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. RESEARCH ARTICLE

Dynamics of Mobile Phosphorus and Potassium in the Soils of Agricultural Lands of Kostanay Region

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Abstract: Soil phosphorus deficiency is a growing constraint on crop productivity in the agricultural lands of the Kostanay Region, Republic of Kazakhstan, yet systematic data on the spatial dynamics of mobile phosphorus and potassium across soil types remain limited. This study assessed the availability of mobile forms of phosphorus and potassium, alongside key physicochemical properties, including soil pH and cation exchange capacity, in Chernozem and chestnut soils of agricultural enterprises across the Kostanay Region. Soil samples were collected from arable fields and analyzed using standard agrochemical methods. Results revealed a widespread deficiency of available phosphorus in arable soils across most surveyed enterprises, with concentrations ranging from 25 to 80 mg/kg, in contrast to consistently high mobile potassium levels of 200-450 mg/kg. In flat, poorly drained areas of steppe plains and low-relief zones, Chernozem and chestnut soils were frequently subject to salinization and alkalinization, exhibiting elevated soil pH values that further constrain nutrient availability and overall fertility. These conditions underscore the need for targeted phosphorus fertilization, optimized crop rotation planning, and soil amelioration measures in affected areas. Continued monitoring of soil degradation and desertification processes on agricultural lands is recommended to support sustainable land management in the Kostanay Region.

Keywords: Agrocenoses, Common Black Earth, Southern Black Earth, Dark Chestnut Soils, Agrochemical Indicators, Mobile Phosphorus, Mobile Potassium, Exchange Cations, Fertility, Soil Degradation, Variability

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Introduction

The study of agrochemical indicators of soils and the assessment of the availability of agricultural crops with nutrients is the most important aspect of rational and efficient land use in the agro-industrial sector. To increase the productivity of agricultural crops, it is necessary to maintain soil fertility and provide plants with nutrients that take into account their biological needs. On the lands involved in agricultural turnover, a scientifically sound way to improve soil fertility is the use of mineral and organic fertilizers. At the same time, insufficient norms for the introduction of nutrients in fertilizers into arable soils against the background of their regular alienation from the production fields, as well as violations in the use of fruit exchange of

agricultural crops can lead to specific technological degradation of agricultural soils, the so-called agro-exhaustion. Concomitant negative changes in the level of agricultural soil fertility can be a shift in the reaction of the soil environment towards their acidification, as well as a decrease in the degree of saturation of the soil absorbing complex.

On the agricultural lands of Kostanay region, which is one of the centers of agricultural production of the Republic of Kazakhstan, production crop rotations of grain, fodder, vegetable, industrial crops are widespread; haymaking; fallow agroecosystems. The basis of the arable fund of Kostanay region consists of common black earths, southern black earths, and dark chestnut soils. The problem of maintaining the level of natural fertility and its intensification is urgent. In a number of districts of Kostanay region, the processes of technological degradation of soils during agriculturaluse are worsened by the processes of salinization and salinization. Salinization of soils can be formed as a result of natural processes, as well as as a result of irrational land use. In addition, arable land in many districts of Kostanay region is subject to degradation processes of water and wind erosion, and pastures are marked by mechanical degradation – which leads to possible desertification of steppe ecosystems.

The development and implementation of agrochemical and land reclamation measures on agricultural land should be carried out on the basis of monitoring soil and environmental indicators. Therefore, comprehensive research of agricultural soils is necessary to ensure the ecological and food security of this region of the Republic of Kazakhstan. Together, comprehensive control of the agrochemical properties of arable soils, their degradation and pollution processes is closely linked to ensuring food security of the population, which is a strategic task of our time and the basis for ensuring national security of the state.

In this regard, the aim of this study was to analyze the availability of phosphorus and potassium compounds available for plants in the soils of Kostanay region, as well as the current levels of accumulation of exchange bases in the soil absorbing complex, the reaction of the soil environment and the content of toxic and non-toxic salts in them on agricultural land.

Methods

Methods for Determining Agrochemical and Physico-Chemical Properties of Soils

To determine the agrochemical and physico-chemical quality indicators of soil samples, control methods are used that meet the regulatory requirements of the Republic of Kazakhstan. The main part of the information on determining the agrochemical and physico-chemical parameters of soils was obtained on the basis of studies performed in accredited research and testing laboratories of the Republic of Kazakhstan.

