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Transition to sustainable agriculture in Russia: Problems of soil resources

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Abstract

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The article discusses the problem of transition to sustainable agriculture in Russia with a focus on the importance of soil resources. The analysis of the current challenges faced by Russia in the field of soil protection and improvement, including erosion, pollution, degradation and irrational use of agricultural chemicals, is carried out. A decrease in the reserves of basic nutrients in soils associated with insufficient use of mineral and organic fertilizers has been established. According to FAOSTAT, after the collapse of the USSR, there has been a downward trend in the intake of macronutrients into soils as part of organic fertilizers, due to a decrease in the number of cattle. The application of mineral fertilizers in the period of 1992–2021 also decreased significantly. Despite the introduction of a system of state subsidies, the level of fertilizer application remains extremely low compared to the Soviet period, which leads to gradual depletion of soils, decrease in potential crop yields and requires further strengthening of state support to ensure the sustainable development of the agricultural sector. Moreover, in a number of regions of the country is observed intensive use of pesticides which leads to pollution of agroecosystems. Territories that do not meet sanitary requirements are identified annually, while both the list of polluting pesticides and the area of contamination, as well as the list of subjects of the Russian Federation with contaminated territories, are changed.

Keywords: sustainable agriculture; soil resources; water and wind erosion; fertilizers; pesticides; agroecosystems

Introduction

The issues of ensuring food security and sustainable development are among the key global problems of our time. In the context of the rapid growth of the world's population and the increasing need for food, the rational and efficient use of soil resources is becoming critically important. Soils, as the main means of agricultural production, play a key role in ensuring food security, acting as natural capital. The productivity of agroecosystems depends on their condition and environmental sustainability (Pattnaik et al., 2023).

Sustainable agriculture is one of the key elements of sustainable development at this time. It involves the rational use of natural resources, the conservation of biodiversity, the protection of soil and water resources, the use of environmentally friendly production methods, the development of rural tourism and support for small agricultural enterprises. One of the main principles of sustainable agriculture is the principle of ecological integrity, which implies maintaining a balance between agricultural systems and the environment. To do this, integrated management methods of agroecosystems, which allow for the interaction of all components of the agricultural system, should be used. Another principle of sustainable agriculture is the principle of social justice, which implies ensuring equal opportunities for all people employed in agriculture, regardless of social status and position. In addition, sustainable agriculture must be economically efficient and profitable. For this purpose, it is necessary to use innovative technologies, improve the management and marketing system in agriculture. In general, sustainable agriculture is an important element of sustainable development, which allows ensuring food security, economic stability and environmental protection. Currently, the global community recognizes the need for a transition to sustainable agriculture and is working to develop and implement appropriate strategies and programs (Bless et al., 2023).

Based on these concepts and principles, research in the field of studying the influence of destabilizing factors on the sustainability of agriculture is currently being actively conducted. However, the vast majority of them is not systemic in nature, or is evaluative in nature. In the available literature, the role of economic and social factors is most often analyzed, which is determined by the greater simplicity in their assessment. Environmental sustainability assessment is a more difficult task, due to the lack of scientifically sound and proven strategies for the development of greening agriculture. Three options are currently being put forward: (1) to reduce the overall environmental burden of farming, regardless of the production consequences; (2) to ensure the maximum possible production while maintaining the volume of use of intensification agents (e.g. fertilizers, pesticides, energy) and the volume of gases released, while reducing the scale of production; (3) adopt a consensus that environmentally unfavorable resources used in agricultural production should be compensated through agroecological activities that create environmental public goods – the so-called "eco-efficiency" (Mitrofanov et al., 2023).

The work of Polish scientists (Nowak et al., 2019), which assessed the sustainability of agriculture in 28 member states of the European Union, deserves attention. The assessments were carried out on the basis of a synthetic technique (TOPSIS). This method synthesizes factors of various natures and assigns them a synthetic aggregate measure. The analysis made it possible to rank the EU member States according to different levels of measures and classify them into one of four groups characterized by different levels of sustainability in agriculture. The differentiated values of synthetic indicators showed differences in the level of sustainability of agriculture between states, due to different levels of production intensity and the associated environmental impact.

Most of the studies devoted to the study of factors influencing the sustainability of agriculture have a regional component. They are linked to individual countries or regions. For example, a study by Ahmed and Ambinakudige (2023) focuses on the impact of land-use changes on agricultural sustainability in the southwestern coastal region of Bangladesh, as well as waterlogging and salinization of soils characteristic of this region. The study of Rahman (2018) examines the sustainability potential of agriculture in Bangladesh by analyzing economic, environmental and social issues at the macro level. Economic issues were considered by assessing the contribution of the agricultural sector to gross domestic product, trends in grain yields, labor force employment in agriculture and the index of domestic food prices covering a 38-year period (1980–2017). Environmental problems have been studied through a retrospective analysis of fertilizers' and pesticides' use, irrigation, crop intensity and CO_2 emissions in agriculture. The social context of agricultural sustainability was analyzed by examining attributes such as the use of arable land for urbanization and other industrial purposes, the unavailability of arable land, trends in increasing imports of food grains and the variability of food production.

Hrabrin Bashev, a scientist of the Institute of Agricultural Economics of Bulgaria, conducted a comprehensive study that includes both analytical studies (assessment of the sustainability of the Bulgarian agro-industrial complex and the effectiveness of management in agriculture), and practical recommendations containing mechanisms, to increase the sustainability of the country's agriculture (Bashev, 2021).

A study by scientists Bulut and Gökalp (2022) found that soil erosion is a key factor affecting the sustainability of Turkish agriculture. About 86% of Turkish soils are subject to erosion, the amount of soil lost as a result of erosion per year in Turkey is estimated at 500 million tons. The authors recommend soil protection systems for soil treatment as measures to prevent soil erosion.

The results of numerous international studies in the vast majority of cases cannot be used to transform the agro-industrial complex of Russia, due to the significant differences in the systems of agriculture and food production. This is due to climatic and soil conditions, pronounced seasonality, more complex logistics and other factors. This position is confirmed by the research of a scientist from Wageningen University (Gerritsen, 2019), as well as scientists from the V.I. Crimean Federal University. Vernadsky (Olkhovaya and Shamileva, 2021), devoted to the role of the regional component in issues of agricultural sustainability.

