2006). Equally important is compliance with the procedures for granting producers the status of SRMZs for the production of raw materials used in the manufacture of infant and dietary food products, in accordance with Resolution of the Cabinet of Ministers of Ukraine No. 1195 (2007).

An important aspect of ensuring the quality of such raw materials is their micronutrient composition, which directly influences the nutritional value of the products. The widespread deficiency of micronutrients in humans is attracting increasing attention from the international scientific community. One promising approach to addressing micronutrient deficiencies in food systems is the biofortification of crops (Mandial *et al.*, 2023). In particular, L. Galić *et al.* (2025) emphasised in their study that optimal human health depends on an adequate dietary intake of essential micronutrients, specifically selenium, zinc, copper, boron, manganese, molybdenum, iron, nickel and chlorine. At the same time, these elements play an important role in plant metabolic processes, and their deficiency is widespread in various agroecosystems around the world. There have been numerous cases where trace elements are found in soils at toxic concentrations, posing a risk to plant growth and human health. There is a need to understand the complex relationship between soil quality and human health, which occurs through the transfer of essential trace elements from the soil, as an abiotic environment, into the biotic systems of plants and animals that make up the human diet.

The increasing intensity of the dispersion of heavy metals and micronutrients in the environment and their involvement in the biogenic cycle has been documented both globally and in Ukraine. The spread of micronutrients in the environment is caused by both natural and anthropogenic factors. Natural causes include the weathering of rocks and minerals and soil erosion, while anthropogenic factors include human economic activities such as industrial emissions, the application of organic and mineral fertilisers to soils, and the widespread use of pesticides containing impurities of heavy metals and micronutrients. S. Razanov *et al.* (2022) also emphasised that the occurrence and accumulation of micronutrients in soils depend on the chemical forms in which they are present in parent materials or enter soils through atmospheric precipitation and dust, while the level of their toxicity within the “soil-plant-animal-human” system is determined by their content in both total and mobile forms. Similar conclusions were reported by (Emam & Soliman, 2022).

Despite the importance of ensuring adequate micronutrient availability in arable land for obtaining high yields and products of appropriate biological quality suitable for infant and dietary nutrition, the assessment of their content and spatial-temporal dynamics in the soils of Rivne region remains insufficiently studied. In this regard, the aim of the study was to assess the level of micronutrient availability in the arable lands of Rivne region for the subsequent establishment of SRMZs. To achieve this aim, the following objectives were set: (1) to evaluate the dynamics of changes in micronutrient content and the level of micronutrient availability in the arable lands of the Polissia and

Forest-Steppe zones of the region; (2) to determine the suitability of these lands, according to their micronutrient content, for the formation of SRMZs; (3) to substantiate the feasibility of measures aimed at restoring the optimal balance of micronutrients in arable soils.

LITERATURE REVIEW

Many scientists from other countries, including G. Ondrasek *et al.* (2025), emphasise that industrialisation, urbanisation, and intensive agriculture accelerate the global accumulation of heavy metals in soils. This is confirmed by the results of studies conducted in various countries around the world. Thus, the study by J. Qi *et al.* (2024) highlighted that industrial zones and chemical production in China increase the risk of soil contamination by heavy metals, among which cadmium poses the greatest threat due to its high concentration and ability to accumulate in plants, thereby negatively affecting soil quality and, consequently, human health. In the work of H. Binner *et al.* (2023), it was established that metals such as lead, zinc, chromium, and nickel exceed national safety limits in urban soils of Italy, Serbia, and the United Kingdom, thereby reducing water quality and posing a threat to human health. According to T.T.H. Truong *et al.* (2025), industrialisation and agricultural development in southern Vietnam contribute to increased concentrations of heavy metals in soils. High concentrations of anthropogenic arsenic, cadmium, manganese, lead, and zinc exceeding permissible limits were identified by A.M.A. Ahogle *et al.* (2023) in peri-urban agricultural soils of Nairobi, creating risks to public health. Similar trends in the accumulation of heavy metals in soils may be caused by various sources of input, particularly agrotechnogenic factors. For example, increases in their concentrations in Belgian soils by 1.7-5.3 times were observed during winter, which has been associated with manure application (Luo *et al.*, 2025).

Elevated concentrations of heavy metals in the human body are associated with metabolic disorders. In particular, the study by S. Cortés *et al.* (2021), conducted among the population of Chile, established that high concentrations of inorganic arsenic and nickel in blood are associated with elevated glucose levels and an increased risk of metabolic diseases. Research by R. Wu *et al.* (2024) indicated the significant role of chronic arsenic exposure in the development of gestational diabetes, while increased blood lead levels, as noted in the work of S. Heidari *et al.* (2022), result in reduced IQ in children under 12 years of age. V.A. Florez-Garcia *et al.* (2022) established that elevated cadmium levels are associated with an increased risk of breast cancer in women, while even low concentrations of mercury are capable of causing long-term adverse effects on the nervous, respiratory, and cardiovascular systems (Charkiewicz *et al.*, 2025). High serum copper levels are associated with an increased risk of stroke, myocardial infarction, and cardiovascular mortality (Muñoz-Bravo *et al.*, 2023). According to F.U. Haque *et al.* (2023), micronutrients such as copper, nickel, and zinc play a key role in crop production and food quality. It should also be noted that the minimum risk associated with human consumption of micronutrients through food products is achieved under conditions where the adequacy criterion, namely the boundary between deficiency and excess, is maintained.