Determination of the content of mobile phosphorus and potassium compounds. The content of mobile phosphorus and potassium compounds was measured for carbonate soils according to the Machigin method (GOST 26205-91), and for non-carbonate soils according to the Chirikov method (GOST 26204-91).

Determination of pH, content of exchange2+Ca2+, Mg2+2+and Na+. The pHof H2O of the soil medium was measured in a water extract (at a soil-water ratio of 1:5) potentiometrically on a pHmeter (GOST 26423-85). Measurement range: 1-12 pH units, error-0.1 pH units. The content of exchangeCa2+ and Mg2+ inthe samples was determined complexometrically in modifications for carbonate and non-carbonate soils (GOST 26487-85). Determination Na+ of exchangeable Na+ was performed in an extract of ammonium acetate (GOST 26950-86).

Content of water-soluble salts, carbonates, total alkalinity. To determine the concentration of water-soluble salts, an analysis of the water extract of the soil was carried out (GOST 26423-85), which was used to determine the amount of toxic salts (sodium chlorides), the content of sulfates, as well as calcium and magnesium carbonates. In the water extract, the content of a dense residue, the composition of anions, total alkalinity, and the content of anions were measured: carbonates CO_3^{2-} and bicarbonates NCO_3^{-} (GOST 26424-85), chlorides Cl^{-}, and sulfates SO_4^{2-} (GOST 26425-85, GOST 26426-85).

Results

Assessment of Mobile Phosphorus Content in the Soils of Agricultural Lands of Kostanay Region

Vertical Distribution of Phosphate Content in the Main Types and Subtypes of Arable Soils of Kostanay Region

The profile distribution of available phosphorus forms in black earths and dark chestnut soils of Kostanay region was studied in the studies of Almanova et al., Kenzhegulova et al. [1-3]. The distribution of phosphates in the profile of ordinary black earth is fairly uniform, while in the profiles of southern black earth and dark chestnut soil it belongs to the accumulative type (fig. **error! bookmark not defined.**). In the considered profiles, the phosphate content for all soil horizons is less than 25 mg / kg, that is, it refers to a very low level of plant supply with this element of nutrition.

