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AGRICULTURAL CHEMISTRY AND SOIL FERTILITY

Dynamics of Agroecological State of Soils in the Belgorod Region during Long-Term Agricultural Use

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Abstract—Results of eleven survey rounds of arable soils performed from 1964 to 2022 in the southwestern part of the central chernozemic region in Belgorod oblast are analyzed. Ordinary chernozems predominate in the steppe zone of the region, and typical and leached chernozems predominate in the forest-steppe zone. During the eleventh survey round (2019–2022), the average application of mineral fertilizers was 114.4 kg a.i./ha; of organic fertilizers, 9.6 t/ha; the rate of liming of acid soils was 43800 ha per year. As a result, the average yield of winter wheat increased to 5.09 t/ha, sugar beet up to 45.6 t/ha, and corn for grain up to 7.15 t/ha. At the same time, the maximum value of the weighted average content of organic matter (5.3%) was recorded in the soils of cropland for the entire observation period. The part of acid soils decreased to 28.6%, and the part of moderately acid soils decreased to 3.0%. The hydrolytic acidity decreased to 2.7 cmol(c)/kg. The weighted average content of available phosphorus (139 mg/kg) and potassium (161 mg/kg) was the highest in the central chernozemic region. Soils with the low content of available sulfur comprised 85.7% of surveyed soils, those with the low content of zinc, 97.2%; copper, 92.5%; cobalt, 98.8%, manganese, 40.1%; and molybdenum, 21.3%. In terms of the content of available boron, 98.2% of soils were classified as very rich.

Keywords: liming, soil acidity, microelements, soil organic matter, fertilizers, productivity, available phosphorus and potassium

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INTRODUCTION

World Soil Charter notifies that soils play the key role in the life on Earth, but anthropogenic load on them approaches to critical level. So, rational use of soils is one of indispensable components of sustainable agriculture and important tool for climate control and preservations of ecosystems. This document recommends to the governments of the all countries to develop national systems of soil control [15].

Chernozems of the central chernozemic region (CCR) are traditionally considered to be among the most fertile soils in Russia. However, long irrational use of land resulted in soil degradation under the impact of erosion, humus loss, acidification, and other adverse processes [25, 27, 28]. Additionally, productivity of agroecosystems in the CCR was very low for many years because of the low level of agrotechnologies, The situation began to change for the better in the recent years: modern agrotechnologies were adopted, application of fertilizers increased, chemical amelioration of acid soils started. As a result, yields significantly increased [11, 24, 33].

Belgorod oblast is the most developed agrarian region in the CCR. The program of farming biologization, an intrinsic component of agriculture ecologization, has started in 2011 [8, 22]. The main goal of this program is to form soil capable of self-restoring and self-enriching due to natural biological factors, and soil productivity should be increased by at least 1.5 times [18].

As an applied matter, this program is accomplished by means of designing and subsequent implementation of the projects of landscape-adaptive systems of agriculture and soil protection for all land users of the oblast [5–7].

The development of the projects of landscape-adaptive systems of agriculture and soil protection and subsequent assessment of their efficiency are carried out on the basis of the data of state agroecological monitoring within the framework of the Agrochemical Service of Russia [11, 30, 31].

The goal of this work is to analyze the dynamics of agroecological state of arable soils in Belgorod oblast in the course of long-term (1964–2022) agricultural use.

OBJECTS AND METHODS

The study was carried out in Belgorod oblast in the southwestern part of CCR in 1964–2022. The territory of the oblast includes forest-steppe and steppe zones.

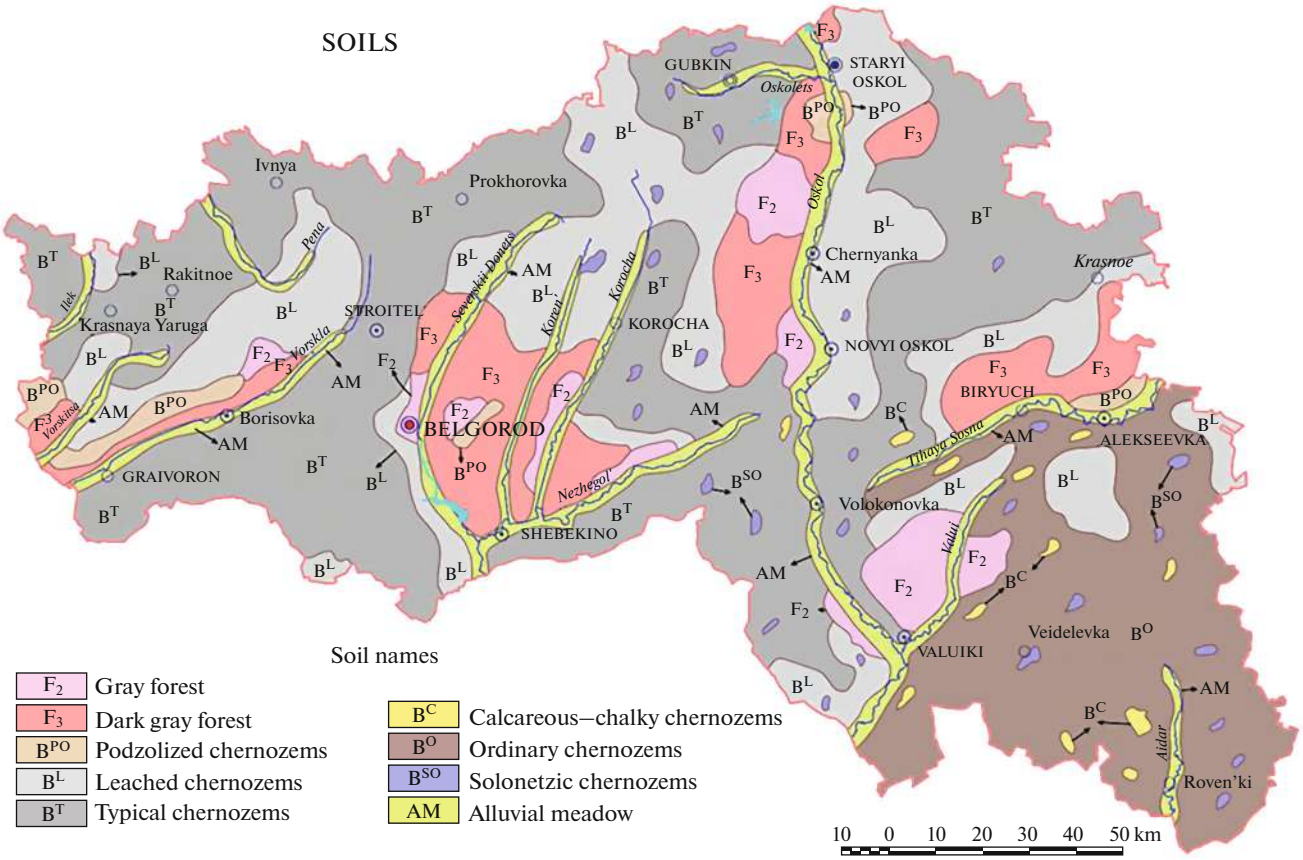

Fig. 1. Soil map of Belgorod oblast [9].