At the same time, most studies provide insufficient coverage of the causes underlying both micronutrient deficiency and excess in the human body, particularly their relationship with soil properties. Manganese deficiency contributes to the development of diabetes and convulsive syndrome; zinc deficiency leads to congenital malformations in infants; a lack of molybdenum in the body results in intellectual disability; cobalt deficiency causes vitamin B12 deficiency and atrophy of the intestinal mucosa; while copper deficiency leads to disorders in the formation of the cardiovascular system, skeleton, and central nervous system, and aggravates hereditary diseases and cholesterol accumulation. Research by D. Jin *et al.* (2024) indicated that zinc deficiency is associated with a high prevalence of infectious diseases, whereas selenium deficiency may contribute to increased incidence of cardiovascular diseases among adults in the United States (Liang *et al.*, 2025). Since both deficiency and excess of micronutrients in the human body cause various pathological conditions, there is a need for their proper regulation within food chains, namely their content in soils, crop and livestock products, food products, dietary nutrition, and subsequent intake by humans, which is consistent with the concept of micronutrient transfer within the "soil-plant-human" system (Kabata-Pendias, 2004). This will contribute to the formation of a balanced micronutrient composition in the human body, which is a prerequisite for the sustainable functioning of its cells, tissues, organs, and systems, as well as for ensuring active longevity.

The content of micronutrients in soils is formed under the influence of a number of natural and anthropogenic factors. The content of mobile forms of micronutrients such as arsenic, chromium, copper, iron, magnesium, molybdenum, nickel, lead, strontium, and zinc is positively influenced by seasonal changes during winter-spring (wet seasons) compared with summer-autumn (dry seasons), whereas under drought conditions manganese, vanadium, and cadmium demonstrate increased extractability. Similar processes of mobilisation and transformation of micronutrients in soils are also largely regulated by soil properties, particularly the content of organic matter. According to the studies of S.S. Dhaliwal *et al.* (2019), organic matter determines the redistribution of zinc, copper, iron, manganese, boron, and molybdenum, since its accumulation promotes the transformation of adsorbed fractions into forms more available to plants.

Agrotechnical measures, particularly fertiliser application, play a significant role in the formation of micronutrient content in soils. It has been established, according to summarised data, that mineral fertilisers contain the following micronutrients: phosphorite meal contains manganese up to 1,800 mg/kg, zinc up to 1,000 mg/kg, copper up to 300 mg/kg, and cobalt up to 10 mg/kg. Simple superphosphate contains manganese up to 1,000 mg/kg, zinc up to 600 mg/kg, copper up to 270 mg/kg, and cobalt up to 10 mg/kg. Potassium sulphate contains manganese up to 13 mg/kg, zinc up to 8 mg/kg, copper up to 10 mg/kg, and cobalt up to 0.1 mg/kg. Calcium carbonate contains manganese up to 1,200 mg/kg, zinc up to 450 mg/kg, copper up to 125 mg/kg, and cobalt up to 0.4 mg/kg. Under conditions of irrational application of organic and mineral fertilisers to arable land and uncontrolled use of pesticides, contamination by heavy metals and micronutrients occurs (Römheld, 1991; Lisoval *et al.*, 2002). As a result, an imbalance of micronutrients available to plants is observed in arable soils due to certain elements occurring either in deficient states (low or very low availability) or in excessive states (high or very high availability).

MATERIALS AND METHODS

The methodological basis of the study consisted of a set of approaches and methods aimed at assessing the content and dynamics of micronutrients in soils. The study was conducted during 2020-2025 in Rivne region, Ukraine, within the Polissia and Forest-Steppe zones (GPS coordinates 50°59′ N, 26°24′ E). In the Polissia zone, sod-podzolic sandy loam soils and grey forest podzolised light loam soils predominate. The Forest-Steppe zone is characterised by typical chernozems and podzolised light loam chernozems, which are mainly used for cultivating cereal and industrial crops (winter wheat, soybean, maize, sunflower, rapeseed, barley, and oats). Soil samples for determining the content of manganese, copper, cobalt, and cadmium were collected using the "envelope" method at a distance of no less than 30 m from roads. The composite sample was formed from 20-25 point samples weighing 400-500 g. The sampling depth was no less than 20 cm.

The location of the composite sample collection was linked to cartographic reference objects using a GPS receiver and recorded in the field according to the coordinate system established by DSTU 4287:2004 (2004). The content of micronutrients in soil samples was determined by the atomic absorption method in accordance with DSTU 4770.6:2007 (2007), 4770.1:2007 (2007), 4770.5:2007 (2007), and 4770.3:2007 (2007) at the measurement laboratory for analytical support of agrochemical and agroecological research at the Rivne branch of the State Soil Protection Agency, which holds a certificate of conformity of the measurement system with the requirements of DSTU ISO 10012:2005 under No. 0117 dated 31 March 2013, issued by Testmetrstandart LLC. The selection of experimental data for 2015-2020 on micronutrient content in the soils of the region included weighted average indicators calculated from three replications, while the error values in determining micronutrient content in soils did not exceed those specified in the certificate, namely: manganese ⩽21%, copper ⩽9%, cobalt ⩽7%, and cadmium ⩽30%. The study also employed methods of retrospective analysis and comparison of data (2015-2020), generalisation (directions of changes in micronutrient content over time), analogy (investigation of similarities in the dynamics of changes in the content of individual micronutrients), and mathematical methods (correlation and regression analyses of micronutrient content dynamics using Microsoft Office Excel 2010), including determination of the correlation coefficient at the 5% significance level and testing of the null hypothesis H_0 when $F_{actual} > F_{theoretical}$.

The qualitative assessment of the obtained correlation coefficients was determined according to a scale ranging from 0 to 1: 0 – no relationship; 0.01-0.20 – very weak relationship; 0.21-0.50 – weak relationship; 0.51-0.70 – moderate relationship; 0.71-0.90 – strong relationship; and 0.91-1.0 – very strong relationship. The suitability of arable land for SRMZ requirements was determined according to the standard indicators of the content of mobile forms of micronutrients, namely: suitable – not lower than manganese 10.1 mg/kg, copper 0.21 mg/kg, cobalt 0.16 mg/kg, and cadmium 1.01 mg/kg; limited suitability – not lower than manganese 7.1 mg/kg, copper 0.16 mg/kg, cobalt 0.11 mg/kg, and cadmium 0.51 mg/kg; unsuitable – lower than manganese 7.0 mg/kg, copper 0.15 mg/kg, cobalt 0.1 mg/kg, and cadmium 0.5 mg/kg. The status of suitability for establishing SRMZs was assigned according to the micronutrient present at the minimum level. To assess the level of soil micronutrient availability, the standard grouping presented in Table 1 was used.

