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Ecological assessment of soil contamination with heavy metals due to the application of mineral fertilisers

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Abstract: The article presents the results of monitoring the aftereffect of the use of excessive zonal doses of mineral fertilisers on soil contamination with heavy metals (HM). With traditional soybean cultivation technology, the level of soil contamination when applying excessive doses ($N_{60}P_{180}K_{90}$) of fertilisers is quite high and indicates violations of the ecological balance of the agroecosystem. By the nature of the accumulation of heavy metals in meadow-chestnut soil, depending on the application of the studied doses ($P_{60}K_{30}$, $N_{30}P_{60}K_{30}$, $N_{60}P_{180}K_{90}$) of fertiliser, the content of HM (Pb, Zn, Cd) increases. The greatest contamination of the soil with Cu was revealed, the content of which increases to 3.2 mg·kg^{-1} of soil, which is higher than the threshold of the maximum permissible concentration (MPC) – 3.0 mg·kg^{-1}. According to the level of contamination of the soil with copper, it belongs to the highly dangerous classes. In a comparative assessment of the level of soil contamination with HM, optimal norms of mineral fertilisers have been established, namely, against the background of effective resource-saving technology for growing soybeans. The application of fertilisers at a dose of $P_{60}K_{30}$ and $N_{30}P_{60}K_{30}$ does not significantly affect the level of soil contamination with HM, optimises the ecological state and nutrient regime of the soil, preserves and restores soil fertility indicators, and increases soybean productivity. This resource-saving technology provides a safe environment for soybean cultivation and a significant increase of 34.5–38.6% in crop productivity (0.53–0.76 Mg·ha^{-1}) and yield (2.57 Mg·ha^{-1}).

Keywords: application, assessment, cultivation technology, heavy metals, mineral fertilisers, soil ecology, soil pollution, soybean, use of fertilisers, yield

INTRODUCTION

Soil, as a component of the biosphere, is rather very specific, since it acts as a buffer that controls the transfer of chemical elements and compounds into the atmosphere, hydrosphere and living matter [Ovsyannikov 2000]. Various elements, coming from different sources, end up on the soil surface, and their further fate depends on their chemical and physical properties.

In this case, trace elements of soil chemical composition, such as heavy metals do not participate in the formation of tissues, such as carbon, nitrogen or phosphorus, but are included in the composition of vitamins, enzymes, hormones, performing biocatalysts function and bioregulators of important physiological processes [Bazdyrev *et al.* 2000; Chernikov *et al.* 2000; Soldat *et al.* 2003]. Even insignificant amounts of metals in living organisms should be maintained at the required level. Finding the patterns of mobilisation and migration of heavy metals in the biosphere is one of the urgent scientific problems.

In terms of anthropogenic impact on the agricultural landscape with food chain influence, fungicides, pesticides and herbicides are in the first place among the chemical agents used in agriculture. Along with this, many scientists have proven that mineral fertilisers, even with their scientifically justified use, are a factor in environmental pollution [Bulgakov 2002; Dezhkin 2008; Kaledin *et al.* 2011]. However, excluding the impact of ever-increasing doses of applying fertilisers on the environment obviously is not possible since the slightest violation of technological methods of crop cultivation leaves possibilities to probable local contamination of soil, groundwater and surface water.

By their possible negative impact on the agricultural landscape and food chains, mineral fertilisers are ranked [Tolokonnikov *et al.* 2002; Yushkevich 2001] in the following decreasing order: nitrogen > phosphorus > potassium.

Environmental pollution with nitrogen fertilisers is possible due to: the vertical migration of nitrogen with its discharge into groundwater; horizontal (underground and aboveground) runoff in agrolandscape situations, enhanced by irrigation; the possible removal of nitrogen into groundwater and surface water bodies; gaseous losses and excessive accumulation of mineral nitrogen in agricultural products. The process of nitrogen transformation of fertilisers in the soil is complex and multifaceted. Part of the nitrogen of fertilisers during the first days after the application is consumed by plants, but its main amount (60–70%) is involved in two cumulative cycles: small (relatively closed) and large (open) circulation [Barsukov, Barsukov 2005; Myakushko, Baranova 1984].