The soil cover of arable lands in the forest-steppe zone is represented mostly by typical chernozems (Haplic Chernozems) (44.8% of all arable soils in the oblast), leached chernozems (Luvic Chernozems) (25.7%), and dark gray forest soils (Luvic Retic Greyzemic Phaeozems) (6.2%). Arable soils in the steppe zone are mainly represented by ordinary chernozems (Haplic Chernozems) (13.0%) (Fig. 1). The share of eroded arable land accounts for 47.9% [9, 23]. The area under all crops in 2019–2022 averaged 1440400 ha [34].

The climate of Belgorod oblast is moderately continental. The Selyaninov hydrothermal coefficient ranges from 0.9 in the southeastern part of the steppe zone to 1.2 in the western part of the forest-steppe zone. Data on the dynamics of mean annual air temperature and annual precipitation in the past decades according to records at weather stations (Belgorod, Bogoroditskoe_Fenino, Valuiki, Gotnya, Novyi Oskol, and Staryi Oskol) are presented in Table 1.

In the forest-steppe zone, the background monitoring was carried out on the watershed plot Yamskaya steppe of the Belogor'e State Reserve within the municipal district (MD) "Gubkin Urban District"; in the steppe zone, on the virgin watershed steppe plot near the village of Viktoropol, MD Veidelevskii raion.

The materials of 11 rounds of soil agroecological monitoring carried out by the Belgorod Center of the Agrochemical Service of the Russian Federation. The whole area of arable lands of the oblast was surveyed during every round. The duration of survey rounds varied from 4 to 8 years. About 70 thousand soil samples were taken and analyzed during every survey round. The contents of organic matter by Tyurin's

Table 1. Dynamics of the mean annual air temperature and precipitation in Belgorod oblast

Parameter	Survey years (rounds)										
	1964–1970 (1)	1971–1975 (2)	1976–1983 (3)	1984–1989 (4)	1990–1994 (5)	1995–1999 (6)	2000–2004 (7)	2005–2009 (8)	2010–2014 (9)	2015–2018 (10)	2019–2022 (11)
T, °C	6.3	6.9	6.2	6.1	6.6	6.9	7.3	7.9	8.0	8.1	8.7
Precipitation, mm	567	524	648	558	562	585	582	549	542	589	553

Table 2. Background contents of organic matter and available forms of the elements in virgin soils of SPNR

Characters		Leached chernozem (layer 10–20 cm) SPNR Yamskaya Steppe		Typical chernozem (layer 10–20 cm) SPNR Yamskaya Steppe		Ordinary chernozem (20–30 cm) SPNR Viktoropol	
		content	supply	content	supply	content	supply supply
Organic matter, %		9.7	High	10.1	Very high	9.5	High
Available species, mg/kg	P_2O_5	24	Low	28	Low	56	Medium
	K_2O	105	Increased	101	Increased	101	Increased
	S	2.90	Low	2.30	Low	2.80	Low
	Zn	0.75	Low	0.79	Low	0.82	Low
	Mn	5.42	Low	10.9	Medium	8.9	Low
	Cu	0.19	Low	0.24	Medium	0.17	Low
	Co	0.14	Low	0.20	Medium	0.14	Low
	Mo	0.09	Low	0.09	Low	0.12	Medium
	B	1.10	High	1.50	High	2.80	High

method (GOST (State Standard) 26213-91), available phosphorus (P_2O_5) and potassium (K_2O) by Chirikov's method (extraction with 0.5 M acetic acid) (GOST 26204-91), available sulfur (extraction with 1 M solution of potassium chloride) with turbidimetric method (GOST 26490-85) were determined in soil samples taken from arable layer of elementary plots 15–20 ha in area. The total (hydrolytic) acidity was determined by GOST 26212-91; the pH of salt (KCl) extract, by GOST 26483-85. Available molybdenum was determined by the Grigg method; the oxalate buffer solution with pH 3.3 was used for extraction (GOST P 50689-94). Available boron (water extraction) was determined by the Berger–Truog method (GOST R 50688-94). Available species of zinc, manganese, copper, and cobalt (extraction with ammonium acetate buffer, pH 4.8) were determined by the Krupskii–Aleksandrova method [14]. The bulk contents of the elements (extraction with 5 M HNO_3) and the contents of their available species were analyzed with AAS method [13]. Specific activity of cesium-137 was determined by γ-spectrometry using a gamma–beta MKGB-01 Radek radiometer/spectrometer.

Statistical treatment of the data of local monitoring included the calculation of confidence interval for the mean ($\overline{x} \pm t_{05}s\overline{x}$). Published materials of the Federal State Statistics Service and Federal Service for Hydrometeorology and Environmental Monitoring were used in the work.

RESULTS AND DISCUSSION

Background monitoring. The presence of the data on background state of virgin soils is the key condition of correct interpretation the results of agroecological monitoring of arable soils. Background monitoring is carried out in the lands of specially protected natural reservations (SPNR).

Background concentration of organic matter in the upper parts of humus horizons of virgin leached and ordinary chernozems accounts in Belgorod oblast for 9.7 and 9.5% respectively (group of high supply) and 10.1% in typical chernozem (group of very high supply). Contents of available P_2O_5 are ranked in leached and typical chernozems as low and in ordinary chernozem as medium. Contents of available K_2O in all subtypes of chernozems correspond to elevated level of supply.

Background concentrations of available compounds of sulfur and zinc in all subtypes of chernozem are ranked as low and boron as high. Low supply with available compounds of manganese, copper, and cobalt is typical for leached and ordinary chernozems. Supply with available forms of molybdenum corresponds to low level in leached chernozems and to medium level in ordinary chernozems. Typical chernozems are characterized by medium supply with available manganese, copper, and cobalt and low supply with molybdenum (Table 2).

Application of fertilizers and ameliorants. The level of application of fertilizers and volumes of chemical amelioration have great influence on the agroecological state of arable soils and productivity of agroecosystems.

For the period from the first to the fourth rounds of survey the mean rates of mineral fertilizers application increased from 41 to 165 kg of active ingredient/ha, and this was the result of large-scale program of agriculture chemicalization. For the last century, the maximal rate of mineral fertilizers application was reached in the fourth round, and 43.2% fell to the share of nitrogen, 28.5% to the share of phosphorus, and 28.3% to the share of potassium. Significant decrease of fertilizers application was observed in the fifth and sixth rounds to 112 and 38 kg of active ingredient/ha respectively. Application of mineral fertilizers increased in the following years and reached maximal for the current century level in eleventh round (114.4 kg of active ingredient/ha), and the fractions of nitrogen, phosphorus, and potassium accounted for 64.8, 17.3, and 17.9% respectively (Fig. 2).