***Table 1**. Levels of agricultural crop supply with mobile forms of micronutrients, mg/kg*

Micronutrient	Very low	Low	Medium	Elevated	High	Very high
Manganese	<5.1	5.1-7.0	7.1-10	10.1-15.0	15.1-20	>20
Copper	<0.11	0.11-0.15	0.16-0.20	0.21-0.30	0.31-0.5	>0.5
Cobalt	0.071	0.071-0.1	0.11-0.15	0.16-0.20	0.21-0.3	>0.3
Cadmium	0.1-0.2	0.21-0.50	0.51-1.0	1.01-1.50	1.51-2.0	>2.0

***Note:** the extractant solution was an ammonium acetate buffer solution with pH = 4.8*
***Source:** developed by the authors*

The indicated approaches and assessment criteria were used to analyse the micronutrient availability of arable land and to determine its suitability for the establishment of special raw material zones.

RESULTS AND DISCUSSION

Analysis of soil survey data from the arable lands of Rivne region showed that the soil cover of the districts within the Polissia zone is predominantly represented by sod-podzolic, gleyed, in some areas drained, sandy loam, meadow, and less frequently meadow-bog soil types. The Forest-Steppe zone is represented by grey forest podzolised light loam soils, typical chernozems, and podzolised light loam chernozems. According to agrochemical monitoring, the content of mobile forms of micronutrients in the soils of the districts within the Polissia zone during 2015-2020 varied within the following ranges: manganese from 4.6 to 17.1 mg/kg; copper from 0.1 to 0.75 mg/kg; cobalt from 0.18 to 2.57 mg/kg; and cadmium from 0.08 to 0.5 mg/kg (Table 2).

***Table 2**. Content of mobile forms of micronutrients in the soils of the Polissia zone, mg/kg*

District	Element	2015	2016	2017	2018	2019	2020
Berezne	Mn	9.23	14.6	14.9	12.9	12.75	12.7
	Cu	0.18	0.19	0.22	0.17	0.15	0.17
	Co	0.41	0.42	0.48	0.35	0.38	0.35
	Cd	0.12	0.12	0.11	0.12	0.11	0.11
Volodymyrets	Mn	4.60	6.70	7.90	6.40	6.24	6.30
	Cu	0.22	0.23	0.25	0.23	0.26	0.26
	Co	0.41	0.40	0.38	0.40	0.36	0.30
	Cd	0.10	0.10	0.11	0.12	0.09	0.10
Dubrovytsia	Mn	6.83	15.2	15.8	14.68	15.0	15.1
	Cu	0.11	0.10	0.12	0.11	0.12	0.12
	Co	0.22	0.20	0.24	0.22	0.25	0.31
	Cd	0.07	0.08	0.08	0.08	0.08	0.08
Zarichne	Mn	12.0	10.1	13.4	12.5	12.0	12.0
	Cu	0.17	0.12	0.18	0.12	0.12	0.12
	Co	0.41	0.44	0.45	0.42	0.41	0.41
	Cd	0.12	0.27	0.28	0.25	0.20	0.18
Kostopil	Mn	15.3	18.3	18.0	17.2	16.9	17.1
	Cu	0.88	0.87	0.81	0.85	0.80	0.75
	Co	2.56	2.54	2.60	2.57	2.61	2.57
	Cd	0.55	0.54	0.49	0.53	0.55	0.50
Rokytne	Mn	10.48	14.6	16.0	14.0	14.0	14.0
	Cu	0.10	0.11	0.12	0.11	0.10	0.10
	Co	0.32	0.31	0.33	0.32	0.31	0.31
	Cd	0.11	0.12	0.12	0.11	0.10	0.10
Sarny	Mn	6.93	10.4	11.08	9.47	10.0	10.12
	Cu	0.15	0.17	0.19	0.16	0.17	0.18
	Co	0.20	0.20	0.24	0.21	0.21	0.18
	Cd	0.11	0.11	0.10	0.11	0.12	0.11

***Source:** compiled by the authors*

The ranges of variation in the content of mobile forms of micronutrients in the Forest-Steppe zone were as follows: manganese from 10.08 to 23.5 mg/kg; copper from 0.08 to 0.23 mg/kg; cobalt from 0.24 to 0.42 mg/kg; and cadmium from 0.05 to 0.14 mg/kg. The micronutrient content by district is presented in Table 3.

***Table 3**. Content of mobile forms of micronutrients in the soils of the Forest-Steppe zone, mg/kg*

District	Element	2015	2016	2017	2018	2019	2020
Hoshcha	Mn	16.2	18.6	19.0	15.83	15.41	15.46
	Cu	0.12	0.12	0.15	0.13	0.11	0.13
	Co	0.35	0.36	0.32	0.34	0.34	0.35
	Cd	0.05	0.07	0.08	0.07	0.05	0.06
Demydivka	Mn	18.3	19.0	21.1	19.63	20.03	20.2
	Cu	0.24	0.19	0.21	0.21	0.19	0.18
	Co	0.33	0.32	0.29	0.31	0.35	0.36
	Cd	0.09	0.09	0.09	0.08	0.09	0.09