To date, many countries around the world conclude limiting the application of mineral fertilisers in high doses into the soil in order to protect the environment [Alisheva 2006; Tupitsyna *et al.* 2013]. For example, Sweden has introduced a tax on the production of mineral fertilisers, which will lead to a decrease in their use by 50% in subsequent years.

In conditions of our Republic crops cultivation at the end of the last and the beginning of the present century was carried out with intensive technology, with higher doses of fertilisers being applied [Novaya ... 2013]. A vivid example of this is the recommended rates of mineral fertilisers ($N_{60}P_{180}K_{90}$) for soybean crops of one of the largest agricultural enterprises – JSC (Rus.: OAO – otkrytoye aktsionernoye obshchestvo – joint-stock company) "Vita", located in the south-eastern of Kazakhstan, engaged in the cultivation of this valuable leguminous and oilseed crop.

That is why in conditions of south-eastern Kazakhstan, it was a very important urgent problem to study and assess soil contamination with heavy metals.

In this connection, we monitored the after-effect of using recommended mineral fertilisers on pollution of soybeans as an example of oilseeds' agroecosystem. When applying mineral fertilisers for the main ploughing at a dose of phosphorus (P_{180}) and potash (K_{90}) fertilisers, in a scattered way from the estimated total dose of NPK – 330 kg·ha^{-1}, it was found that they have a significant impact on the ecosystem's soil pollution.

The revealed aggravation of the ecosystem's ecological situation associated with soil pollution aimed us to study the possible rejection of large doses or use of fertiliser at a low rate. We set a task to determine the optimal dose of mineral fertilisers that meet the crop requirements for agrochemical indicators of soil fertility, for growing environmentally friendly products and for obtaining the planned soybean yield of the technological crop zone.

During the study, we analysed, and made a comparative assessment of the impact of four options for three doses of mineral fertilisers against the background of traditional and resource-saving soybean cultivation technology on the content of heavy metals (HM):

- against the background of traditional soybean cultivation technology, an absolute control variant was studied – without fertilisers and $N_{60}P_{180}K_{90}$, the recommended dose of mineral fertilisers during soybean sowing under research conditions;
- against the background of resource-saving soybean cultivation, the influence of mineral fertilisers was studied in two variants of norms: $P_{60}K_{30}$ and full dose – $N_{30}P_{60}K_{30}$.

The main purpose of this article is the development and establishment of the optimal rate of applying mineral fertilisers, providing an ecological balance in terms of soil contamination with heavy metals, as well as establishing the agroecosystem's stability and increasing the productivity of soybean as a valuable ecological and technological oilseed.

MATERIALS AND METHODS

The test site of research is the arid zone of irrigated agriculture, characterised by a sharply continental climate, low humidity, lots of sunshine, and a short, but a quite cold winter. The formation of climate features and soil in the region is subject to the law of vertical zoning, which is most clearly expressed in the central part of the northern Tien Shan, formed by the Zailiyskiy Alatau ridge. Experimental studies were carried out at the territory of the research and experimental station of KazNARU "Agrouniversitet", 37 km, and the private farm "Turgen", 59 km from Almaty, which are located in the Enbekshikazakh District of the Almaty Region.

Soil conditions are characterised by a wide variety of soil types. In accordance with the complexity of the foothill zone, the following types of chestnut soil are common: dark chestnut, chestnut, light chestnut and meadow chestnut. Field experiments were carried out on meadow-chestnut soil of heavy mechanical composition, which is a characteristic type of foothill belt. These soils are almost all ploughed. Grain, industrial, oilseed and vegetable crops are cultivated there.

The meadow-chestnut soils of the foothill plain of the Zailiysky Alatau have a dark chestnut colour of the humus horizon, the thickness of which reaches 30–40 cm. Moreover, its colour is more saturated on irrigated soils than in untouched areas. The soils are distinguished by the absence of a pronounced illuvial-carbonate horizon. In the case of very close occurrence of groundwater, the lower horizons have signs of swamping. The heavy granulometric composition causes unfavourable physical properties of the soil: stickiness when wet, compaction and hardening when dry, which in turn leads to high ploughing resistance and to a blocky field surface.