Russian research in the field of sustainable agricultural development focuses primarily on the economic component of the concept of "sustainability". However, it is obvious that the transition to a sustainable model of agriculture is impossible without a comprehensive analysis of the main destabilizing factors of the industry, in particular, environmental issues and the manufacturability of the industry.

Soils are the fundamental basis of crop production, ensuring global food security. In this regard, sustainable soil management is a strategic priority for the agricultural sector. However, soils all over the world have different levels of fertility. In some regions of the world soils are inherently infertile and practically unsuitable for agriculture. In other regions low soil fertility has resulted from their degradation. In both cases crop yields are limited by a lack of nutrients in the soil. This fully applies to the Russian Federation as well. The differentiation of natural conditions in different parts of the country leads to a wide variety of soils on its territory, which today number 76 types of soils and 25 types of soil complexes.

One of the main problems associated with the use of soil for food production and the maintenance of ecosystem services is the need for optimal use of nutrients. However, often the degree of mobilization of these substances in the soil does not correspond to the increasing demand of plants for them, especially with increasing agricultural yields. To ensure the growth and development of crops, it is necessary to return the vital nutrients to the soil. Therefore, the crop production requires the use of fertilizers. The growth of yields and gross production of crop and livestock products is impossible without the intensification of agriculture and use of chemicals. Soil stability can be maintained only with the scientifically justified use of mineral and organic fertilizers, as well as measures for land reclamation, reduction of wind and water erosion, improvement of their water regime. This, in turn, in the long term will make it possible not to disrupt natural ecosystems and other types of land use currently used to provide ecosystem services, and avoid the conversion of these lands for use in agriculture.

The use of fertilizers significantly increases the availability of nutrients to plants, thereby improving the ecosystem services of the soil, which directly or indirectly provide about 95% of global food production. The rational use of nutrients contributes to the production of more plant biomass, increases the content of organic matter in the soil (FAO, 2019).

On the other hand, in some countries (China, the Netherlands, the United Kingdom, the Republic of Korea, etc.) the intensification of production, excessive fertilization led to soil, air and water pollution and serious violations of the diversity of biocenoses.

These highly contrasting scenarios of nutrient imbalance contribute to a decrease in food security, environmental and economic sustainability, and social justice. They exacerbate global climate change and lead to increased greenhouse gas emissions.

Along with the application of fertilizers, the sustainability of the crop industry is largely determined by the negative effects of diseases and pests of crops. Without proper measures to protect crops, yield losses from harmful organism's amount to about 25%, including 8% from pests.

Therefore, in most countries producing agricultural products, for example in Germany, Argentina, India, etc., there is a tendency to increase the use of plant protection products, and in a number of countries (Japan, the Netherlands, the Republic of Korea, Brazil, etc.) the use of pesticides has reached such a level that poses a threat to the environment and people's health.

In this regard, the purpose of the study is to assess the impact of fertilizers' and pesticides' use on the soil and sustainability of agriculture in Russia.

Materials and Methods

The work uses general scientific methodological approaches and methods of economic statistics. The information base of the study consists of: the FAOSTAT database of the Food and Agriculture Organization of the United Nations; data from the International Association of Fertilizer Producers (IFA); data from the Organization for Economic Cooperation and Development (OECD); reports of the Ministry of Natural Resources and Ecology of the Russian Federation and the Federal Service for Hydrometeorology and Environmental Monitoring. Data sources were searched in scientific electronic libraries and search engines, including eLibrary.RU, ScienceDirect, Scopus and the ResearchGate portal for the period 1960–2024.

Results and Discussion

The expanded use of chemicals has led to a worldwide problem of anthropogenic pollution of the environment and food. The share of agricultural production in environmental pollution is very noticeable and, according to various estimates, can reach 30%, in pollution of reservoirs and rivers – 40%.

Residues of chemicals are included in ecological food chains, getting through water and products into the organisms of animals, birds and at the final stage into the human body, which contributes to the increase in human morbidity. Data from the World Health Organization indicate that environmental problems contribute to an increased risk of more than 100 dangerous diseases in humans, as a result of which about 12.6 million people die annually. In addition, residues of pesticides and fertilizers can accumulate in the human body and cause chronic diseases. It is important to note that children are the most vulnerable group of the population in relation to the effects of pesticide residues and fertilizers (Juvelikyan and Cherepukhina, 2017).

Intensive use of chemicals in agricultural enterprises of the Russian Federation does not always give the expected effect. Thus, in the USSR in 1980–1986, despite a significant increase in the number of agricultural machinery used, the volume of fertilizers, pesticides and land reclamation work, the yield of major crops increased extremely slowly, and according to some data even decreased, which as a result led to the need to import grain and other agricultural products. This is due to the fact that, despite the concentration of about 52% of the global reserves of chernozems, a significant part of the territories is located in areas with a shortage of heat or an acute shortage of precipitation, especially during the warm period. The natural bioclimatic potential of the country, especially hydrothermal, is 2.4–3.2 times lower than in the USA and Western European countries (Gordeev et al, 2006).

International and domestic best practices accumulated over the past decades show that the development of crop industry and increasing the competitiveness of products obtained both in the domestic and international markets, is due to introduction of innovative technologies into production that meet the concept of "sustainability", adapted to landscape and climatic conditions and technical and economic indicators of a certain agricultural enterprise (Papaskiri, 2016).

The transition to sustainable agriculture is one of the key factors in ensuring Russia's food security. The Strategy for Scientific and Technological Development, approved by Decree of the President of the Russian Federation No. 145 dated February 28, 2024, emphasizes the importance of innovative development in agriculture, including the use of sustainable, environmentally safe and energy-efficient technologies.

Soil and soil cover are an indispensable component not only of the agricultural sphere, but also of the biosphere as a whole, regulating the hydrological, gas and hygienic regimes of the terrestrial globe and the surface atmosphere. Due to intensive cultivation of fields, saturation of crop rotations with row crops and the use of erosively hazardous lands for their cultivation, the processes of anthropogenic soil degradation are 30–40 times faster (Zhuchenko, 2009). The water retention capacity of each hectare on eroded lands decreases by 500–600 m^3, which is equivalent to a decrease in the potential yield of grain crops by 5–6 and even 10–12 kg/ha. It is important to take into account that onset of negative effects of chemical and man-made factors on the natural environment is significantly delayed in time, and many indicators of its environmental degradation are not amenable to strict economic assessment (Zhuchenko, 2012).