Table 3. Continued

District	Element	2015	2016	2017	2018	2019	2020
Dubno	Mn	12.21	13.45	14.01	13.5	13.21	13.4
	Cu	0.11	0.09	0.09	0.10	0.10	0.08
	Co	0.23	0.29	0.31	0.28	0.30	0.34
	Cd	0.12	0.12	0.12	0.11	0.11	0.11
Zdolbuniv	Mn	10.08	12.3	12.1	11.5	12.23	12.31
	Cu	0.1	0.14	0.16	0.13	0.15	0.14
	Co	0.33	0.37	0.23	0.31	0.27	0.30
	Cd	0.11	0.11	0.14	0.12	0.13	0.12
Korets	Mn	12.8	16.6	25.8	18.4	17.91	18.0
	Cu	0.18	0.18	0.28	0.21	0.19	0.20
	Co	0.31	0.36	0.29	0.32	0.34	0.31
	Cd	0.09	0.10	0.08	0.09	0.08	0.08
Mlyniv	Mn	16.9	16.8	16.3	17.65	18.02	17.9
	Cu	0.12	0.13	0.14	0.13	0.13	0.13
	Co	0.39	0.34	0.33	0.35	0.37	0.40
	Cd	0.09	0.10	0.11	0.10	0.11	0.12
Ostroh	Mn	12.6	11.2	19.69	14.5	15.1	15.0
	Cu	0.11	0.12	0.17	0.13	0.11	0.11
	Co	0.25	0.24	0.30	0.26	0.30	0.27
	Cd	0.11	0.10	0.10	0.10	0.10	0.10
Radyvyliv	Mn	12.4	15.8	16.3	15.9	15.31	15.2
	Cu	0.12	0.13	0.12	0.13	0.15	0.17
	Co	0.38	0.36	0.40	0.38	0.38	0.42
	Cd	0.12	0.12	0.12	0.14	0.15	0.14
Rivne	Mn	23.5	24.5	24.78	20.70	21.0	21.0
	Cu	0.16	0.21	0.19	0.19	0.21	0.23
	Co	0.46	0.44	0.41	0.44	0.40	0.42
	Cd	0.15	0.15	0.14	0.16	0.15	0.14

Source: *compiled by the authors*

Analysis of the dynamics of micronutrient content in the soils of the region demonstrates that during the observation period of 2015-2020 not only increases but also stabilisation or decreases in the investigated micronutrients occurred in soils (Tables 2, 3). According to D.R. Binde *et al.* (2025), the increase in the content of certain micronutrients and toxic elements in soils is caused by the intensification of agricultural land use, which serves as an important signal for long-term monitoring. Similar results regarding increases, stabilisation, and decreases in the content of individual elements in soils are demonstrated by Finnish monitoring studies reported by H. Soinne *et al.* (2022), as well as by the 25-year monitoring programme in Poland, where A. Wdowczyk *et al.* (2023) observed an increase in cadmium content in soils, while copper content remained relatively stable. Element losses in soils may be caused by filtration waters, whereas accumulation may occur through fertilisers or irrigation with wastewater, as demonstrated in the experiments of J. Wang *et al.* (2021), where increases in cadmium and lead content were recorded.

As shown in Tables 2 and 3, according to the content of mobile forms of micronutrients in the investigated soil types, the following descending sequence was formed: manganese > cobalt > copper > cadmium. Regarding micronutrients important for the nutrition of agricultural crops, manganese content varied from very low to very high availability, while cobalt content ranged from elevated to very high availability. The content of the moderately toxic micronutrient copper ranged from very low to very high availability, whereas the highly toxic cadmium ranged from very low to elevated availability.

As a result, an imbalance between the content of mobile forms of manganese, copper, cobalt, and cadmium is observed in the soils of the region at levels of very low, low, and very high availability, which, according to D. Hou *et al.* (2025), poses a threat to agricultural production and public health and requires regulation towards optimal values of elevated and high availability. The advisability of combining the analysis of micronutrients essential for plants with toxic elements was also noted by Q. Devalloir *et al.* (2023), who indicated that this approach provides a more comprehensive ecological picture; otherwise, conclusions may be oversimplified. Based on correlation and regression analyses, an assessment of the dynamics of changes in the content of mobile forms of micronutrients in the arable lands of the districts was carried out, the results of which are presented in Tables 4-7.

The table data demonstrate that the dynamics of micronutrient changes in the arable lands of most districts are described by stochastic models represented by increasing or decreasing linear trends with correlation coefficients ranging from very weak to strong relationships. Thus, in the arable lands of the districts of the Polissia zone, manganese content increased continuously during 2015-2020, most sharply in Dubrovytsia district and, conversely, more slowly in Kostopil district. According to the strength of the identified relationships, the arable lands of the Polissia zone in terms of annual manganese dynamics were assessed as follows: one district – 0.20, very weak relationship; five districts – 0.24-0.49, weak relationship; and one district – 0.62, moderate relationship. In the arable lands of the Forest-Steppe zone, manganese content changed inconsistently. In the soils of Hoshcha and Rivne districts, manganese content decreased during 2015-2020, whereas in the other seven districts it increased. According to the strength of the identified relationships, the arable lands of the Forest-Steppe zone in terms of manganese dynamics were assessed as follows: four districts – 0.28-0.46, weak relationship; three districts – 0.54-0.63, moderate relationship; and two districts – 0.76-0.77, strong relationship (Table 4).

***Table 4**. Relationships of changes in mobile forms of manganese in the arable lands of Rivne region, 2015-2020*

District	Equation	Correlation coefficient
	Polissia zone	
Berezne	$Y_1 = -552.0533 + 0.28x$	0.266
Volodymyrets	$Y_2 = -317.5962 + 0.1606x$	0.280
Dubrovytsia	$Y_3 = -2270.6181 + 1.1323x$	0.620
Zarichne	$Y_4 = -264.6857 + 0.1371x$	0.240
Kostopil	$Y_5 = -213.4381 + 0.1143x$	0.200
Rokytne	$Y_6 = -781.6248 + 0.3943x$	0.400
Sarny	$Y_7 = -747.7605 + 0.3754x$	0.490
	Forest-Steppe zone	
Hoshcha	$Y_8 = 964.3986 - 0.4697x$	-0.540
Demydivka	$Y_9 = -621.2786 + 0.3177x$	0.600
Dubno	$Y_{10} = -258.7776 + 0.1349x$	0.420
Zdolbuniv	$Y_{11} = -584.2738 + 0.2954x$	0.630
Korets	$Y_{12} = -1280.4419 + 0.6437x$	0.280
Mlyniv	$Y_{13} = -559.7433 + 0.286x$	0.770
Ostroh	$Y_{14} = -1052.2876 + 0.5289x$	0.340
Radyvyliv	$Y_{15} = -684.0562 + 0.3466x$	0.460
Rivne	$Y_{16} = 1583.5486 - 0.7737x$	-0.760