The data on the chemical composition of the soil shows that the meadow-chestnut soil is characterised by a moderate content of humus. In the distribution of humus along the profile, the following regularity should be noted: its relatively high content in the upper horizon drops sharply, more than twice when moving to the next subsurface horizon (Tab. 1).

A further decrease in the humus content occurs gradually, stretching to a considerable depth. The content of gross nitrogen in the soil is low and is 0.12%, due to which the ratio of humus carbon to total nitrogen is wide – 11.8%. In this case, it varies from 10 to 12%, i.e., a wider (compared to zonal soils) ratio of humus carbon to total nitrogen in comparison with zonal analogues.

Table 1. Main agrochemical indicators of meadow-chestnut soil

Depth (cm)	Humus	Total nitrogen	C:N	Gross potash	Total phosphorus	CO_2
	%			%		
0–24	4.45	0.120	11.8	2.60	0.19	5.80
24–32	4.40	0.119	11.9	2.10	0.16	5.84
32–59	1.00	0.060	9.6	1.09	0.17	5.88
59–103	0.46	0.039	6.8	1.10	0.14	7.30

Explanations: C:N = the ratio of carbon and nitrogen.
Source: own study.

The gross content of phosphoric acid in the humus horizon does not go beyond 0.14–0.19%, which characterises a low level of availability. The amount of CO_2 varies from 5.80 to 7.30%, with a minimum on the upper horizon and a maximum on the lower one. The growth in the percentage of CO_2 with increasing depth occurs gradually, which is apparently associated with hydrogenic accumulation.

As for the presence of available nutrients, the experimental plot soils are characterised as medium-supplied with easily hydrolysable nitrogen, high in potassium, and in terms of the content of mobile phosphorus, belong to the group of poorly supplied soils. The meadow-chestnut soil of the study area has a pH of 7.3, which varies within family types (pH of 7–8).

Thus, the meadow-chestnut soil, in terms of its water-physical properties and the level of potential fertility, fully satisfies the conditions for the cultivation of all types of crops, including the valuable soybean crop.

The object of research is a unique leguminous oilseed – soybeans (Eureka variety). As a control reference in the experiments, we used the traditional technology of soybean cultivation in accordance with the recommendations of the Agricultural Management System of the Almaty Region [Kenenbayev *et al.* 2005].

Field experiments and test studies were carried out by the generally accepted classical techniques: experiment and observation. All methodological requirements for the method of setting up field experiments were met and were carried out according to B.A. Dospekhov and according to the methodological recommendations of JSC "Vita" [Boyko, Karyagin 2004; Dospekhov 1985]. Biometric and phenological observations were carried out according to the recommendation of the Institute of Field and Vegetable Crops (Sr.: Institut za ratarstvo i povrtarstvo), and the Methodology of the State Agricultural Standards for the cultivation of cereals, legumes and oilseeds [Bechei 2001; Korsakov *et al.* 1968]. The obtained experimental data were processed statistically [Novikova, Novikova 2010].

In agrochemical studies to determine the content of heavy metals in the soil, a Shimadzu AA7000 atomic absorption spectrophotometer was used, with hollow cathode lamps made of Cr, Zn, Cu, Pb, and Cd elements. The RD 52.18.286-91 method was used for preparing the samples for research [Hadgu *et al.* 2014].

RESULTS AND DISCUSSION

During the years of research, we have studied and carried out a comparative assessment of mineral fertilisers' usage against the background of traditional and resource-saving soybean cultivation technology:

- against the background of traditional technology, two options were studied: 1) the control case without fertilisers; 2) the studied case – the use of the recommended dose of $N_{60}P_{180}K_{90}$ of a complete set of mineral fertilisers for the study area, where their introduction is carried out during the main ploughing in a scattered way at a dose of 180 kg·ha^{-1} of phosphorus and 90 kg·ha^{-1} of potash fertilisers. In the pre-sowing period supplementary 60 kg·ha^{-1} of nitrogen fertilisers, from the recommended dose of NPK – 330 kg·ha^{-1}, are added to the study area;
- against the background of resource-saving soybean cultivation technology: 3) case – a combination of phosphorus and potash fertilisers at a dose of $P_{60}K_{30}$; 4) case – a complete set of mineral fertilisers at a dose of $N_{60}P_{180}K_{90}$ was studied.