Table 1 shows data on monitoring of agricultural lands conducted by state institutions subordinate to the Ministry of Agriculture of the Russian Federation, presented in the report of the Ministry of Natural Resources and Ecology of the Russian Federation (Minprirody of Russia, 2023).

In 2020 (Minprirody of Russia, 2021), the area of agricultural land surveyed for negative processes was 12912.63 thousand hectares (in 2019 – 12773.25 thousand hectares, in 2018 – 13822.14 thousand hectares). Among them agricultural lands subject to wind erosion amounted to 1136.94 thousand hectares (8.8% of the surveyed area), salinized – 235.86 thousand hectares (1.8%), waterlogged – 830.73 thousand hectares (6.4%).

The largest areas of arable land subject to wind and water erosion are located in the Volga Region, the smallest in the Northwestern Federal District (Table 2).

Wind erosion (deflation) removes the smallest soil particles and appears on all types of terrain. According to the degree of deflation's manifestation, in accordance with the loss of humus horizon, the following soils are distinguished: (1) poorly ventilated – a decrease in the humus layer up to 20%; (2) me-

Table 1. Causes and intensity of agricultural land degradation in the federal districts of the Russian Federation

Type of degradation	Federal District							
	Central	North-western	Southern	North Caucasian	Volga	Ural	Siberian	Far Eastern
Water erosion	+	+	++	++	++	+	+	+
Wind erosion	+		+	++	++	+	++	+
Waterlogging and waterlogging	+	++	+	+	+	++	++	++
Salting	+		+	+	+	+	+	+
Desertification			+	+	+		+	
Flooding			+	+	+		+	+
Overconsolidation	+	+	+	+	+	+	+	+
Overgrazing of forage lands/overgrazing			+	+	+	+		

Notes: + < 10% of agricultural land has been degraded; ++ > 10% of agricultural land has been degraded. Data as of 01.01.2020 based on reports of the Ministry of Natural Resources of Russia.

Source: Authors' own elaboration

Table 2. The spread of arable land degradation processes in the Federal Districts of the Russian Federation

Federal District	Surveyed	Wind erosion		Water erosion		Salinization		Waterlogging	
	thousand hectares	thousand hectares	%	thousand hectares	%	thousand hectares	%	thousand hectares	%
Central	2750.23	49.45	1.80	177.01	6.30	7.36	0.30	85.83	3.10
North-West	480.40	0.00	0.00	14.33	2.80	0.00	0.00	183.98	38.30
South	2565.57	170.35	6.60	542.20	22.70	75.67	2.90	10.54	0.40
North Caucasian	793.80	299.10	37.70	186.54	25.60	48.83	6.20	78.83	9.90
Volga	3000.18	314.04	10.50	1132.20	37.50	17.97	0.60	34.73	1.20
Ural	1005.99	9.10	0.90	6.33	0.60	16.83	1.70	101.25	10.10
Siberian	1859.40	288.40	15.5	396.36	20.0	59.90	3.20	215.54	11.60
Far Eastern	457.06	6.50	1.40	12.95	2.90	9.30	2.00	120.03	26.30

Note: data as of 01.01.2020 based on reports from the Ministry of Natural Resources of Russia.
Source: Authors' own elaboration

dium–ventilated – a decrease in humus layer by 21–40%; (3) highly ventilated – a decrease in humus layer by 41–60%. In 2020, the main part of the eroded soils was poorly ventilated soils – 930.65 thousand hectares, or 81.9% of the total area of the surveyed agricultural land subject to wind erosion. The share of medium–leached soils was 14.8% (168.06 thousand hectares), highly leached – 3.4% (38.23 thousand hectares).

As of the beginning of 2020, agricultural land subject to water erosion amounted to 2,467.92 thousand hectares (19.3%).

Table 3 shows data from surveys conducted in 2014 – 2020. It follows from them that one of the factors limiting soil fertility and crop yields is water erosion. It is a process of destruction of soil cover under the influence of thawed, rain or irrigation waters, which at the same time contributes to the occurrence of soil drought due to drainage of significant part of precipitation from slopes, as well as siltation of rivers and reservoirs by washed-away soil layer. According to the intensity of annual erosion, soil erosion is divided into the following gradations: (1) slightly washed – the intensity of annual erosion of the fertile soil layer is 0.5–1.0 t/ha; (2) average washed – 1.0–5.0 t/ha; (3) heavily washed – 5.0–10.0 t/ha. As of 31.12.2019, the areas subject to water erosion were distributed as follows: slightly washed soils – 2,046.20 thousand hectares (82.9%), medium–washed – 352.94 thousand hectares (14.3%), heavily washed – 68.78 thousand hectares (2.8%).

Soil salinization is a process of excessive accumulation of water-soluble salts in soils in quantities harmful to plants. Anthropogenic activity can enhance soil salinization. According to the degree of salinity, soils are classified as slightly saline – the content of water-soluble salts is 0.25–0.4%; medium-saline – 0.4–0.7%; highly saline – 0.7–1.0%; very heavily saline (salt marshes) – more than 1%. The results of the study of the identified saline soils in 2020 allowed us to establish that the most common are slightly saline soils – 125.75 thousand hectares (53.3%). Medium-saline soils cover an area of 73.54 thousand hectares (31.2%), heavily saline – 24.96 thousand hectares (10.6%), salt marshes – 11.61 thousand hectares (4.9%).

Table 3. The spread of negative processes in the surveyed territories of the Russian Federation in 2014-2020, thousand hectares*

Year	Surveyed	Wind erosion		Water erosion		Salinization		Waterlogging	
	thousand hectares	thousand hectares	%	thousand hectares	%	thousand hectares	%	thousand hectares	%
2014	4233.88–6673.42*	1403.35	21.00	1512.51	24.20	108.89	2.60	234.45	4.40
2015	2869.64–3750.64*	551.93	18.90	591.31	15.80	101.48	3.50	149.25	4.30
2016	4233.88–6673.42*	1403.35	21.10	1512.51	24.20	108.88	2.60	234.45	4.40
2017	10485.45	1427.17	13.60	1847.17	17.60	432.58	4.10	763.78	7.30
2018	13822.14	1252.79	9.10	2048.08	14.80	241.53	1.70	722.51	5.20
2019	12773.25	1643.74	12.90	2467.89	19.30	277.51	2.20	849.76	6.70
2020	12912.63	1136.94	8.80	2467.92[2]	19.30[2]	235.86	1.80	830.73	6.40

Note: data as of 01.01.2020 based on reports from the Ministry of Natural Resources of Russia.
*depending on the type of negative process.
Source: Authors' own elaboration

Waterlogged soils are those that form under conditions of excessive moisture compared to normal for a given natural and climatic zone. Excessive moisture is a soil condition in which average moisture content during the growing season exceeds 70–80% of total moisture capacity. Waterlogged soils are divided into floodplain, non-floodplain and swampy (soils with excessive moisture during most of the growing season).