***Note:** Y – content of mobile forms of manganese, mg/kg; X – year of calculation (forecast)*
***Source:** developed by the authors*

According to the results of the regression analysis of changes in the dynamics of the content of mobile forms of manganese in the soils of the districts, linear equations were obtained with regression coefficients ranging from +0.1143 to +0.3943 in the Polissia zone and from +0.1349 to +0.6437 and from -0.4697 to -0.7737 in the Forest-Steppe zone. The obtained regression coefficients indicate a gradual increase in manganese content in the soils of the Polissia zone, whereas in the soils of the Forest-Steppe zone a more substantial increase in this micronutrient occurred in seven districts, while in two districts, conversely, its content decreased. The content of mobile forms of copper during 2015-2020 in the arable lands of Berezne, Zarichne, Kostopil, and Rokytne districts of the Polissia zone decreased, whereas in the other three districts it increased, most significantly in Volodymyrets district from 0.22 to 0.26 mg/kg. According to the strength of the identified relationships, the annual dynamics of copper in the arable lands of the Polissia zone were assessed as follows: three districts – 0.26-0.50, weak relationship; two districts – 0.58 and 0.65, moderate relationship; and two districts – 0.84 and 0.89, strong relationship. In the arable lands of the Forest-Steppe zone, copper content also changed inconsistently. Thus, in the arable lands of Hoshcha, Demydivka, Dubno, and Ostroh districts, copper content decreased, whereas in the other five districts it gradually increased. According to the strength of the identified relationships, the arable lands of the Forest-Steppe zone in terms of annual copper dynamics were assessed as follows: two districts – 0.08 and 0.16, very weak relationship; two districts – 0.30 and 0.34, weak relationship; two districts – 0.52 and 0.56, moderate relationship; and three districts – 0.74-0.87, strong relationship (Table 5).

Table 5. Relationships of changes in mobile forms of copper in the arable lands of Rivne region, 2015-2020

District	Equation	Correlation coefficient
	Polissia zone	
Berezne	$Y_1 = 12.8614-0.0063x$	-0.500
Volodymyrets	$Y_2 = -15.3219+0.0077x$	0.840
Dubrovytsia	$Y_3 = -5.651+0.0029x$	0.650
Zarichne	$Y_4 = 18.1225-0.0089x$	-0.580
Kostopil	$Y_5 = 48.0938-0.0234x$	-0.890
Rokytne	$Y_6 = 2.4124-0.0011x$	-0.260
Sarny	$Y_7 = -6.7471+0.0034x$	0.450
	Forest-Steppe zone	
Hoshcha	$Y_8 = 4.1502-0.00199x$	-0.30
Demydivka	$Y_9 = 17.4962-0.00857x$	-0.740
Dubno	$Y_{10} = 6.4357-0.0031x$	-0.420
Zdolbuniv	$Y_{11} = -11.3919+0.0057x$	0.520
Korets	$Y_{12} = -3.2519+0.0017x$	0.080
Mlyniv	$Y_{13} = -2.1757+0.0011x$	0.340
Ostroh	$Y_{14} = 4.16-0.0020x$	-0.160
Radyvyliv	$Y_{15} = -18.309+0.0091x$	0.870
Rivne	$Y_{16} = -19.9767+0.0100x$	0.780

Note: *Y – content of mobile forms of copper (mg/kg), X – year of calculation (forecast)*
Source: *developed by the authors*

According to the results of the regression analysis of changes in the dynamics of the content of mobile forms of copper in the soils of the districts, linear equations were obtained with regression coefficients indicating an increase in this micronutrient from +0.0029 to +0.0077 in three districts and a decrease from -0.0011 to -0.0089 in four districts of the Polissia zone. In the districts of the Forest-Steppe zone, the obtained linear equations had regression coefficients indicating an increase in copper content from +0.0011 to +0.01 in five districts and a decrease from -0.00199 to -0.00857 in four districts. The content of mobile forms of cobalt during 2015-2020 in the arable lands of Kostopil and Dubrovytsia districts of the Polissia zone increased, whereas in the other five districts it decreased. According to the strength of the identified relationships, the annual dynamics of cobalt in the arable lands of the districts of the Polissia zone were assessed as follows: four districts – 0.27-0.48, weak relationship; one district – 0.59, moderate relationship; and two districts – 0.80-0.85, strong relationship. In the arable lands of the Forest-Steppe zone, cobalt content changed as follows: in four districts it decreased over the years, whereas in the other five districts it increased, most significantly in Dubno district up to 0.34 mg/kg. According to the strength of the identified relationships, the arable lands of the Forest-Steppe zone in terms of annual cobalt dynamics were assessed as follows: two districts – 0.06-0.16, very weak relationship; two districts – 0.30-0.41, weak relationship; four districts – 0.51-0.70, moderate relationship; and one district – 0.80, strong relationship (Table 6).

Table 6. Relationships of changes in mobile forms of cobalt in the arable lands of Rivne region, 2015-2020

District	Equation	Correlation coefficient
	Polissia zone	
Berezne	$Y_1 = 32.1019 - 0.0157x$	-0.590
Volodymyrets	$Y_2 = 37.8429 - 0.0186x$	-0.850
Dubrovytsia	$Y_3 = -33.1929 + 0.0166x$	0.800
Zarichne	$Y_4 = 7.3405 - 0.0034x$	-0.370
Kostopil	$Y_5 = -10.6829 + 0.0066x$	0.480
Rokytne	$Y_6 = 3.7752 - 0.0017x$	-0.39
Sarny	$Y_7 = 5.971 - 0.0029x$	-0.270
	Forest-Steppe zone	
Hoshcha	$Y_8 = 2.649 - 0.0011x$	-0.16
Demydivka	$Y_9 = 14.6605 + 0.0074x$	0.540
Dubno	$Y_{10} = -31.4119 + 0.0157x$	0.800
Zdolbuniv	$Y_{11} = 21.6295 - 0.0106x$	-0.410
Korets	$Y_{12} = 2.051 - 0.0009x$	-0.060
Mlyniv	$Y_{13} = -8.8595 + 0.0046x$	0.300