Table 3. Dynamics of application of fertilizers and crop yields [34]

Parameter		Survey years (rounds)						
		1990–1994 (5)	1995–1999 (6)	2000–2004 (7)	2005–2009 (8)	2010–2014 (9)	2015–2018 (10)	2019–2022 (11)
Winter wheat								
Yield, t/ha		3.23	2.23	2.68	3.30	3.54	4.50	5.09
Applied fertilizers	organic, t/ha	15.5	8.2	4.5	2.3	4.0	4.5	6.1
	mineral, kg/ha	119	49	64	79	100	115	133
Corn for grain								
Yield, t/ha		2.25	2.32	2.66	3.93	4.97	6.65	7.15
Applied fertilizers	organic, t/ha	3.7	0.8	0.2	2.0	11.1	25.1	28.3
	mineral, kg/ha	222	75	98	152	133	130	130
Sugar beet								
Yield, t/ha		21.2	17.9	23.4	21.8	36.8	44.1	45.6
Applied fertilizers	organic, t/ha	6.6	3.6	2.7	3.1	4.5	5.9	5.0
	mineral, kg/ha	308	199	252	346	303	323	367

Application of organic fertilizers increased from 1.6 t/ha in the first to 5.4 t/ha in the fourth round, and then decreased to 1.2 t/ha in the eighth round. Poultry farming and swine husbandry developed successfully in Belgorod oblast in the following years, hence, the production of organic fertilizers increased, and the level of their application reached the all-time high 9.6 t/ha in the eleventh round.

The efficiency of fertilizers significantly increased in the last years due to the use of heavy-productive varieties and hybrids of agricultural crops, modern plant-protecting agents, systems of machinery, allowing to increase the quality of application of agrochemicals and other technological operations. For example, in average 6.6 t/ha of organic fertilizers and 308 kg a.i./ha of mineral fertilizers were applied under sugar beet in the fifth round, and the yield reached 21.2 t/ha; average rate of organic fertilizers application decreased in the eleventh round by 24.2% to 5.0 t/ha, the rate of mineral fertilizers application increased by 19.2% to 367 kg a.i./ha, but the yield increased 2.15 times. The yield of winter wheat increased over the same period by a factor of 1.58, but average rate of mineral fertilizers application increased only by 11.8%, and that of organic fertilizers decreased by 2.54 times. The yield of corn for grain increased by 3.18 times, but mineral fertilizers application decreased by 41.4%, and organic fertilizers application increased by 7.65 times (Table 3).

The volumes of liming of acid soils in the fourth and fifth rounds accounted for 33.1 and 31.3 thousand hectares per year respectively. The volumes of chemical amelioration decreased to minimum 1.2 and 1.7 thousand hectares per year in the seventh and eighth rounds. The volumes of liming increased significantly in the next years due to implementation of the oblast and then of federal programs on the support of these works. Annual liming reached 75 thousand hectares of acid soils (30.2% of the volume in the Russian Federation) in the tenth round.

The maximal mean rates of mineral fertilizers application in CCR in 2015–2020 were recorded in Kursk oblast (156 kg a.i./ha) and the minimal rates – in Voronezh oblast (88 kg a.i./ha). Maximal rate of organic fertilizers was applied in Voronezh oblast (3.34 t/ha) in these years additionally to Belgorod oblast, and the minimal rate was observed in Tambov oblast (0.24 t/ha). Annual area of liming of acid soils accounted for 27.0 thousand hectares in Lipetsk oblast, 13.5 in Tambov oblast, and 13.0. thousand hectares in Kursk and Voronezh oblasts [11, 34].

Organic matter content in soils is traditionally considered the most important index of soil ecological state, material and energy basis of functioning the ecosystems of all levels [12]. The most important role in sequestering the emissions of carbon dioxide is assigned in last years to soil organic matter [1, 4]. It is not a mere coincidence that humus soil layer is considered the special energy sphere—humus sphere [21].

In extensive agriculture, at low rate of fertilizers application, the organic matter content determines largely the nutrient status of soils, and first of all status of nitrogen, because organic matter accumulates more than 90% of total stock of this element. Close direct correlation was found between the organic matter content in soilarable layer (x, %) and easily hydrolyzable nitrogen by Cornfield (Y, mg/kg). A mathematical model, which allows calculating with high accuracy the concentrations of easily hydrolyzable nitrogen, was developed on the basis of results of treatment the sample composed of 100 individual samples with organic matter content 4 to 6%.

$$Y = 23x + 51;\ R^2 = 0.90.$$

When using modern intense agrotechnologies with high rate of fertilization, the correlation between

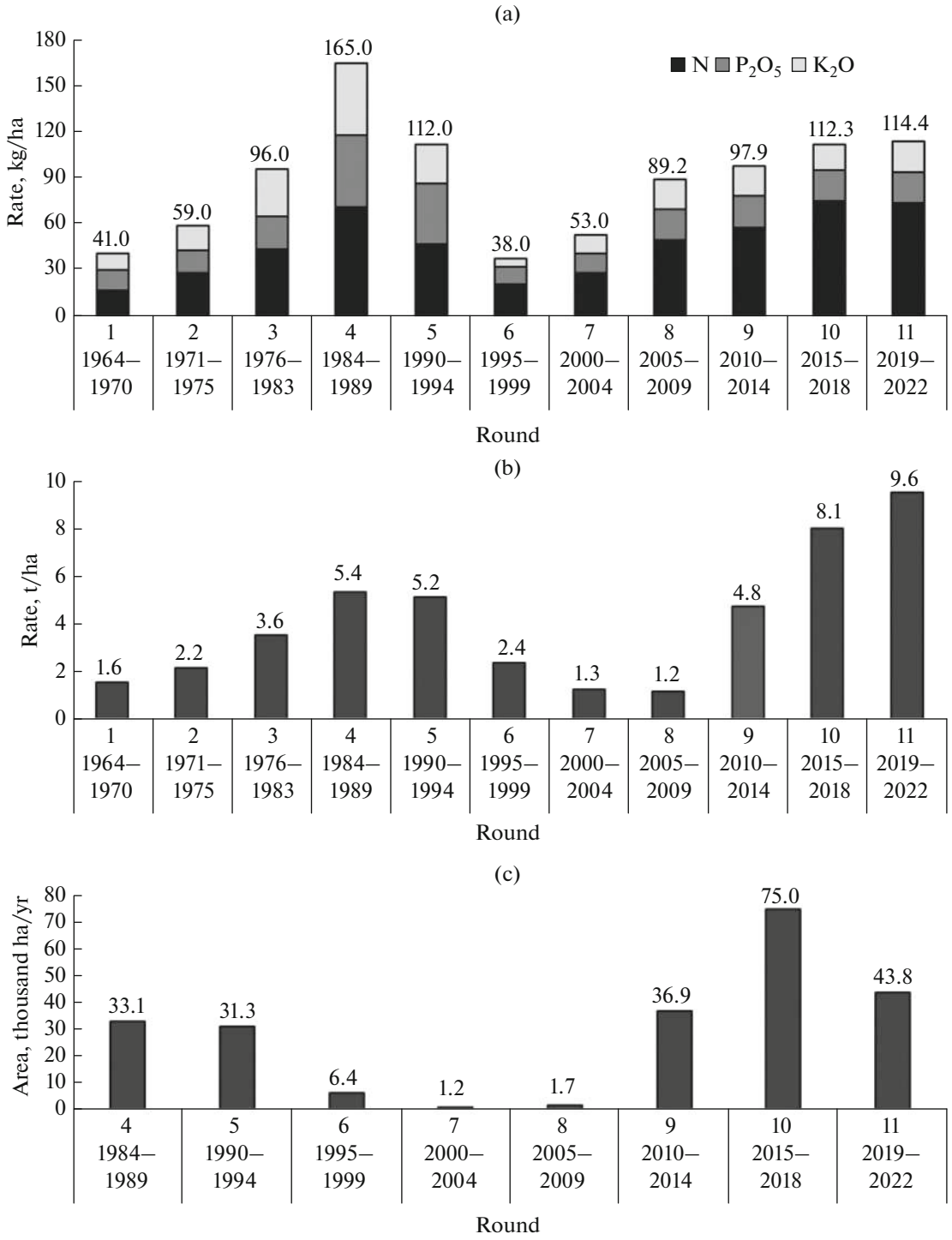

Fig. 2. Dynamics of application of (a) mineral and (b) organic fertilizers; (c) area of annual liming.