These options were studied in full factorial experience in previous years and were chosen to assess soil contamination with heavy metals when using high doses of mineral fertilisers against the background of traditional and resource-saving soybean cultivation technology. When the ratio of types of mineral fertilisers is 1:3:1.5, the doses correspond to the following norm, $N_{60}P_{180}K_{90}$, which is considered a fairly high norm for a variety of fertile foothill chestnut soil for the soybean field crops. Under these conditions, to maintain the fertility of the chestnut soil, high doses of mineral fertilisers were also used in the fruit plantation after harvesting the fruits. The results of soil contamination with heavy metals when using high doses of mineral fertilisers against the background of traditional technology for preparing fields of fruit crops are identical to the data of field crops.

When cultivating soybeans according to traditional technology, we used ammonium sulphate, superphosphate and potassium salt to apply the recommended dose of $N_{60}P_{180}K_{90}$. Ammonium sulphate $(NH_4)_2SO_4)$ – the average salt of sulfuric acid contains up to 21% nitrogen and up to 24% sulphur. According to the degree of danger, ammonium sulphate is a moderately hazardous substance and, according to the degree of impact on the body, belongs to the 3rd hazard class [Eleshev *et al.* 2014]. Plants from the applied rate of fertiliser assimilate the NH_4^+ cation much more intensively than the SO_4^{2-} anion since nitrogen is required by plants in much larger quantities than sulphur. Ammonium sulphate is a typical representative of physiologically acidic fertilisers. Under the conditions of our research, meadow chestnut and dark chestnut soils have a slightly alkaline environment, so ammonium sulphate, which has an acidic environment, is considered the most optimal type of nitrogen fertiliser.

The composition of ammonium sulphate contains heavy metals from 5 varieties of HM (Tab. 2). These are such heavy metals as cadmium – no more than 0.5 mg·kg^{-1} (with maximum permissible concentration (MPC) 0.01 ±0.005 mg·m^{-3}), cobalt – 5.0 mg·kg^{-1} (0.05 ±0.01 mg·m^{-3}), arsenic – not more than 2.0 mg·kg^{-1} (0.04 ±0.01 mg·m^{-3}), nickel – not more than 4.0 mg·kg^{-1} (0.05 mg·m^{-3}), lead – not more than 32 mg·kg^{-1} (0.01 ±0.005 mg·m^{-3}), copper – not more than 33 mg·kg^{-1}

Table 2. The content of heavy metals in the composition of the applied nitrogen fertilisers

Applied mineral fertilisers	Heavy metals	Content of heavy metals	MPC of heavy metals in soil
		$mg \cdot kg^{-1}$	
Ammonium sulphate $(NH_4)_2SO_4$	Pb	32	6.0
	Zn	55	23.0
	Cu	33	3.0
	Cd	0.5	20.0
Common superphosphate $Ca(H_2PO_4)_2$	Pb	20	6.0
	Cr	6.0	–
	Cd	0.5	6.0
	As	2	–

Explanations: MPC = maximum permissible concentration.
Source: own elaboration based on MINEEV and BOLYSHEVA [2005].

(1 ±0.05 $mg \cdot m^{-3}$), and zinc – not more than 55 $mg \cdot kg^{-1}$ [SULEIMENOVA *et al.* 2016b].

The applied fertiliser (simple superphosphate – $Ca(H_2PO_4)_2$) is a highly effective granular phosphate fertiliser. They contain heavy metals within the following limits: lead (Pb) – no more than 20 $mg \cdot kg^{-1}$, cadmium (Cd) – no more than 0.5 $mg \cdot kg^{-1}$, arsenic (As) – no more than 2 $mg \cdot kg^{-1}$, chromium (Cr) – no more than 6 $mg \cdot kg^{-1}$. According to literary sources, it is well known that in the year of application of mineral fertilisers, plants use about 30–50%, the rest remains in the soil as an aftereffect of fertilisers on soil pollution [Gossort 1989; MINEEV, BOLYSHEVA 2005].