Table 6. Continued

District	Equation	Correlation coefficient
Ostroh	$Y_{14} = -13.5643 + 0.0069x$	0.510
Radyvyliv	$Y_{15} = -13.4476 + 0.0069x$	0.620
Rivne	$Y_{16} = 17.1448 - 0.0083x$	-0.700

Source: *compiled by the authors*

According to the results of the regression analysis of changes in the dynamics of the content of mobile forms of cobalt in the soils of the districts, linear equations were obtained with regression coefficients indicating an increase in this micronutrient from +0.0066 to +0.0166 in two districts and a decrease from -0.0017 to -0.0186 in five districts of the Polissia zone. In the districts of the Forest-Steppe zone, the obtained linear equations had regression coefficients indicating an increase in cobalt content in soils from +0.0046 to +0.0157 in five districts and a decrease from -0.0009 to -0.0106 in four districts. The content of mobile forms of cadmium during 2015-2020 in the arable lands of the Polissia zone increased noticeably in three districts, namely Dubrovytsia, Zarichne, and Sarny districts, whereas in the other four districts it gradually decreased. According to the strength of the identified relationships, the annual dynamics of cadmium in the arable lands of the Polissia zone were assessed as follows: two districts – 0.05-0.10, very weak relationship; two districts – 0.34-0.37, weak relationship; two districts – 0.65-0.68, moderate relationship; and one district – 0.72, strong relationship. In the arable lands of the Forest-Steppe zone, cadmium content decreased in seven districts to values of 0.06 mg/kg, whereas in two districts it increased to values of 0.14 mg/kg. According to the strength of the identified relationships, the annual dynamics of cadmium in the arable lands of the Forest-Steppe zone were assessed as follows: two districts – 0.09-0.13, very weak relationship; two districts – 0.21-0.41, weak relationship; two districts – 0.65-0.65, moderate relationship; and three districts – 0.84-0.88, strong relationship (Table 7).

Table 7*. Relationships of changes in mobile forms of cadmium in the arable lands of Rivne region, 2015-2020*

District	Equation	Correlation coefficient
	Polissia zone	
Berezne	Y_1=4.15-0.002x	-0.680
Volodymyrets	Y_2=1.2562-0.0006x	-0.100
Dubrovytsia	Y_3=-2.8038+0.0014x	0.650
Zarichne	Y_4=-3.2419+0.0017x	0.050
Kostopil	Y_5=10.9024-0.0051x	-0.370
Rokytne	Y_6=7.0271-0.0034x	-0.72
Sarny	Y_7=-2.1957+0.0011x	0.340
	Forest-Steppe zone	
Hoshcha	Y_8=1.2162-0.0006x	-0.090
Demydivka	Y_9=0.6648-0.0003x	-0.130
Dubno	Y_{10}=5.3029-0.0026x	-0.880
Zdolbuniv	Y_{11}=5.0662-0.00245x	-0.410
Korets	Y_{12}=5.851-0.0029x	-0.650
Mlyniv	Y_{13}=-9.6943+0.0049x	0.870
Ostroh	Y_{14}=2.9838-0.0014x	-0.650
Radyvyliv	Y_{15}=-11.9733+0.006x	0.840
Rivne	Y_{16}=1.8776-0.0009x	-0.210

Note: *Y – content of mobile forms of cadmium, mg/kg; X – year of calculation (forecast)*
Source: *compiled by the authors*

According to the results of the regression analysis of changes in the dynamics of the content of mobile forms of cadmium in the soils of the districts, linear equations were obtained with regression coefficients indicating an increase in this micronutrient from +0.0011 to +0.0017 in three districts and a decrease from -0.0006 to -0.0051 in four districts of the Polissia zone. In the districts of the Forest-Steppe zone, the obtained linear equations had regression coefficients indicating an increase in cadmium content in soils from +0.0049 to +0.006 in two districts, whereas in seven districts it decreased from -0.0003 to -0.0029. At the same time, it should be noted that according to forecast calculations for 2025, manganese content in the arable lands of the region is characterised by accumulation levels that meet the requirements for the establishment of SRMZs for the cultivation of products intended for infant and dietary nutrition. In the soils of the Polissia zone, six out of seven districts correspond to the categories of elevated, high, and very high availability; accordingly, these lands are assessed as suitable for the establishment of such zones, whereas the lands of Volodymyrets district, with medium manganese content, belong to the category of limited suitability (Table 8).

***Table 8**. Assessment of the suitability of arable lands in the Polissia zone for the establishment of special raw material zones*

District	Element	2015	2020	2025	Micronutrient availability	Suitability for the establishment of SRMZs
Berezne	Mn	9.23	12.7	14.95	elevated	suitable
	Cu	0.18	0.17	0.10	very low	unsuitable
	Co	0.41	0.35	0.31	very high	suitable
	Cd	0.12	0.11	0.10	very low	unsuitable
Volodymyrets	Mn	4.60	6.30	7.62	medium	limited suitability
	Cu	0.22	0.26	0.27	elevated	suitable
	Co	0.41	0.30	0.18	elevated	suitable
	Cd	0.10	0.10	0.041	very low	unsuitable
Dubrovytsia	Mn	6.83	15.1	22.29	very high	suitable
	Cu	0.11	0.12	0.22	elevated	suitable
	Co	0.22	0.31	0.42	very high	suitable
	Cd	0.07	0.08	0.031	very low	unsuitable
Zarichne	Mn	12.0	12.0	12.94	elevated	suitable
	Cu	0.17	0.12	0.10	very low	unsuitable
	Co	0.41	0.41	0.46	very high	suitable
	Cd	0.12	0.18	0.20	very low	unsuitable
Kostopil	Mn	15.3	17.1	18.02	high	suitable
	Cu	0.88	0.75	0.71	very high	suitable
	Co	2.56	2.57	2.68	very high	suitable
	Cd	0.55	0.50	0.58	medium	limited suitability
Rokytne	Mn	10.48	14.0	16.83	high	suitable
	Cu	0.10	0.1	0.18	medium	limited suitability
	Co	0.32	0.31	0.33	very high	suitable
	Cd	0.11	0.10	0.14	very low	unsuitable
Sarny	Mn	6.93	10.1	12.42	elevated	suitable
	Cu	0.15	0.18	0.14	low	unsuitable
	Co	0.20	0.18	0.10	medium	limited suitability
	Cd	0.11	0.11	0.032	very low	unsuitable