organic matter content in soil and yields of crops is relatively weak. For example, maximum weighed mean content of organic matter in arable soils in CCR was typical for Tambov oblast (6.5%), and minimum weighed mean for Kursk (4.7%) oblast. However, average yields of cereals and grain legumes over 2015–2020 years accounted for 4.95 t/ha in Kursk oblast and 3.67 t/ha in Tambov oblast due to high rates of application of mineral fertilizers [11, 34].

Weighted mean content of organic matter in arable soils of Belgorod oblast varied within 4.8–5.0% from the fourth to the ninth rounds of survey and increased to 5.3% in the eleventh round (Fig. 3). The increase of this parameter by 0.3% corresponded to

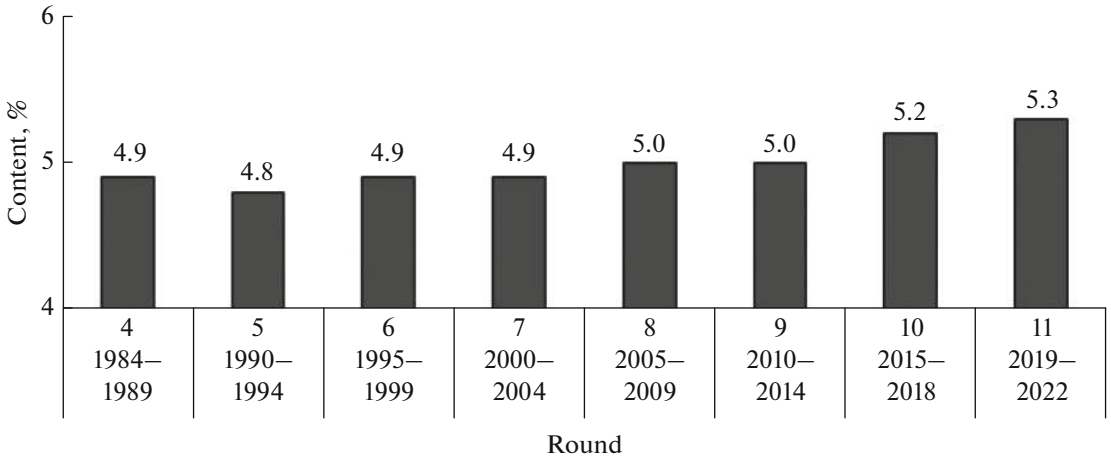

Fig. 3. Dynamics of the mean weighted content of organic matter in arable soils.

the growth of organic matter stock in the plow layer (with mass 3000 t/ha) by 9 t/ha, in which 5.2 t/ha of carbon (or 19 t/ha of CO_2) are deposited.

The fraction of soils with an elevated content of organic matter increased to a historical high level (20.0%) in the last round, and the fraction with low content decreased to minimum 10.9%. Arable soils with medium content of organic matter (68.9%) predominated (Fig. 4). Weighted mean content of organic matter in soils of municipal districts varied from 4.07 (Graivoronskii raion) to 6.03% (Prokhorovskii raion).

The observed regularity of increase in soil supply with organic matter was caused by combined effect of several factors.

First, the rate of organic fertilizers application in the tenth and eleventh rounds exceeded 8 t/ha. According to generalized data, the rate of cattle manure in grain-row crop rotations in CCR, under which the deficit-less budget of soil organic matter is formed, ranges within 6–8 t/ha of rotation area [11].

Second, the input of plant residues significantly increased due to higher productivity of agroecosystems. For example, the increase of the yield of grains of winter wheat and corn, respectively, from 3.30 and 4.97 in the ninth round to 5.09 and 7.15 t/ha in the eleventh round resulted in the increase of output of by-products from 5.2 and 7.7 to 6.7 and 10.3 t/ha. The practice of cultivation of green manure crops (mostly of white mustard) was widely used owing to implementation of the regional program of farming biologization. Green manure crops were sown in the area of 124 thousand ha/year in the ninth round, 303 in the tenth round, and 317 thousand ha/year (22.0% of total area under crops) in the eleventh round. According to the content of organic matter, 1 t of straw is equated with 3.6 t of cattle manure, and 1 t of cruciferous cover crop of with 0.7 t [17]. Additionally, 5.7% of the area under crops was occupied by perennial legume grasses in the eleventh round, under which positive of soil organic matter budget was formed at the expense of plant residues.

Third, the area of black fallow significantly decreased in the oblast, and mineralization of organic matter decreased. If the area of black fallow accounted for 128.6 thousand ha in the ninth round, so in accounted for 64.7 in the tenth round and 47.1 thousand ha in the eleventh round ha. The mineralization of soil organic matter under black fallow is estimated as 0.02% of its stock in plow layer, and this averaged about 3 t/ha for soils of the oblast. The transition to minimal soil tillage, technology of direct seeding and "no-till" system (which is not comprehensively studied in Russia) is the factor, which decreases significantly organic matter mineralization. For example, direct seeding was carried out in 23.5% of total area under crops in 2020. This technology of seeding is used mostly in crop rotation link soybeans-winter wheat. The system "no-till" (complete refusal from soil tillage in crop rotation) was used in 11.8% total area under crops.

Acidity is very important agroecological parameter of soil state. Soil acidity determines largely the availability of phosphorus, microelements, radionuclides for plants, symbiotic nitrogen fixation by legumes, and microbiological activity of soil.

Arable soils of forest-steppe zone of CCR were rather strongly acidified in the course of long agricultural use, if periodical liming was not carried out. The main cause of acidification of soil solution is the permanent leaching of calcium form the plow layer. This process is intensified, when physiologically acid mineral fertilizers are used [11, 24, 31].