The results of the study especially highlight the increased content of heavy metal elements in the 0–20 cm soil layer when applying fertilisers at the recommended dose of $N_{60}P_{180}K_{90}$ – for the study area (Tab. 3). With the prolonged application of such

Table 3. Influence of mineral fertilisers on the content of heavy metals in 0–20 cm soil layer depending on the technology of soybean cultivation

Heavy metals	Content of heavy metals ($mg \cdot kg^{-1}$)				
	traditional technology		resource-saving technology		MPC
	without fertilisers	$N_{60}P_{180}K_{90}$	$P_{60}K_{30}$	$N_{30}P_{60}K_{30}$	
Cr	0.586 ±0.017	2.78 ±0.13	0.94 ±0.05	1.12 ±0.03	6.0
Pb	0.490 ±0.018	2.34 ±0.01	1.06 ±0.025	1.53 ±0.03	6.0
Zn	0.462 ±0.012	10.65 ±0.25	1.27 ±0.04	2.46 ±0.45	23.0
Cu	0.412 ±0.064	3.92 ±0.5	0.62 ±0.02	0.69 ±0.03	3.0
Cd	0.328 ±0.053	7.98 ±0.14	1.22 ±0.017	1.85 ±0.06	20.0

Explanations: $N_{60}P_{180}K_{90}$ = doses of nitrogen, phosphoric and potash fertilisers, $P_{60}K_{30}$ = doses of phosphoric and potash fertilisers, $N_{30}P_{60}K_{30}$ = doses of nitrogen, phosphoric and potash fertilisers, MPC = maximum permissible concentration.
Source: own study.

a dose of fertilisers, the content of chromium (Cr) in this layer increases from 0.586 to 2.78 $mg \cdot kg^{-1}$ of soil, the content of lead (Pb) increases from 0.49 to 2.34 $mg \cdot kg^{-1}$, the content of zinc (Zn) – from 0.462 to 10.65 $mg \cdot kg^{-1}$, and copper (Cu) from 0.412 to 3.92 $mg \cdot kg^{-1}$, and cadmium (Cd) increases – from 0.328 to 7.98 $mg \cdot kg^{-1}$ of soil. Soil contamination with heavy metals when using high doses of mineral fertilisers ($N_{60}P_{180}K_{90}$) indicates a violation of the ecological balance of the soybean agroecosystem.

High contamination of soil with copper (Cu) was revealed, the content of which rises from 0.412 to 3.92 $mg \cdot kg^{-1}$ of soil, which is above the threshold of the permissible limit, the MPC of which is only 3.0 $mg \cdot kg^{-1}$ of soil. Thus, when studying and assessing soil contamination against the background of traditional soybean cultivation technology, high soil contamination with heavy metals, in particular copper, the content of which in the soil rises to 3.92 $mg \cdot kg^{-1}$, was proved. The results of soil contamination, within 30.7%, indicate significant soil contamination, which has a negative impact on the level of ecological stability of the soybean agroecosystem.

Considering the above, we carried out a comparative assessment of the impact of using two cases for applying mineral fertilisers with a resource-saving technology of soybean cultivation on the content of heavy metals (HM) in soil, in compliance with the experimental scheme. According to the results of the research, the content of HM in the variants of the field experiment in the 0–20 cm soil layer was different according to the studied variants (Tab. 3).

In case with traditional technology usage without the application of mineral fertilisers, the soil is characterised by a rather low content of almost all elements of heavy metals: chromium contains – 0.586 $mg \cdot kg^{-1}$, lead – 0.490 $mg \cdot kg^{-1}$, zinc – 0.462 $mg \cdot kg^{-1}$, which is respectively 11, 13.0, 50.5 times below the MPC level. Especially low content was noted for cadmium – 0.328 $mg \cdot kg^{-1}$ and copper – 0.412 $mg \cdot kg^{-1}$, which are respectively 7.3 and 61.2 times lower than the MPC level (20.0 and 3.0 $mg \cdot kg^{-1}$).