Floodplain soils are common throughout Russia (Minprirody of Russia, 2021), but they have their own characteristics. In 2020, they accounted for 16.1% of total area of soils subject to waterlogging (133.68 thousand hectares), non–floodplain – 68.8% (571.3 thousand hectares), swampy – 15.1% (125.75 thousand hectares).

According to the results of monitoring the phosphate state of soils as of 01.01.2020, 2.2 million hectares of soils with very low and low mobile phosphorus content (19.4% of total surveyed arable land area) were identified out of 11.3 million hectares of surveyed arable land. Soils with an average content of mobile phosphorus accounted for 4.0 million hectares (35.6%), with an increased content – 2.6 million hectares (23.4%), with a high content – 1.6 million hectares (14.0%), with a very high content – 0.8 million hectares (7.5%).

The distribution of soils' area with very low and low phosphorus content, requiring the primary application of phosphorus fertilizers, by federal districts is presented as follows: the Central Federal District – 9.5% (spread over an area of 261.5 thousand hectares), the North-Western – 11.1% (34.7 thousand hectares), the Southern – 26.3% (482.3 thousand hectares), North Caucasian – 39.6% (151.1 thousand hectares), Volga – 15.3% (522.7 thousand hectares), Ural – 47.9% (384.1 thousand hectares), Siberian – 11.6% (167.8 thousand hectares), Far Eastern – 59.1% (186.1 thousand hectares).

As of 01.01.2020, from 11.1 million hectares of surveyed arable land, soils characterized by very low and low levels of exchangeable potassium amounted to 0.2 million hectares (1.5% of the total surveyed arable land area) and 0.9 million hectares (8.2%), respectively. Arable land with an average availability of mobile potassium occupied 1.8 million hectares (15.9%), with an increased content – 2.9 million hectares (25.7%), high – 3.6 million hectares (32.8%), very high – 1.8 million hectares (15.9%). The largest areas of low-potash soils are distributed in the Central (0.3 million hectares or 33.3%), Volga (0.2 million hectares or 22.2%) and North Caucasus (0.1 million hectares or 11.1%) federal districts (Minprirody of Russia, 2021).

The collapse of the USSR had a significant impact on various spheres of life in Russia. During the Soviet period, agriculture was consolidated and controlled by the state, which meant that fertilizers, as well as other resources, were allocated and used centrally. After the collapse of the USSR in the 1990s and early 2000s, significant changes took place in the Russian agricultural sector. These changes included a complete reorientation towards a market economy, the elimination of state and collective farms, and increased private ownership of land. During this period, agricultural enterprises faced problems related to financing and availability of resources, including fertilizers, the centralized supply of which was disrupted. Market mechanisms for regulating the fertilizer market have led to an increase in their cost, an increase in the disparity between prices for agricultural products and fertilizers, which has led to a decrease in their use. According to the research of Academician of the Russian Academy of Sciences (Sychev, 2019), as a result of economic transformations in this period, the use of fertilizers decreased by 84.8% from 9.9 million tons in 1990 up to 1.5 million tons in 1999.

In view of this, the Government of the Russian Federation adopted Resolution No. 1405 of December 21, 1999 "On measures to provide agricultural producers with mineral fertilizers and plant protection products in 2000." In 2000, it provided agricultural producers with 2 million tons of mineral fertilizers (in terms of 100% of nutrients) and 20 thousand tons of plant protection products at prices subsidized by the federal budget. Subsidies in the amount of 40% of the selling price (excluding VAT) of chemical products supplied to agricultural producers as part of the implementation of this resolution were paid to enterprises producing chemicals. Agricultural producers paid for the supplied chemicals at prices reduced by the amount of the specified subsidy.

According to FAOSTAT data (Figure 1), in 1992, the nitrogen balance was 1848.4 thousand tons (13.82 kg/ha), in subsequent years it decreased annually and became deficient (negative) in 2002 – (-29.7 thousand tons (-0.24 kg/ha)). In 2003–2007, it was close to deficit – free (zero) – 0.55 kg/ha on average over the period. However, since 2008, the nitrogen balance has been negative almost annually (-0.76 kg/ha on average for 2008–2021), which is largely due to a reduction in the number of cattle and, as a result, the use of organic fertilizers. Nitrogen intake in organic fertilizers in 1992–2021 decreased by 56.9%, from 2,659.1 to 1,145.1 thousand tons, and the CAGR (Compound annual growth rate) was -2.77%.

The situation was somewhat different with the use of mineral fertilizers (Figure 2). In 1992–2004, nitrogen deposition in the form of mineral salts decreased by 65.5%, from 19.61 to 6.76 kg/ha. However, it can be stated that in subsequent years, the volume of nitrogen fertilizer use began to grow and peaked in 2021 at 15.52 kg/ha, with a CAGR of 4.73% in 2004–2021.