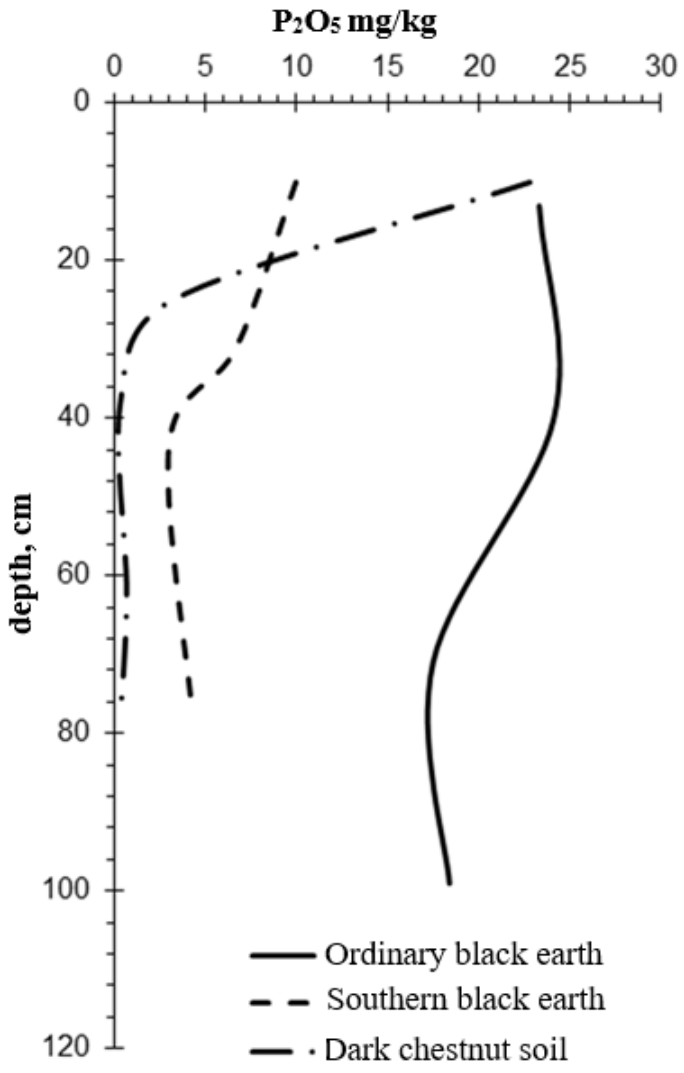


Fig. Error! Bookmark not defined.**: Vertical distribution of phosphates (P_2O_5) in the profiles of ordinary black earth, southern black earth and dark chestnut soil on agricultural lands of Kostanay region, according to stationary studies [1-3]**

To determine the content of mobile forms of phosphorus in black earths and chestnut soils, methods are used with extracts from soil with different reactions of the medium (from slightly acidic to alkaline) and the presence of carbonates. For non-carbonate black earths, the Chirikov method with an extract of 0.5NH3COOH is used, while for carbonate black earths and chestnut soils, the Machigin method with an extract of 1% (NH44) 2co3 is recommended2CO3. When assessing soils by the degree of availability of mobile forms of phosphorus, it is necessary to take into account the determination method used (**Error! Reference source not found.**) (Workshop on Agrochemistry, 2001). In the agrochemical studies in the Kostanay region of the Republic of Kazakhstan, generalized in our work, the method of determining mobile phosphorus by Chirikov was usually used, but in some works the determination was carried out by the Machigin method, and this is a more correct

approach, because most of the black earths and chestnut soils of the territory are carbonate and characterized by an alkaline reaction of the medium (see section 3.3.2).

Table Error! Bookmark not defined.**: Grouping of soils by mobile phosphorus content measured by Chirikov and Machigin methods for black earths and chestnut soils**

Group of soil availability levels by mobile phosphorus	Content Mobile P2o5O5 content, mg / kg	
	According to Chirikov (in 0.5$_{NH3}$COOH) for Non-Carbonate Black Earths	According to Machigin (in 1% $(NH_4)_2CO_3$2co3) for Carbonate Black Earths, Chestnut Soils
Very low	less than 25	less than 10
Low	25-5050	10-15-15
Medium	50-100-100	15-3030
Elevated	100-150-150	30-45-45
High	more than 150	more than 45

Spatial Variation of Phosphate Content

Spatial variability of the phosphate content in the arable horizon on individual agricultural lands was studied by employees of the Agricultural Experimental Station "Zarechnoye" in Kostanay and Fedorovsky districts of Kostanay region [4-7]. On most of the studied agricultural lands, the average level of phosphate supply prevails in the arable horizon (50-100-mg / kg). The maximum values in some fields indicate a high level of phosphate availability (> 150 mg / kg), but there are also points with minimum values that refer to a very low level of availability (<25 mg/kg). The coefficients of variation of the phosphate content in the arable horizon in individual fields range from 15.1 to 58.3%, indicating the average degree of variation of this agrochemical indicator (**Error! Reference source not found.**).

Table 2: Statistical characteristics of the variability of phosphate content (mg / kg) in the upper arable horizon of agricultural soils on individual agricultural lands of Kostanay region

District, soil	Economy, field	Sample size	Average	Minimum	Maximum	Coefficient of variation, %
Fedorovsky, Troyana common black earth	"Trojan"	21	66.2	48.0	96.0	15.1
Kostanay, Lugovoye southern black earths	№11704	15	45,1	17,0	102,0	55,0
	"Lugovoye", №14	13	62,6	12,0	103,0	46,3
	"Zarechnoye", No.91	39	101.3	50.0	250.0	37.9
	"Zarechnoye", №132	30	103,8	49,0	154,0	33,1
	"Zarechnoye", No.133	35	99,5	31,0	404,0	58,5