Soil acidification in CCR can be considered one of the most broad-scale types of soil degradation with extremely negative effect on the productivity of agroecosystems, and first of all on yields of sugar beet, production of which in the region accounts for about a

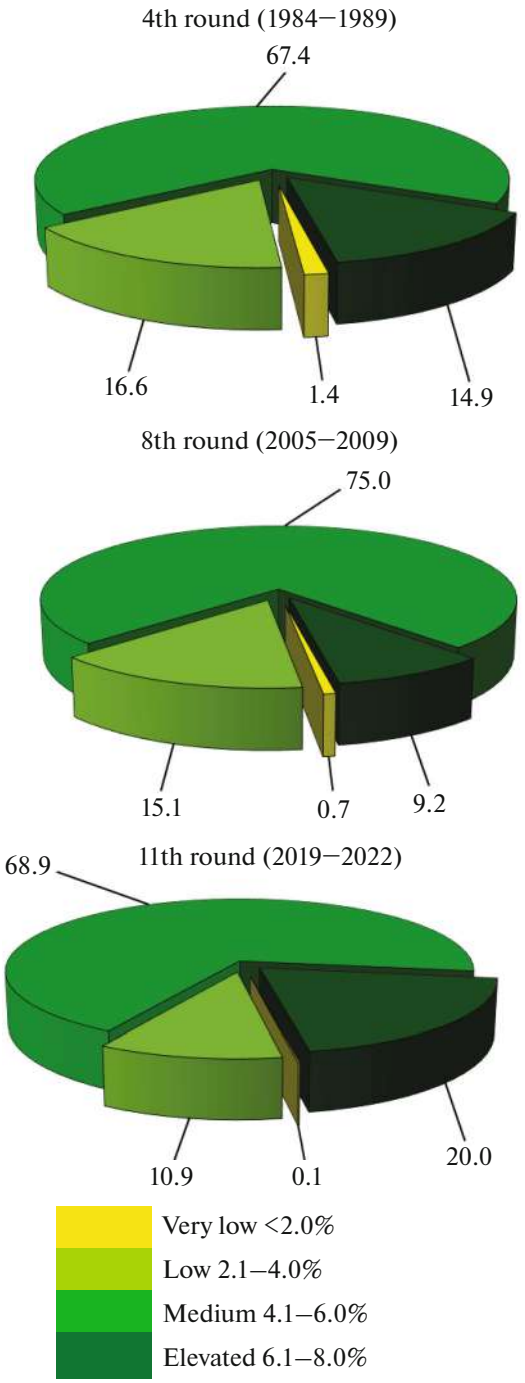

Fig. 4. Dynamics of distribution of arable soils according to the organic matter content, % of surveyed area.

half of Russian production. The fractions of acid soils in Kursk, Lipetsk, and Tambov oblasts, which are completely situated in the forest-steppe zone, account for respectively 71.0, 77.9, and 77.3%, including sum total medium and strongly acid soils 32.8, 30.6, and 30.0% [11].

Minimal fraction of acid soils 22.8%, including 1.5% of medium acid and 0.1% of strongly acid soils, was recorded in the third round of agrochemical survey. Then the fraction of acid soils began to increase regularly because of insufficient volumes of liming and reached its maximal level 45.8%, including medium and strongly acid soils 12.6% and 0.2% respectively, in the ninth round. However, the fraction of acid soils decreased to 35.5% (including 5.8% of medium acid soils) in the tenth round, and to 28.6% (3.0% of medium acid soils) in the eleventh round due to successful implementation of the oblast program of chemical amelioration (Fig. 5). Maximal fraction of acid soils was recorded in the last round of survey in the municipal district (MD) Ivnyanskii raion of Belgorod oblast (56.2%) situated in the western part of forest-steppe zone of the oblast, and acid soils were not found in MD Roven'skii raion of Belgorod oblast, situated in the steppe zone (Table 4).

Weighted mean hydrolytic acidity (Hh) in soils of the oblast was minimal in the fourth round (2.4 cmol(c)/kg) and maximal in the ninth round (3.1 cmol(c)/kg). This value decreased to 2.7 cmol(c)/kg in the eleventh round. In municipal districts of the oblast, weighted mean hydrolytic acidity (Hh) ranged from 1.03 in the steppe zone (Roven'skii raion) to 3.57 cmol(c)/kg in forest-steppe zone (Ivnyanskii raion).

Contents of available compounds of phosphorus and potassium in arable soils is one of primary parameters of soil cultural state. These data are used for calculating the rates of phosphorus and potassium fertilizers.

Minimal weighted mean concentration of available forms of phosphorus in soils of the oblast, close to background values, was recorded in the first round of survey (55 mg/kg). As the rates of applied fertilizers increased, the value of this parameter increased to 131 mg/kg in the sixth round of survey. The decrease of application of fertilizers resulted in the decrease of available phosphorus for plants to 116 mg/kg in the eighth round, and then, as application of fertilizers increased, weighted mean content of available phosphorus increased to 138 mg/kg in the ninth round and to 146 mg/kg in the tenth round (Fig. 6).

The value of this parameter decreased to 139 mg/kg in the eleventh round due to high rates of liming of acid soils. The decrease of acidity resulted in the decrease of mobility of phosphates in soil. Maximal weighted mean concentration of available phosphorus in the oblast was recorded in arable soils of MD Novyi Oskolskii raion (185 mg/kg) and minimal weighted mean concentration (99 mg/kg) was recorded in MD Krasnenskii raion (Table 4). The fraction of soils with very high content of available phosphorus accounted for 16.5% in the last round of survey (Fig. 7). It is recommended to limit the application of phosphorus fertilizers in the case of such soil supply with available phosphorus. Soils with medium supply with this element predominated (32.5%).

Arable soils of Belgorod oblast were characterized by maximum weighted mean concentration of avail-