The trend of increasing the content of HM in the 0–20 cm soil layer should be noted for the options of applying mineral fertilisers of traditional technology.

According to the nature of the studied heavy metals accumulation in the meadow-chestnut soil, it can be noted that the content of lead (Pb), copper (Cu), and cadmium (Cd) in the soil increases within the MPC. Soil contamination with heavy metals when using high doses of mineral fertilisers ($N_{60}P_{180}K_{90}$) in terms of zinc (Zn) points to the identification of a violation of the ecological balance of the agroecosystem. According to the level of soil contamination with copper, it belongs to a highly dangerous class. This situation causes destabilisation of the agroecosystem, where the soil is contaminated with heavy metals copper (Cu), which hinders the growth and development of crops and reduces the productivity of soybean as a cultivated crop.

It was revealed that by the content in the 0–20 cm layer of soil, with the traditional technology on the option without fertilisers, HMs form a series in decreasing order: Cr > Pb > Zn > Cu > Cd. A different picture emerges with the introduction of complete mineral fertilisers with rather overestimated doses ($N_{60}P_{180}K_{90}$), where the series for the HM content looks in the following order Zn > Cd > Cu > Cr > Pb.

The possibility of reducing the rate of mineral fertilisers to optimal parameters with resource-saving technology has been studied. At the same time, the following regularity was observed in the distribution of Cd along the soil profile. The largest amount of cadmium was noted in the arable horizon (in the 0–20 cm layer) of the soil, Cd on the variant with the use of $N_{60}P_{180}K_{90}$ – increased to 7.98 mg·kg^{-1}, and when fertilisers were applied at a dose of $P_{60}K_{30}$ – 1.27 mg·kg^{-1} and with a full set of mineral fertilisers at a dose of $N_{30}P_{60}K_{30}$ – 1.85 mg·kg^{-1} with resource-saving technology. The highest Cr content is 0.54–0.62 mg·kg^{-1} in the variants of using mineral fertilisers ($P_{60}K_{30}$ and $N_{30}P_{60}K_{30}$) with resource-saving technology much lower than the MPC level (i.e., 11.1 and 9.7 times). On the same variant, the Cd content was more overestimated and amounts to 0.62 and 0.82 mg·kg^{-1}, which are 32.2 and 23.5 times lower than the MPC.

The developed resource-saving technology with the introduction of reduced norms $P_{60}K_{30}$ and $N_{30}P_{60}K_{30}$ is aimed at improving the ecological situation, maintaining the stability of the agroecosystem and increasing the productivity of a valuable ecological and technological soybean oilseed crop. It should be noted that the content of the mobile form of heavy metals in the soil is dynamic over time. The reasons for the changes can be different, in most cases, fluctuations are explained by age-related changes in plants in the intensity of absorption of chemical elements [Suleimenova *et al.* 2016a].

Thus, with resource-saving technology, the environmental conditions of the soil for soybean cultivation are optimised, and the content of heavy metals is significantly lower than the MPC, for Cr – by 8.1–7.4 times, Pb – by 4.6–3.7 times, Zn – by 16.7–9.0 times, Cu – by 4.3–4.2 times and Cd – by 15.6–10.9 times.

At the same time, it can be stated that the scientifically grounded use of mineral fertilisers in the cultivation of soybeans does not lead to the accumulation of heavy metals in the arable layer of the soil. The data obtained with the resource-saving technology of soybean cultivation showed that the application of mineral fertilisers in a dose of $P_{60}K_{30}$ and $N_{30}P_{60}K_{30}$ does not significantly affect the level of soil contamination with heavy metals, whereas at the same time, with resource-saving technology, the ecological state of the soil for soybean cultivation is boosted, the optimal nutrient regime of the soil is formed and ensures reliable preservation and improvement of soil fertility indicators and an increase in the productivity of the soybean agroecosystem. The results obtained show that resource-saving technology when applying mineral fertilisers in a dose of $P_{60}K_{30}$ and $N_{30}P_{60}K_{30}$ provides an ecologically safe environment for soybean cultivation.