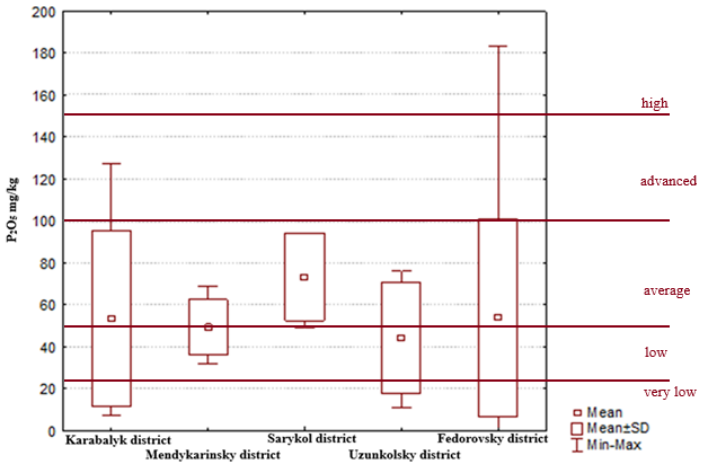
Phosphate Content in Arable Soils by Districts of Kostanay Region

In agrochemical studies conducted on agricultural land in various administrative districts of Kostanay region, the levels of phosphate content in the arable horizon of the main soil subtypes were revealed [8]. Based on the results of this work, statistical characteristics of this indicator were calculated for all districts of Kostanay region (fig. **error! bookmark not defined.**).

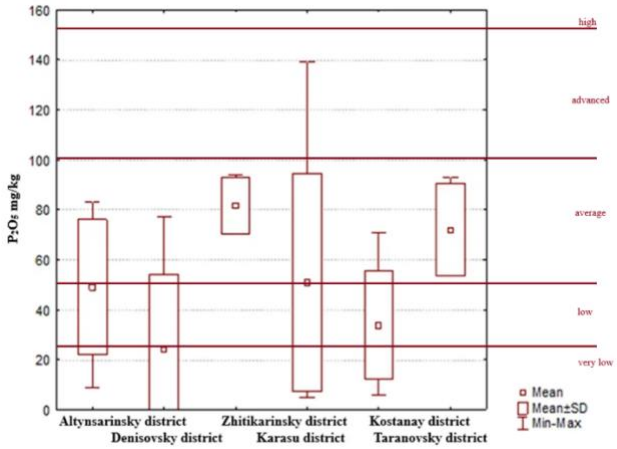
In the common black earth subzone, the average values of mobile phosphorus content in the arable horizon of agricultural lands of the Sarykol, Karabalyk and Fedorovsky districts refer to an average level (50-100-mg/kg) of availability of these elements, while in Mendykarinsky and Uzunkolsky – to a low level (25-50-mg/kg) of availability. The greatest variation in the phosphate content is observed in arable soils of the Fedorovsky and Karabalyk districts, where the minimum values correspond to agricultural land with a very low level of supply (< 25 mg/kg), and the maximum values correspond to high (100-150-mg/kg) and high (> 150 mg/kg) (fig. **error! bookmark not defined.**-a). Mineral phosphorous and organic fertilizers seem to be used in these areas.

In the southern black earth subzone, the average values of phosphate content in the Zhitikarinsky, Taranovsky, and Karasu districts refer to an average level (50-100 mg/kg) of water availability, while in the Altynsarinsky, Kostanay, and Denisovsky

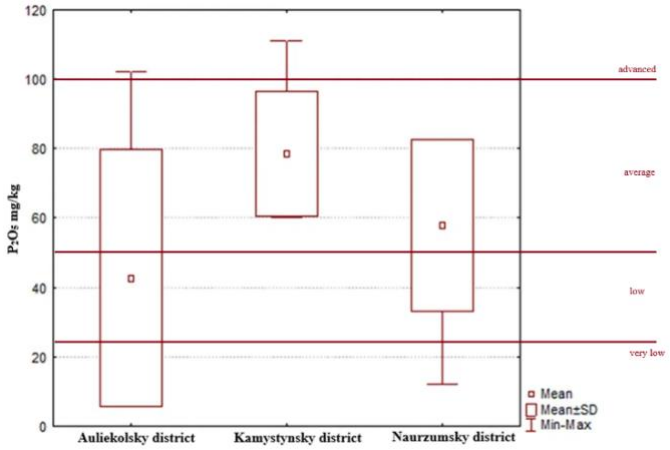
districts – to a low level (fig. **error! bookmark not defined.**-b). The greatest variation in the phosphate content is observed in the soils of agricultural lands of the Karasu district. This can be considered as a result of the use of phosphorous fertilizers in individual farms of the Karasuksky district.