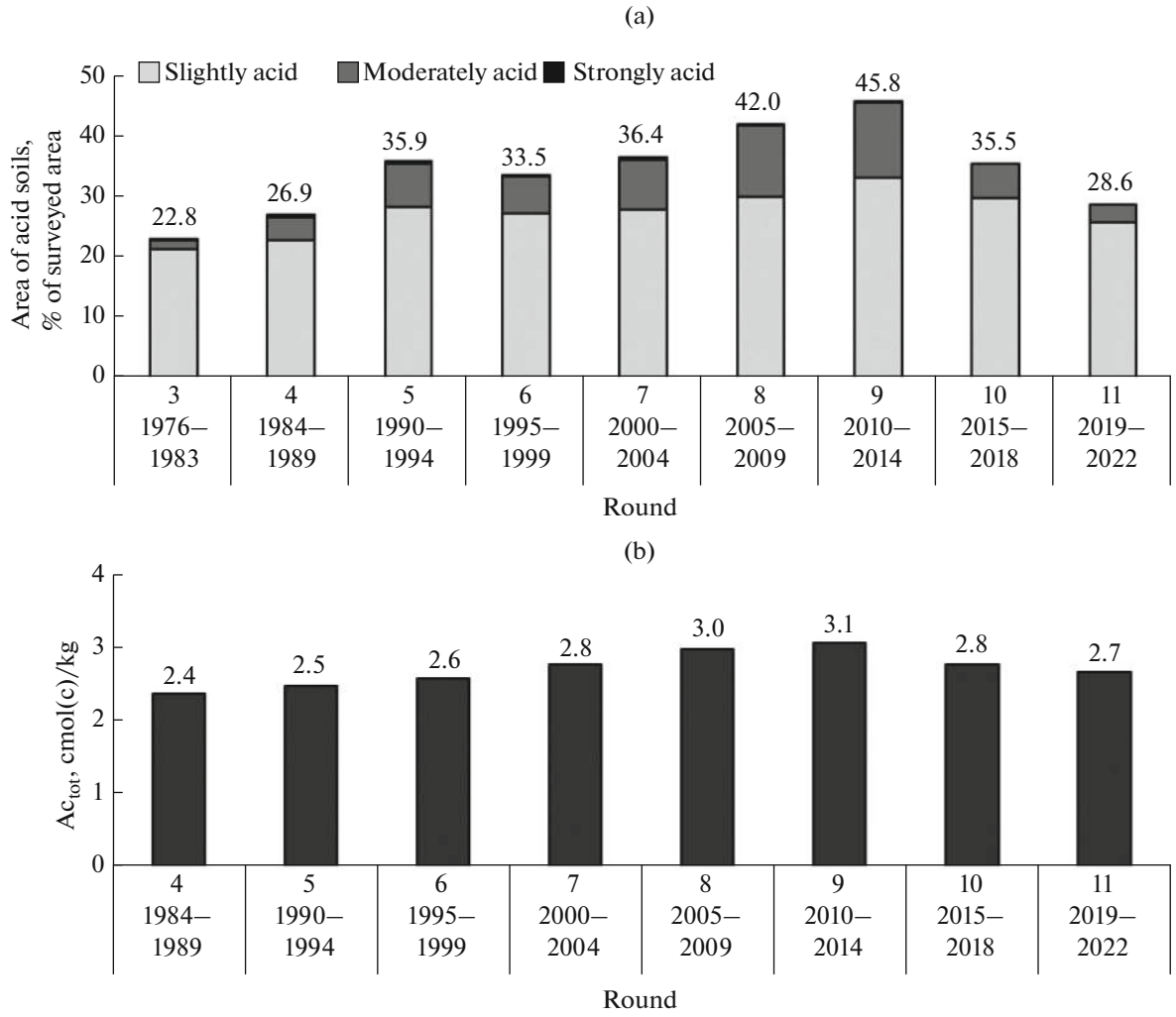

Fig. 5. Dynamics of the (a) area of acid soils and (b) total soil acidity.

able forms of phosphorus in CCR. The values of this parameters accounted for 129, 104, 98, and 88 mg/kg respectively in arable soils of Kursk, Voronezh, Lipetsk, and Tambov oblasts [11].

Weighted mean concentration of available compounds of potassium in arable soils accounted for 105 mg/kg in the first round of survey, and this corresponded to potassium content in background soil. The value of this parameter reached 130 mg/kg in the fourth round and decreased to 121 mg/kg by the seventh round. Increased rates of application of fertilizers, and especially of organic ones, caused the increase of available potassium to 172 mg/kg in the tenth round. The value of this parameter slightly decreased and accounted for 161 mg/kg in the eleventh round. Maximal weighted mean concentration of available potassium was recorded in arable soils of MD Novyi Oskolskii raion (199 mg/kg) and minimal one was recorded in MD Krasnenskii raion (124 mg/kg) (Table 5). The fraction of soils with very high supply with available potassium, on which it is advisable to limit the application of potassium fertilizers, accounted for 28.1%. Most arable soils of the oblast (42.1%) belong to the category with high supply with available potassium (Fig. 7).

Weighted mean concentration of available potassium in arable soils of Belgorod oblast were much higher than in other oblasts of CCR. These values in soils of Lipetsk, Voronezh, Kursk, and Tambov oblasts accounted for 138, 135, 112, and 106 mg/kg respectively [11].

Concentrations of available compounds of sulfur and microelements is an important parameter of soil fertility, which affects significantly the productivity of agroecosystems and the quality of crop products [2, 10, 16]. It should be emphasized that low concentrations in the soil, as well as extremely high ones, exceeding the maximum permissible concentrations (MPC), can be the factors, limiting productivity of agroecosystems.

Table 4. The rates of application of fertilizers, winter wheat yields, and weighted mean values of parameters of agroecological state of arable soils over the 11th round of survey (2019–2022)

Municipal district	Applied mineral fertilizers, kg/ha	Winter wheat yield, t/ha	Fraction of acid soils, %	Ac_{tot}, cmol(c)/kg	Organic matter, %	Concentrations of available forms, mg/kg of soil							
						P_2O_5	K_2O	S	Mn	Zn	Cu	Co	Mo
Forest-steppe zone													
Graivoron urban district	144	5.54	52.8	3.56	4.07	127	137	2.78	10.7	0.40	0.14	0.086	0.18
Gubkin urban district	110	4.84	48.9	3.57	5.96	119	141	3.22	10.9	0.51	0.14	0.085	0.12
Novyi Oskol urban district	119	5.40	24.7	2.64	5.45	185	199	4.22	12.1	0.48	0.10	0.079	0.11
Staryi Oskol urban district	96	4.72	22.3	2.25	5.39	122	141	2.95	11.0	0.46	0.12	0.081	0.13
Shebekino urban district	120	5.58	36.3	3.00	5.08	157	183	5.08	12.4	0.45	0.15	0.074	0.12
Yakovlevskii urban district	92	5.44	41.2	3.22	5.31	168	182	4.12	11.1	0.52	0.11	0.080	0.12
Belgorodskii raion	102	5.57	26.6	2.94	4.91	174	163	3.70	9.6	0.64	0.14	0.093	0.12
Borisovskii raion	149	5.30	42.5	3.10	4.52	118	168	4.10	12.1	0.56	0.11	0.074	0.11
Ivnyanskii raion	129	5.81	56.2	3.74	5.67	157	162	3.54	14.0	0.61	0.12	0.075	0.15
Korochanskii raion	113	5.51	36.8	3.17	5.48	140	181	4.06	12.1	0.55	0.13	0.083	0.12
Krasnenskii raion	59	4.46	21.5	2.24	5.51	99	124	1.93	10.4	0.28	0.19	0.083	0.13
Krasnoyaruzhskii raion	N. d.	5.92	36.2	3.02	4.62	130	117	3.08	7.9	0.80	0.11	0.083	0.14
Prokhorovskii raion	164	5.61	46.9	3.68	6.02	136	171	5.16	12.9	0.56	0.13	0.074	0.13
Rakityanskii raion	88	5.77	45.8	3.30	5.49	168	165	5.33	10.8	1.12	0.14	0.084	0.14
Chernyanskii raion	103	5.05	22.0	2.42	4.78	154	160	3.37	9.4	0.36	0.13	0.084	0.13
Municipal districts partially situated in steppe and forest-steppe zones													
Alekseevka urban district	89	4.34	9.2	1.69	5.22	118	153	5.61	11.4	0.43	0.14	0.070	0.13
Valuiki urban district	113	4.48	10.8	1.81	5.00	123	148	2.73	9.4	0.37	0.10	0.072	0.14
Volokonovskii raion	148	5.14	19.3	2.49	5.44	162	167	2.68	11.1	0.45	0.10	0.079	0.12
Krasnogvardeiskii raion	130	4.74	22.1	2.38	5.32	149	186	2.41	9.4	1.35	0.15	0.091	0.12
Steppe zone													
Veidelevskii raion	130	4.73	3.4	1.64	5.61	108	155	3.91	9.0	0.39	0.12	0.082	0.13
Roven'skii raion	70	3.80	0.0	1.03	5.30	99	136	6.14	14.7	0.45	0.18	0.066	0.12