Thus, it has been established that a significant increase in the yield of the leading crop in agricultural zones, soybeans, cultivated in the 21st century, is possible only on the basis of the widespread introduction of resource-saving technology, which provides an additional increase in the production of the agroecosystem up to 26.9 and 34.5%.

It is generally known that the greatest potential for cost savings in agroecosystems lies in tillage and planting. About 40% of energy and 27% of labour resources are spent on annual ploughing, which is used in the traditional technology of crop cultivation. Moldboard tillage during ploughing is not only useless but also causes irreparable harm, intensifying erosion processes and reducing soil fertility. Therefore, the system of resource-saving technology presupposes the refusal of plough usage.

In recent years, we have studied the elements of resource-saving soybean cultivation on plantations in between the strips of crops, as a soil protection technology, where minimal tillage increases environmental sustainability and stabilises the structure of the topsoil, allowing to ensure the rational use of soil resources with the subsequent preservation and restoration of their fertility.

Analysis of the acceptance of soybean cultivation technology for agrophysical factors of soil fertility in the agroecosystem made it possible to give a comparative assessment of soil density, aggregate composition and coefficient of soil structure against the background of traditional and resource-saving technologies. With resource-saving technology, the minimum tillage has led to reliable preservation and an increase in soil fertility indicators.

It was found that on soybean crops with resource-saving technology, the density of the upper 0–30 cm soil layer increases by 0.08–0.11 g·cm^{-3}, approaches the optimal density (1.20–1.23 g·cm^{-3}), and is higher during ploughing (1.12 g·cm^{-3}). The subsequent increase in this indicator greatly impairs the most important processes occurring in the soil, first of all, air, water and thermal regimes, which leads to a decrease in the yield of soybean grain. Compared to the background of traditional technology with moldboard ploughing, the sum of macro-aggregates of the arable soil layer is 33.7%, the sum of water-resistant aggregates is 25.8%, and the structural coefficient is only 0.65.

With resource-saving minimal tillage, the content of agronomically valuable macro-aggregates increases to 42.5–50.2% and the structural coefficient – from 0.65 to 1.13, which indicates the restoration of agrophysical indicators of soil fertility. The transition from the traditional technology to the resource-saving one, together with the improvement of the agrophysical indicators of soil fertility, causes biotic changes in the environment of the formation of the agrophytocenosis, which differ in their characteristics [Suleimenova *et al.* 2021].

Depending on the degree of anthropogenic load of the basic soil cultivation system, soil fertility deteriorates with traditional technology. With resource-saving technology, under the influence of soil protection methods, an optimal ratio of the components of the agroecosystem is observed with an increase in the specific gravity of cultural component biomass. The biotic relationships of organisms are stabilised, the best conditions for the growth and development of crops are created and the yield of soybeans increases from 1.95 to 2.57 Mg·ha^{-1}, as well as the productivity of the agroecosystem (Tab. 4).

The transition from traditional technology to resource-saving, along with the improvement of agrophysical indicators of soil fertility, contributes to the development of biotic changes in the environment of the formation of an agroecosystem.

Minimal soil tillage with resource-saving technology along with the agroecosystem's ecological improvement in regard to HM pollution provides a reduction in energy costs by reducing the number and depth of tillage, combining several operations and improving the environmental situation. With the minimum technology of soybean cultivation, the impact on the soil by the working bodies of agricultural machines and implements is reduced by 2.0 times or more in comparison with traditional technology. At the same time, with resource-saving technology, the best conditions are created for the growth and development of soybeans and the yield increases from 1.95 Mg·ha^{-1} (with traditional technology) to 2.57 Mg·ha^{-1} (with resource-saving technology), the yield increases significantly to 34.5–38.6%.