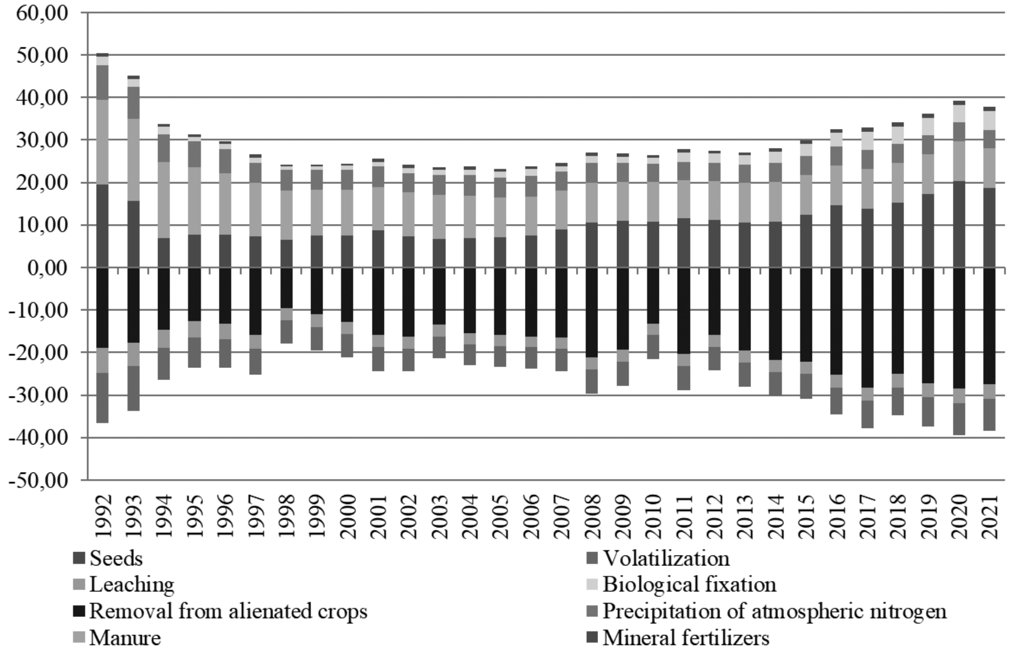

Fig. 1. Nitrogen balance in soil per unit area, kg/ha
Source: Authors' own elaboration

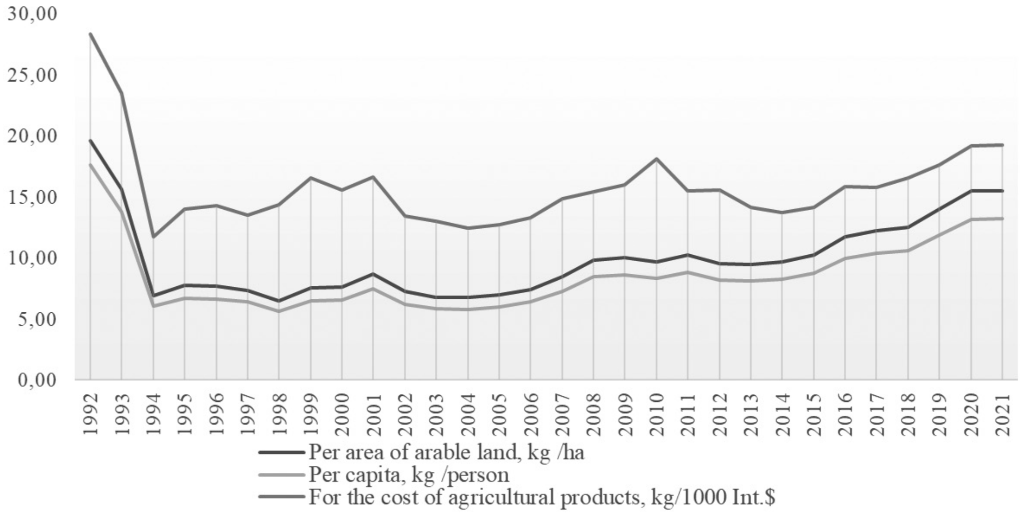

Fig. 2. Application of nitrogen fertilizers in the Russian Federation
Source: Authors' own elaboration

This growth is largely due to government support in the form of compensation for part of the costs to agricultural producers for the purchase of mineral fertilizers. Initially, subsidizing the cost of purchasing mineral fertilizers and plant protection products in Russia was carried out through an indirect financing scheme. Under this scheme, funds from the federal budget were allocated to producers of agrochemicals and pesticides as equity financing to cover the cost of purchasing chemicals. The amount of subsidy was determined based on competitive prices, the volume of supplies and available funds in the budget. However, under this scheme, an unequal exchange has arisen between agricultural producers and other market participants, due to the use of commodity loans to agricultural producers who do not have the financial means to purchase chemicals from intermediary, and processing organizations with the necessary financial resources. Later, another system was introduced, under which compensation for part of the cost of purchasing fertilizers is carried out at rates approved by the Ministry of Agriculture of Russia per 1 hectare of fertilized crop acreage, subject to the following requirements: (1) the regional budget provides for co-financing of compensation payments for the purchase of fertilizers; (2) the list of crops included in the subsidy scheme, defines the Ministry of Agriculture of Russia; (3) subsidy recipients comply with minimum fertilizer application requirements and are required to participate in an agrochemical soil survey of farmland; (4) measures have been taken in the region to prevent farmland from being out of circulation (Efremov and Sychev, 2012).

Referring to the accompanying statistical information reflecting the impact of fertilizers on the sustainability of agriculture, it can be concluded that the policy pursued by the Government of the Russian Federation has created an increasing trend in nitrogen application per capita and the cost of products in 2004–2021 (Figure 2). So, in 2021 the use of nitrogen was 13.21 kg per capita, the use of nitrogen for the cost of agricultural products was 19.25 kg/1000 Int. $, which is, respectively, 127.4% and 54.4% higher than in 2004. However, these figures are significantly lower than in other key agricultural producing countries. So, in France in 2021, the use of nitrogen per area of arable land amounted to 87.3 kg/ha, per capita – 28.5 kg/person, for the cost of agricultural products – 31.7 kg/1000 Int. $, and this is against the background of a decrease in use of mineral fertilizers as part of the ongoing reforms in the country aimed at the development of sustainable agriculture (Mitrofanov et al., 2023).

The phosphorus balance in Russian agriculture in 1992–2021 was deficit-free, with the exception of 2016 and 2017. However, it decreased significantly in 1992–2006 from 6.33 to 0.56 kg/ha (91.2%), and then stabilized at 0.32 kg/ha in 2007–2021 (Figure 3). The volume of phosphorus application in organic fertilizers in 1992–2021 decreased from 627.6 to 258.2 thousand tons, with a CAGR of (-2.6%).

According to the data shown in Figure 4, it can be clearly seen that the application of phosphorous mineral fertilizers in 1992–1994 decreased critically: per area of arable land from 11.5 to 2.0 kg per hectare (82.7%), per capita by 83.1% – from 10.4 to 1.8 kg per capita, for the cost of agricultural products – from 16.7 to 3.4 kg/1000 Int. $ (79.7%). Since 2000, there has been an increasing trend in the application of phosphorous fertilizers, associated both with the stabilization of the country's economy and with the use of compensation payments for the purchase of chemicals. In 1999–2021, the use of P_2O_5 increased: for the area of arable land – by 3.83 kg/ha (221.4%), per capita – by 3.24 kg/person (217.5%), for the cost of agricultural products – by 3.1 kg/1000 Int. $ (81.8%).