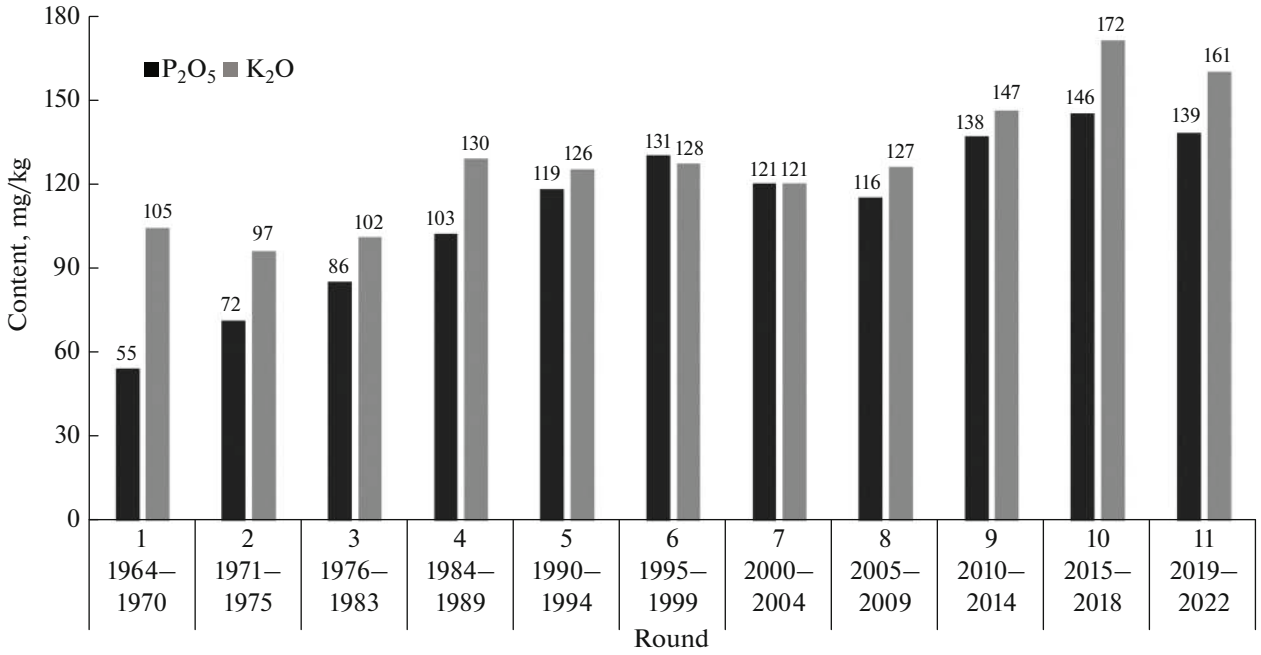

Fig. 6. Dynamics of the mean weighted content of available phosphorus and potassium in arable soils.

Weighted mean concentration of available sulfur decreased from 6.80 mg/kg in the fifth round to 2.60 mg/kg in the eighth round, and then began to increase and reached 3.88 mg/kg in the eleventh round. Rejecting application ordinary and double superphosphates, in which sulfur concentrations were 13 and 6% respectively, was the main cause of sharp decrease of available sulfur content in soils. According to the data of the last round of survey, 85.7% of arable lands belong to the category with low supply with this element (Table 5).

Weighted mean concentration of available zinc in soils was maximum (1.4 mg/kg) in the fifth round, but

Table 5. Dynamics of arable soils distribution by concentrations of available species of sulfur and microelements

Parameter		Years of survey (rounds)						
		1990–1994 (5)	1995–1999 (6)	2000–2004 (7)	2005–2009 (8)	2010–2014 (9)	2015–2018 (10)	2019–2022 (11)
S								
Weighted mean concentration, mg/kg		6.80	5.47	3.47	2.60	2.80	3.30	3.88
Groups of supply, % of the area	high >12 mg/kg	6.1	2.3	1.1	0.3	0.9	1.2	2.9
	medium 6–12 mg/kg	45.7	27.7	10.9	2.5	4.1	8.4	11.4
	low <6 mg/kg	48.2	70.0	65.7	97.2	95.0	90.4	85.7
Mn								
Weighted mean concentration, mg/kg		17.5	12.1	9.8	9.2	10.3	11.7	11.4
Groups of supply, % of the area	high >20 mg/kg	30.4	10.8	3.2	0.6	4.0	4.9	2.4
	medium 10–20 mg/kg	44.5	44.2	31.1	35.0	42.4	56.6	57.5
	low <10 mg/kg	25.1	45.0	65.7	64.4	53.6	38.5	40.1
Zn								
Weighted mean concentration, mg/kg		1.40	0.66	0.51	0.50	0.52	0.49	0.54
Groups of supply, % of the area	high >5 mg/kg	1.9	0	0	0	0.1	0.1	0.5
	medium 2–5 mg/kg	13.6	1.1	0.9	0.2	0.7	1.1	2.3
	low <2 mg/kg	84.5	98.9	99.1	99.8	99.2	98.8	97.2
Co								
Weighted mean concentration, mg/kg		No data			0.08	0.10	0.08	0.08
Groups of supply, % of the area	high >0.3 mg/kg	″			0.5	0.1	0.1	0
	medium 0.15–0.3 mg/kg	″			2.5	5.6	0.6	1.2
	low <0.15 mg/kg	″			97.0	94.3	99.3	98.8