Table 4. The yield of soybeans when using mineral fertilisers, depending on the technology of soybean cultivation ($Mg \cdot ha^{-1}$)

No.	Cultivation technology	Fertilisers used	Yield in research years ($Mg \cdot ha^{-1}$)			Average yield ($Mg \cdot ha^{-1}$)	Gain in	
			2018	2019	2020		$Mg \cdot ha^{-1}$	%
1	traditional	without fertilisers	1.95	1.99	1.98	1.97	–	–
2		$N_{60}P_{180}K_{90}$	2.42	2.53	2.55	2.50	0.53	26.9
3	resource-saving	$P_{60}K_{30}$	2.54	2.58	2.56	2.57	0.68	34.5
4		$N_{30}P_{60}K_{30}$	2.71	2.68	2.85	2.73	0.76	38.6
$LSD_{0.05}$ ($Mg \cdot ha^{-1}$)			2.11	0.27	0.19	–	–	–
S_x (%)			3.1	3.5	2.7	–	–	–

Explanations: $N_{60}P_{180}K_{90}$ = doses of nitrogen, phosphoric and potash fertilisers, $P_{60}K_{30}$ = doses of phosphoric and potash fertilisers, $N_{30}P_{60}K_{30}$ = doses of nitrogen, phosphoric and potash fertilisers, $LSD_{0.05}$ = least significant difference at p = 0.05, S_x = error accuracy of the experiment.
Source: own study.

CONCLUSIONS

1. When studying soil contamination, it was revealed that with the traditional technology of soybean cultivation, the level of soil contamination with heavy metals when applying excessive norms ($N_{60}P_{180}K_{90}$) of mineral fertilisers is quite high.
2. By the nature of the accumulation of the studied heavy metals on the meadow-chestnut soil, it can be noted that the content of lead (Pb) increases from 0.49 to 2.34 $mg \cdot kg^{-1}$, the content of zinc (Zn) – from 0.462 to 10.65 $mg \cdot kg^{-1}$, copper (Cu) from 0.412 to 3.92 $mg \cdot kg^{-1}$, and cadmium (Cd) rises – from 0.328 to 7.98 $mg \cdot kg^{-1}$ of soil. Soil contamination with heavy metals when using high doses of mineral fertilisers ($N_{60}P_{180}K_{90}$) indicates a violation of the ecological balance of the agroecosystem.
3. Soil contamination with copper (Cu) has been revealed, the content of which rises to 3.2 $mg \cdot kg^{-1}$ of soil, which is above the threshold of the permissible limit, the MPC of which is only 3.0 $mg \cdot kg^{-1}$ of soil and, according to the level of soil contamination with copper, belongs to highly hazardous classes. This situation causes the destabilisation of the agroecosystem, where the soil is contaminated with heavy metal Cu, which hinders the growth, development of culture and reduces the productivity of the cultivated crop – soybeans.
4. The possibility of reducing the rate of mineral fertilisers to optimal parameters with resource-saving technology has been studied. The developed resource-saving technology with the introduction of reduced norms ($P_{60}K_{30}$ and $N_{30}P_{60}K_{30}$) is aimed at improving the ecological situation, maintaining the stability of the agroecosystem and increasing the productivity of a valuable ecological and technological soybean oilseed crop.
5. It should be noted that the scientifically grounded use of mineral fertilisers in the cultivation of soybeans does not lead to the accumulation of the content of heavy metals in the topsoil, except for copper. With resource-saving soybean cultivation technology, the application of mineral fertilisers in a dose of $P_{60}K_{30}$ and $N_{30}P_{60}K_{30}$ does not significantly affect the level of soil contamination with heavy metals. Thus, the ecological state of the soil is optimised, where the optimal nutrient regime of the soil is formed, the reliable preservation and increase of soil fertility indicators and productivity of the soybean agroecosystem are determined. Resource-saving technology with the introduction of optimal doses of mineral fertilisers $P_{60}K_{30}$ and $N_{30}P_{60}K_{30}$ provides environmentally friendly conditions for the cultivation of soybeans and a significant increase in crop productivity up to 0.53–0.76 $Mg \cdot ha^{-1}$, increases the yield from 1.95 $Mg \cdot ha^{-1}$ (traditional) to 2.57 $Mg \cdot ha^{-1}$ (resource-saving), i.e. significantly, up to 34.5–38.6%.

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