The potassium balance in agriculture in Russia during the study period was purely positive. However, it decreased significantly per unit area (Figure 5) in 1992–2008 from 21.7 to 3.9 kg/ha (-82.3%).

In Russia, organic fertilizers are the main source of potassium in the soil. The share of manure in the total potassium intake in soil during the study period averaged 84.3%.

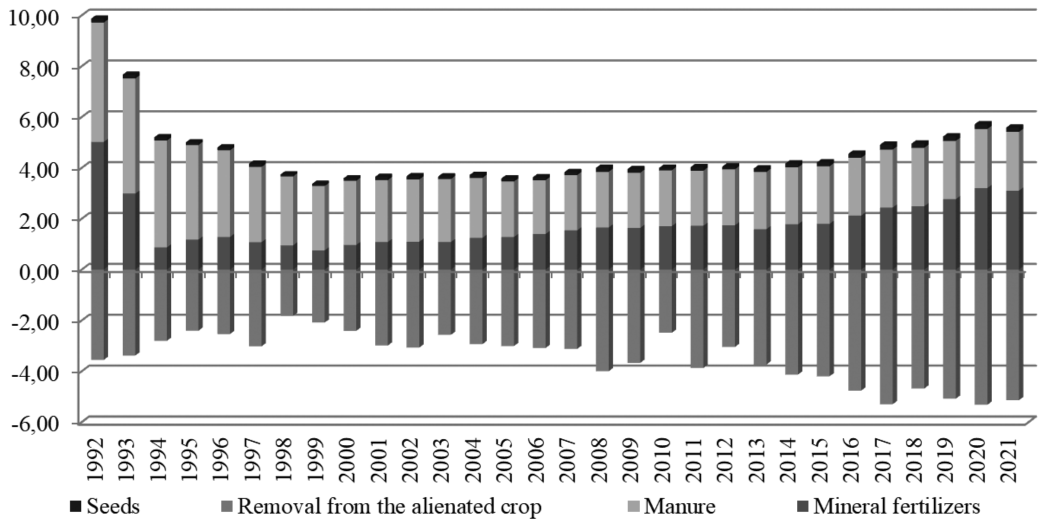

Fig. 3. Phosphorus balance in the soil per unit area, kg/ha
Source: Authors' own elaboration

However, as noted earlier, there is a tendency in Russia to reduce the number of cattle, which is why the volume of production and use of organic fertilizers of animal origin is decreasing annually. In this regard, since 2013, there has been a downward trend in the application of K_2O with organic fertilizers – from 85.2% in 2013 to 68.7% in 2021.

In 1992–1998, the application of K_2O in the form of mineral salts decreased (Figure 6): on the area of arable land – from 10.1 to 1.2 kg per hectare (-88.1%), per capita – from 9.1 to 1.0 kg per capita (-88.5%), on the cost of agricultural products – from 14.6 to 2.6 kg/1000 Int. $ (-81.9%). In 1999–2021, there was an increasing trend. The application of potash fertilizers increased during this period: per area of arable land from 1.44 to 3.87 kg per hectare (CAGR – 4.6%), per capita – from 1.24 to 3.30 kg per capita. (166.1%), on the cost of agricultural products – from 2.92 to 4.80 kg/1000 Int. $ (64.4%).

Based on the data presented, it can be concluded that despite the fact that Russia is one of the largest producers and exporters of mineral fertilizers, and there are growing trends in their application, their domestic use remains

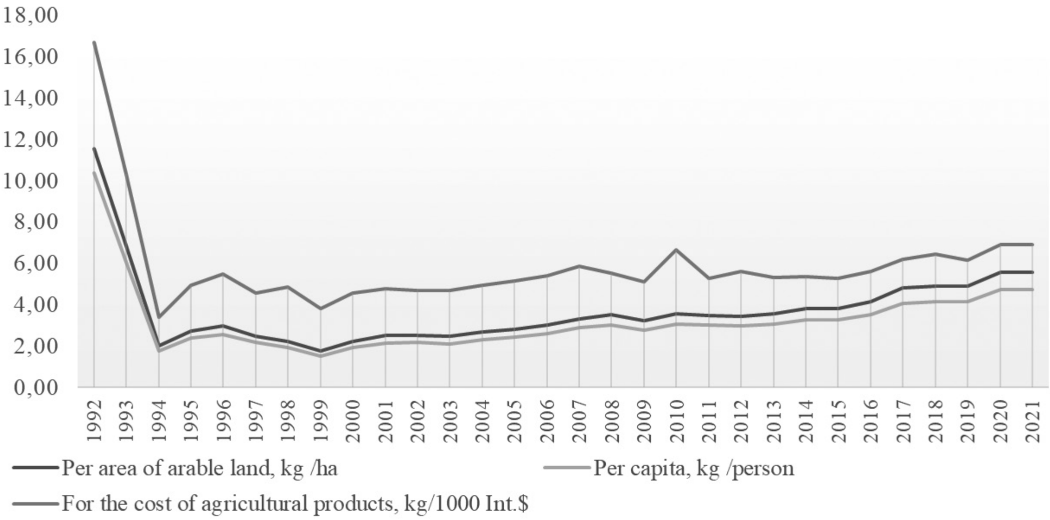

Fig. 4. Application of phosphorous fertilizers in the Russian Federation
Source: Authors' own elaboration