***Source:** compiled by the authors*

According to the content of mobile forms of manganese, the arable lands of the Forest-Steppe zone belong to the categories of elevated, high, and very high availability, which provides grounds for assessing them as suitable for the establishment of special raw material zones (Table 9). According to the forecast up to 2025 regarding copper content, the arable lands of the Polissia zone are characterised predominantly by elevated and very high availability (three districts). At the same time, Rokytne district, with medium copper content, belongs to the category of limited suitability, whereas Berezne, Zarichne, and Sarny districts, with very low and low content, are classified as unsuitable (Table 8). In the Forest-Steppe zone, according to the content of mobile forms of copper, Rivne district corresponds to the category of elevated availability and is suitable for the establishment of raw material zones. Dubno and Korets districts belong to the category of medium availability and are assessed as having limited suitability. The lands of the other six districts, characterised by very low and low copper content, were classified as unsuitable (Table 9).

***Table 9**. Assessment of the suitability of arable lands in the Forest-Steppe zone for the establishment of special raw material zones*

District	Element	2015	2020	2025	Micronutrient availability	Suitability for the establishment of SRMZs
Hoshcha	Mn	16.2	15.46	13.28	elevated	suitable
	Cu	0.12	0.13	0.12	low	unsuitable
	Co	0.35	0.35	0.42	very high	suitable
	Cd	0.05	0.06	0.001	very low	unsuitable

Table 9. Continued

District	Element	2015	2020	2025	Micronutrient availability	Suitability for the establishment of SRMZs
Demydivka	Mn	18.3	20.2	22.06	very high	suitable
	Cu	0.24	0.18	0.14	low	unsuitable
	Co	0.33	0.36	0.32	very high	suitable
	Cd	0.09	0.09	0.06	very low	unsuitable
Dubno	Mn	12.21	13.4	14.40	elevated	suitable
	Cu	0.11	0.08	0.16	medium	limited suitability
	Co	0.23	0.34	0.38	very high	suitable
	Cd	0.12	0.11	0.04	very low	unsuitable
Zdolbuniv	Mn	10.08	12.31	13.91	elevated	suitable
	Cu	0.1	0.14	0.15	low	unsuitable
	Co	0.33	0.30	0.16	elevated	suitable
	Cd	0.11	0.12	0.10	very low	unsuitable
Korets	Mn	12.8	18.0	23.05	very high	suitable
	Cu	0.18	0.20	0.19	medium	limited suitability
	Co	0.31	0.31	0.23	high	unsuitable
	Cd	0.09	0.08	0.02	very low	unsuitable
Mlyniv	Mn	16.9	17.9	19.41	high	suitable
	Cu	0.12	0.13	0.05	very low	unsuitable
	Co	0.39	0.40	0.46	very high	suitable
	Cd	0.09	0.12	0.23	low	unsuitable
Ostroh	Mn	12.6	15.0	18.73	high	suitable
	Cu	0.11	0.11	0.11	low	unsuitable
	Co	0.25	0.27	0.41	very high	suitable
	Cd	0.11	0.10	0.15	very low	unsuitable
Radyvyliv	Mn	12.4	15.2	17.81	high	suitable
	Cu	0.12	0.17	0.12	low	unsuitable
	Co	0.38	0.42	0.52	very high	suitable
	Cd	0.12	0.14	0.18	very low	unsuitable
Rivne	Mn	23.5	21.0	16.81	high	suitable
	Cu	0.16	0.23	0.27	elevated	suitable
	Co	0.46	0.42	0.34	very high	suitable
	Cd	0.15	0.14	0.06	very low	unsuitable

Source: *compiled by the authors*

According to forecast calculations up to 2025 regarding cobalt content, the arable lands of the Polissia zone are predominantly characterised by elevated and very high availability (six districts), which provides grounds for classifying them as suitable for the establishment of special raw material zones. At the same time, in Sarny district, where a medium level of availability was recorded, the lands are assessed as having limited suitability (Table 8). In the Forest-Steppe zone, according to the content of mobile forms of cobalt, eight districts belong to the categories of elevated and very high availability, indicating the feasibility of establishing special raw material zones on these lands. The lands of Korets district, characterised by a very low cobalt content, were classified as unsuitable (Table 9). According to forecast calculations up to 2025 regarding cadmium content, the arable lands of the Polissia zone are predominantly characterised by a very low level of availability (six districts) and belong to the category unsuitable for the establishment of SRMZs. Only in Kostopil District was a medium level of availability recorded, corresponding to the status of lands with limited suitability (Table 8). In the Forest-Steppe zone, the arable lands of all nine districts, according to the content of mobile forms of cadmium, belong to the categories of low and very low availability and were therefore classified as unsuitable for the establishment of special raw material zones (Table 9).

According to the availability of the four micronutrients, the arable lands of the Polissia zone were assessed up to 2025 as follows. In Kostopil district, where medium cadmium content, high manganese content, and very high copper and cobalt content were recorded, the lands were classified as having limited suitability for the establishment of SRMZs. In Dubrovytsia, Rokytne, and Volodymyrets districts, the lands were unsuitable due to the very low cadmium content. In Berezne, Zarichne, and Sarny districts, the lands also belonged to the category of unsuitable because of the very low and low contents of copper and cadmium.