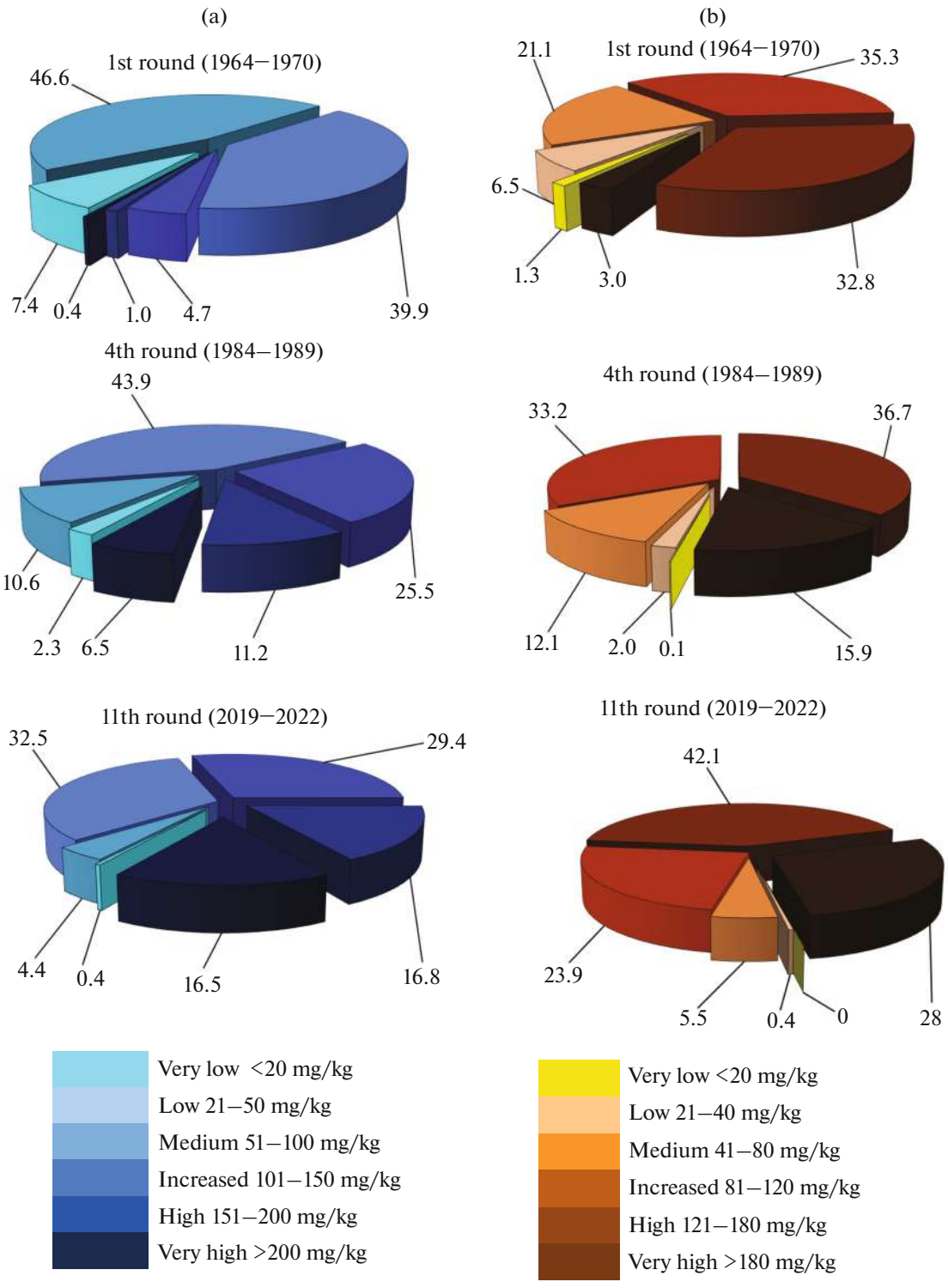

Fig. 7. Dynamics of arable soils distribution according to the contents of available (a) phosphorus and (b) potassium, % of surveyed area.

it decreased to 0.51 mg/kg already in the seventh round and changed insignificantly in the following. The fraction of soils with low supply with this element accounted for 97.2% in the eleventh round.

Maximum weighted mean concentration of available manganese (17.5 mg/kg) was observed in the fifth, and the minimum one (9.2 mg/kg) in the eighth round. Then, the value of this parameter increased to

11.7 mg/kg in the tenth round. Weighted mean concentration of available manganese accounted for 11.4 mg/kg, and the fraction of soils with its low supply was 40.1% in the eleventh round.

Weighted mean concentration of available cobalt in soils was relatively stable during all rounds of survey. The value of this parameter was 0.08 mg/kg, and the fraction of soils with its low content was 97.2% in the eleventh round.

The trend was observed over the period from the ninth to eleventh rounds towards the increased of weighted mean concentration of available forms of copper from 0.11 to 0.13 mg/kg and decrease of the fraction of soil with low supply with this element from 96.9 to 92.5%.

Concentrations of available forms of molybdenum were first determined in soils of the oblast in eleventh round. It was found that weighted mean concentration of available molybdenum accounted for 0.13 mg/kg, the fraction of soils with low supply was 21.3%, medium supply 76.9, and high supply 1.8%.

Concentrations of available boron in virgin and arable chernozems of CCR are evaluated as a rule as high, so the program of total survey does not include this parameter. Sample survey in the area 225 thousand ha in the eleventh round demonstrated that weighted mean concentration of available boron accounted for 2.07 mg/kg, and 98.2% of soils belonged to the category with high supply (>0.7 mg/kg).

The rates of applied organic fertilizers and volumes of liming were the main factors, affecting the concentrations of available compounds of sulfur and microelements in the soil. As application of organic fertilizers increased, input of sulfur and microelements to agroecosystems increased as well, but the mobility of zinc, manganese, copper, and cobalt in the soil decreased in the result of intense liming. The facts were never recorded of exceeding MPC for available zinc, copper, cobalt, and manganese in soils of the oblast.

The fraction of soils in Voronezh, Kursk, Lipetsk, and Tambov oblasts with low supply with available forms of sulfur varied within 74.1–95.1%, zinc – 99.3–99.9, and copper 96.4–99.5%. The fraction of soils with low content of available cobalt in Voronezh, Kursk, and Tambov oblasts accounted for 98.3–99.7%, and manganese 51.9–88.3% [3, 11].

Concentrations of arsenic, cadmium, lead, and mercury, and specific activity of ^{137}Cs were determined within the framework of local agroecological monitoring in reference objects. Mean total concentrations of arsenic, cadmium, lead, and mercury accounted for in ordinary chernozem 5.48 ± 0.34, 0.35 ± 0.02, 11.2 ± 0.4, and 0.023 ± 0.002 mg/kg, respectively, and in typical chernozem 4.18 ± 0.38, 0.32 ± 0.01, 10.3 ± 0.6, and 0.022 ± 0.002 mg/kg. These elements belong to the first class of danger, and their concentrations are limited in soils of many countries of the world [26, 32]. The facts were not recorded of exceeding the approximate permissible concentration (APC) of lead, cadmium, and arsenic and MPC of mercury in soils [19, 20, 29]. Mean specific activity of artificial radionuclide ^{137}Cs in the plow layer of ordinary chernozem was 24.9 ± 2.2 and in typical chernozems it was 17.3 ± 1.6 Bq/kg.

Analysis of crop products demonstrated that overage of MPC of these elements for food products and APC for forage were not recorded.

CONCLUSIONS

It was found in the course of surveying that the average rate of mineral fertilizers application accounted for 114.4 kg a.i./ha, organic 9.6 t/ha, and the volume of liming of acid soils 43.8 thousand ha per year during the eleventh round of survey (2019–2022). As a result, the average yield of winter wheat increased to 5.09, sugar beet to 45.6, and corn for grain to 7.15 t/ha. Maximum over the whole period of survey weighted mean concentration of organic matter (5.3%) was determined in arable soils. The fraction of acid soils decreased to 28.6%, and that of medium acid ones to 3.0%. The value of hydrolytic acidity decreased to 2.7 cmol(c)/kg. Weighted mean concentrations of available forms of P_2O_5 (139 mg/kg) and K_2O (161 mg/kg) were the maximal in CCR. The category of low supply with available sulfur included 85.7% of surveyed soils, zinc—97.2, copper—92.5, cobalt—98.8, manganese—40.1, and molybdenum—21.3%. According to the content of available forms of boron, 98.2% of soils belonged to the category of high supply.

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CONFLICT OF INTEREST

The author of this work declare that he has no conflicts of interest.

CONSENT TO PARTICIPATE

Informed consent was obtained from all individual participants included in the study.

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