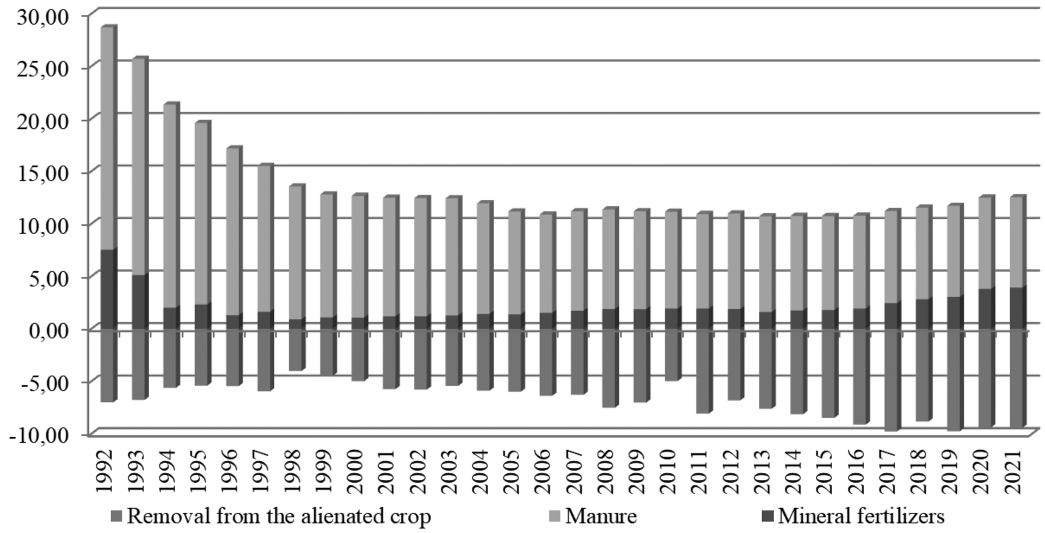

Fig. 5. Potassium balance in soil per unit area, kg/ha
Source: Authors' own elaboration

extremely low. According to Sychev et al. (2019), mineral fertilizers are applied only on half of the cultivated areas. Due to this, crop yields of 50% of the acreage are provided only by the natural background of fertility, which leads to soil depletion. In other cases, the discrepancy between the standards of fertilizers used and the actual needs of crops negatively affects the economic and agronomic effectiveness of their use. On the other hand, in some countries (China, the Netherlands, the United Kingdom, the Republic of Korea, etc.) intensification of production and excessive fertilization have led to soil, air and water pollution and serious violations of the diversity of biocenoses. These highly contrasting nutrient imbalance scenarios contribute to reduced food security, environmental and economic sustainability and social justice. They exacerbate global climate change and lead to increased greenhouse gas emissions (Shilnikov et al., 2008).

In most cases, the reaction of soil environment is a factor limiting the yield, which has a number of environmental and economic consequences, especially with a high content of active aluminum. On such soils the effectiveness of mineral fertilizers decreases by 30–40% and the accumulation of heavy metals, and radionuclides in plants increases by 3–8 times. As a result, the shortage of agricultural crops in the Non–Chernozem zone annually amounts to about 8–10 million tons, and in Russia as a whole – 16–18 million tons (Shilnikov et al., 2008). Acidic soils are characterized by complex of negative properties: (1) toxicity of acidity, often manifested on peat soils with pH_{KCl} 2.8–3.9, with a low content of exchangeable calcium; (2) low content of exchangeable bases (calcium and magnesium); (3) excessive accumulation of mobile manganese and iron in soils.

According to a number of studies (Sychev et al., 2009), the application of lime ameliorants has a strong effect on the decomposition of soil organic matter and various plant residues.

As of 01.01.2020, the area of arable land surveyed for soil acidity amounted to 12.5 million hectares, of which 1.6 million hectares (13.2% of the total surveyed area of arable land) were occupied by acidic soils requiring priority liming, of which 2.3% were strongly acidic (pH 4.4–4.5) and very strongly acidic (pH < 4). Soils with a favorable level of acidity (pH 5.6–6.0) were identified on an area of 2 million hectares (16.2%). Soils with a neutral reaction of the environment (pH 6.1–7.5) were located on 4.6 million hectares (36.6%). Soils with a pH above 7.5 were located on 1.8 million hectares (14.8%). In context of federal districts of the Russian Federation, the largest areas of arable land in need of liming are located in the Central Federal District (44.3%). The largest area of arable land with a high degree of acidity was found in the Central (34.9%) and Volga (33.5%) federal districts (Minprirody of Russia, 2021).

For soils with a flushing moisture regime, which is characterized by the migration of bases with infiltration waters, optimization of the reaction of environment in soil and saturation of its absorbing complex with bases is a prerequisite for the farming system. At the same time, the reaction of the environment in soil affects not only the leaching of bases, but also heavy metals, the ingress of which with infiltration into groundwater can affect their suitability for public water supply.

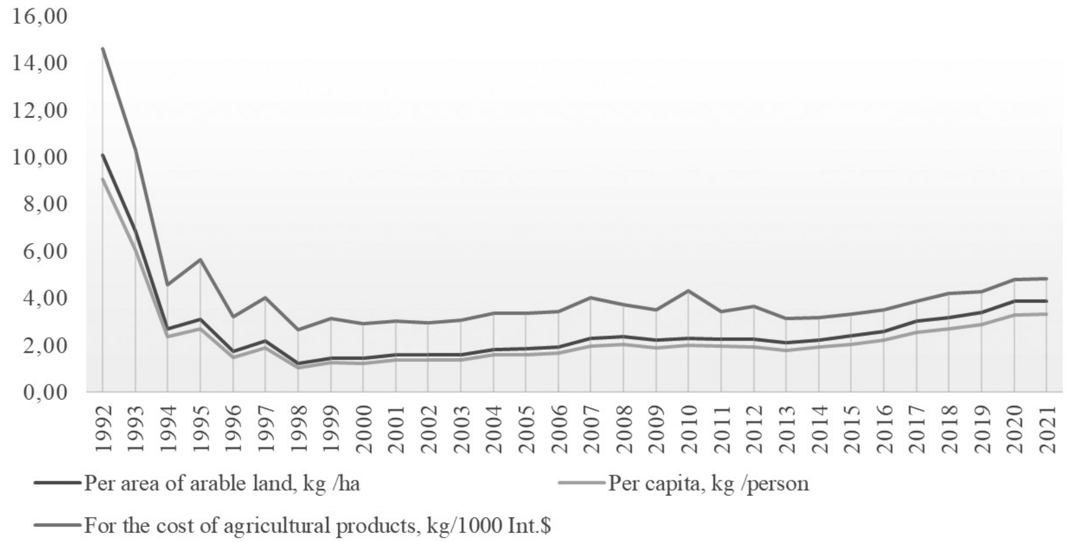

Fig. 6. Application of potash fertilizers in the Russian Federation

Source: Authors' own elaboration

Due to its crucial environmental and economic importance, liming has found wide application in agricultural practice in a number of countries around the world. In the USA, Germany and England 70–80% of liming costs are compensated by the state (Aristarkhov, 2019)

Currently, the problem of human society's interaction with nature has become particularly acute. One of the fundamental principles of sustainable development is to ensure environmental safety by taking direct action to conserve, protect and enhance natural resources. One of the most intensely polluting groups of substances is pesticides, which, once in the soil, dissolve in the soil solution, then they migrate to the lower horizons. The most persistent and mobile compounds can migrate with natural waters over long distances, including persistent pesticides included in the list of persistent organic pollutants of the Stockholm Convention. Pollutants accumulate in plant tissues, then enter the tissues of animals, birds that eat fruits and seeds, or people who feed on them. The concentration of many pollutants increases as they move up the food chain, which increases their danger to human health. Organisms living in soil, such as earthworms, can also absorb pollutants.