According to the forecast up to 2025, the arable lands of the Forest-Steppe zone are assessed as unsuitable for the establishment of SRMZs. In Rivne district, this is due to the very low cadmium content, whereas in the other eight districts it is caused by the low and very low content of mobile forms of copper and cadmium. In order to transfer the arable lands of the region into the category suitable for the establishment of SRMZs and to obtain high-quality raw materials for the production of infant and dietary food products under conditions of very low copper and cadmium content in sod-podzolic, grey forest, and podzolised chernozem soils, the application of modern biotechnologies is considered appropriate. In particular, according to M. Tavan *et al.* (2024), such approaches involve the use of traditional plant breeding and agronomic practices aimed at increasing micronutrient content to elevated and high levels of soil availability through the application of organic and mineral fertilisers (manure, superphosphate containing cadmium, and double superphosphate containing copper). This analysis of micronutrient dynamics reveals the presence of certain limitations that may be addressed in further research and publications. In particular, this concerns the study of the dynamics of heavy metals such as nickel, lead, molybdenum, and arsenic in different soil types of the region, the excess of which in organisms may produce toxic effects and influence the classification of these soils as unsuitable for the establishment of SRMZs. The absence of such data indicates the limitations of the present study and points to directions for further investigation.

CONCLUSIONS

For the first time, it was established that the dynamics of changes in the content of mobile forms of micronutrients in the arable lands of the region are described by stochastic models of the following types: for manganese, increasing linear trends were identified in all seven districts of the Polissia zone, while in the Forest-Steppe zone increasing linear trends were identified in seven districts and decreasing linear trends in two districts. For copper, increasing linear trends were identified in three districts of the Polissia zone, whereas decreasing linear trends were identified in four districts; in the Forest-Steppe zone, the content remained unchanged or followed increasing linear trends in five districts, while decreasing linear trends were observed in four districts. For cobalt, increasing linear trends were identified in two districts of the Polissia zone and decreasing linear trends in the remaining five districts; in the Forest-Steppe zone, increasing linear trends were observed in five districts and decreasing linear trends in the remaining four districts. For cadmium, increasing linear trends were observed in three districts of the Polissia zone and decreasing linear trends in four districts, whereas in the Forest-Steppe zone increasing linear trends were identified in two districts and decreasing linear trends in the remaining seven districts.

According to the indicators of mobile forms of micronutrient availability, the arable lands of the region, based on the forecast up to 2025, were assessed for the establishment of SRMZs as follows: in Kostopil District of the Polissia zone, with a limiting medium cadmium content, the lands were classified as having limited suitability; in Volodymyrets, Dubrovytsia, and Rokytne districts, with limiting very low cadmium content, and in three other districts of this zone, with low and very low copper and cadmium content, the lands were classified as unsuitable. In Rivne District of the Forest-Steppe zone, with limiting very low cadmium content, and in the other eight districts of this zone, with low and very low copper and cadmium content, the lands were classified as unsuitable. The sod-podzolic, grey forest, typical chernozem, and podzolised chernozem soils of the region, since the content of mobile forms of manganese, copper, cobalt, and cadmium does not exceed the maximum permissible levels, are suitable for obtaining environmentally safe agricultural products. However, for the production of raw materials suitable for the manufacture of infant and dietary food products, adjustment of the micronutrient content in these district soils is required in order to restore their optimal balance (at the level of elevated and high availability), namely: manganese from 15 to 20 mg/kg, copper from 0.31 to 0.5 mg/kg, cobalt from 0.16 to 0.30 mg/kg, and cadmium from 1.0 to 1.5 mg/kg.

Producers of raw materials cultivated on the arable lands of the region and used in the manufacture of infant and dietary food products are advised to maintain an optimal balance of mobile forms of micronutrients through the application of organic and mineral fertilisers containing micronutrients as impurities, namely phosphorite meal, simple superphosphate, 40% potassium salt, potassium sulphate, calcium carbonate, and manure. Prospects for further research include the refinement and validation of the proposed stochastic models describing the dynamics of mobile forms of micronutrients, the expansion of spatial analysis to other soil-climatic zones, and the assessment of the effectiveness of measures aimed at optimising their content while taking environmental risks and the impacts of climate change into account.

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CONFLICT OF INTEREST

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Оцінювання забезпеченості мікроелементами орних земель Рівненської області для створення спеціальних сировинних зон

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Анотація. Забруднення ґрунтів важкими металами та дефіцит мікроелементів у сільськогосподарських угіддях знижують якість продукції та обмежують можливість її використання для дитячого і дієтичного харчування, що зумовлює необхідність комплексного дослідження вмісту мікроелементів у ґрунтах. Метою дослідження було оцінювання забезпеченості мікроелементами орних земель Рівненської області для створення на них спеціальних сировинних зон. Дослідження було виконано на основі даних агрохімічного моніторингу за 2015-2020 роки з використанням кореляційного та регресійного аналізів. Встановлено, що у зоні Полісся вміст мікроелементів становив: рівень марганцю був – 4,6-17,1 мг/кг, міді – 0,1-0,75 мг/кг,, кобальту – 0,18-2,57 мг/кг,, кадмію – 0,08-0,5 мг/кг,; у зоні Лісостепу – марганцю 10,08-21 мг/кг,, міді 0,08-0,23 мг/кг,, кобальту 0,24-0,42 мг/кг,, кадмію 0,05-0,14 мг/кг,. Кореляційний та регресійний аналізи показали, що динаміка змін цих елементів мала значні коливання, що описуються стохастичними моделями зі слабкими та сильними кореляційними зв'язками. Встановлено, що більшість районів досліджуваних зон є непридатними або обмежено придатними для створення спеціальних сировинних зон через низький вміст міді та кадмію; у зоні Лісостепу дев'ять районів оцінюються як непридатні. Для забезпечення виробництва сировини, придатної для дитячого та дієтичного харчування, необхідно підтримувати високий рівень забезпеченості марганцем, мідію та кадмієм. Отримані дані дозволяють обґрунтувати заходи щодо оптимізації забезпеченості ґрунтів мікроелементами та формування спеціальних сировинних зон для виробництва безпечної дитячої та дієтичної продукції

Ключові слова: якість ґрунту; оцінка придатності ґрунтів; забруднення ґрунтів; дитяче харчування; якість продукції; виробництво сировини