The Review of State and Pollution of the environment in the Russian Federation for 2021, presented by Roshydromet (2022), provides the results of a sample survey of soils of 39 subjects of the Russian Federation. The total surveyed area was 29.8 thousand hectares, including agricultural land. According to the data provided in the review, in previous studies it was found that total DDT was the main pollutant of agricultural land. According to GOST 17.4.1.02-83, this pesticide belongs to the first hazard class, and is also a persistent organic pollutant (POP). However, by Resolution No. 2 of Chief Sanitary Doctor of the Russian Federation dated January 28, 2021, SanPiN 1.2.3685-21 "Hygienic standards and requirements for ensuring the safety (or) harmlessness of environmental factors for humans" was approved. This document does not contain standards for the content of DDT in soil and other objects. In this regard, data on cases of high levels of total DDT were not taken into account when calculating contaminated areas.

On the territory of 5 subjects of the Russian Federation (including DDT in 10 subjects), the soil did not comply with established hygienic standards. In 2021, the contaminated areas were: 1. 2.4-D – 0.1% of surveyed area of 10676 ha (in 2020 – 0.2% of the area of 10041 ha, in 2019 – 4.2% of the area of 9830 ha, in 2018 – 0.5% of the area of 13100 ha); 2. hexachlorobenzene (HCB) – 0.14% of the surveyed area of 14673 ha (in 2020 – 0.13% of the area of 12444 ha, in 2019 no pollution was detected, in 2018 – 0.1% of the area of 14200 ha); 3. metaphos – 0.9% of the surveyed area of 4740 hectares (the last time contaminated territories were observed in 2016 – 0.42% of the area of 4.3 thousand hectares); 4. dalapone – 11.5% of the surveyed area of 532 hectares (in 2020 – 3.86% of the area of 726 hectares, in 2019 – 43.5% of the area 600 ha); 5. PCBs – 3% of the surveyed area of 874 ha (in 2020 – 1.1% of the area of 897 ha (the last time contaminated areas were identified in 2016 – 4.6% of the area of 578 ha).

FAOSTAT data indicate that there is an increasing trend in the use of pesticides (Figure 7). In 1992–2021, the vol-

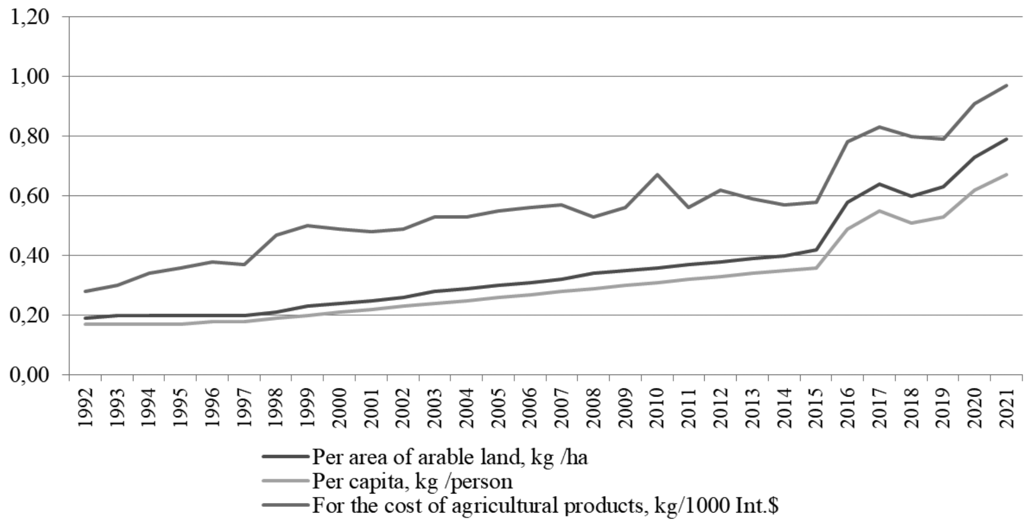

Fig. 7. The use of pesticides in the Russian Federation
Source: Authors' own elaboration

ume of use of plant protection products per area of arable land increased from 0.19 to 0.79 kg/ha (CAGR – 4.86%), per capita – from 0.17 to 0.67 kg/person (+294.1%), for the cost of agricultural products – from 0.28 to 0.97 kg/1000 Int. $ (+246.4%).

Despite this, the volume of pesticide use in Russia is still lower than in most countries. For example, in Japan, the Netherlands, the Republic of Korea, Brazil and others the use of pesticides has reached such a level that it poses a threat to the environment and public health. However, according to FAO data (FAO, 2021), some of subjects of the Russian Federation belong to regions where soil contamination with pesticides is dangerous. These include subjects of the Russian Federation located in the North Caucasus, Central Chernozem and Central economic regions where intensive agriculture is developed (Stavropol and Krasnodar Territories, Belgorod, Voronezh, Rostov regions, etc.).

Conclusions

Thus, in Russia there is a degradation of soils, a decrease in stocks of basic nutrients. The main factors limiting these processes are the inefficient use of land resources, the irrational use of pesticides and agrochemicals, as well as climate change. The combination of these factors leads to soil leaching, decreased fertility, increased erosion processes and changes in composition of soil biota components. In a number of regions of the country, the intensive use of pesticides and the lack of quality management of the work carried out cause pollution of agroecosystems. Territories that do not meet sanitary requirements are identified annually, while both the list of polluting pesticides and the area of contamination are changed, as well as the list of subjects of the Russian Federation with polluted territories. In conclusion, it should be noted that ensuring the sustainable development of agriculture requires an integrated approach, including strategies for the rational use of agrochemicals and pesticides. The use of agrochemicals should be optimized taking into account the real needs of soils for nutrients, compensating for the historical decline, but doing so in compliance with environmental standards and the requirements of sustainable land use. An important area is the introduction of innovative precision farming technologies, modern methods of integrated plant protection, biotechnologies, resource-saving tillage technologies, etc.

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