(a) Common black earths



(b) Southern black earths



(c) Dark chestnut soils

Fig. Error! Bookmark not defined.**: Mean levels (Mean), standard deviation (SD), minimum (Min) and maximum (Max) values of phosphate content ($_{P2o5}O_5$) in the arable soil horizon in various districts of Kostanay region: a - on ordinary black earths, b-on**

southern black earth, c - on dark chestnut soils, and their comparison with the levels of mobile phosphorus availability (high, high, medium, low, very low) (according to Ismuratov et al. [8])

In the subzone of dark chestnut soils, the average values of phosphate content in the arable horizon for the soils of Kamystynsky and Naurzumsky districts correspond to the average availability (50-100 mg/kg), while for the soils in Auliekolsky district-to a low level (25-50 mg/kg) (fig. **error! bookmark not defined.**-c). At the same time, a wide range of values is observed in the soils of the Auliekol district, and agricultural lands with maximum values have an increased level (100-150 mg/kg) of phosphorus supply.

Assessment of the Content of Mobile Forms of Potassium in the Soils of Agricultural Lands of Kostanay Region

Vertical Distribution of Mobile Potassium Content in the Main Types and Subtypes of Arable Soils of Kostanay Region

The distribution of mobile forms of potassium in the profiles of arable black earths and chestnut soils of Kostanay region was considered in the studies of [1-3]. The content of mobile potassium in the studied profile of ordinary black earth is about 600 mg / kg, while the vertical distribution is fairly uniform (fig. 313). The content of mobile potassium in dark chestnut soil is about 400 mg / kg, and the profile distribution is also quite uniform. The profile of southern black earth shows an accumulative type of distribution, while the content of mobile potassium in the arable horizon reaches 750 mg / kg. In the profiles for all soil horizons, the content of mobile potassium corresponds to a very high level of availability (> 180 mg / kg), which is typical for natural black earths and chestnut soils formed on loess-like loamy soil-forming rocks [9].

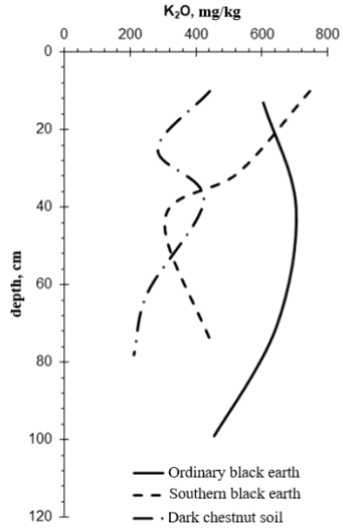


Fig. 31: Vertical distribution of mobile potassium (K_2O) in the profiles of ordinary black earth, southern black earth and dark chestnut soil on agricultural lands of Kostanay region, according to stationary studies [1-3]

To determine the content of mobile potassium in black earths and chestnut soils, methods are used with extracts from soil with different reactions of the medium (from slightly acidic to alkaline) and the presence of carbonates. For non-carbonate black earths, the Chirikov method with an extract of $0.5_{NH3}COOH$ is used, while for carbonate black earths and chestnut soils, it is recommended to use the Machigin method with an extract of 1% $(NH4_4)_2CO_32co3$, there is also a method for determining Maslova. When assessing soils by the degree of mobile potassium availability, the determination method used should be indicated (**Error! Reference source not found.**). In the agrochemical studies in the Kostanay region of the Republic of Kazakhstan, summarized in our work, the most frequently used method was the Chirikov method for determining mobile potassium, but in some studies the determination was carried out by the Machigin method, and this is a more correct approach, because most of the black earths and chestnut soils are carbonate with an alkaline reaction of the medium.

Spatial Variation of Mobile Potassium Content

Spatial variability of mobile potassium content in the arable horizon on certain agricultural lands was studied by employees of the Agricultural Experimental Station "Zarechnoye" in Kostanay and Fedorovsky districts of Kostanay region [4-7]. On all

the studied agricultural lands, the average values of mobile potassium content in the arable horizon belong to a very high level of mobile potassium supply (> 180 mg/kg). The minimum values in some fields refer to a high (121-180-mg/kg) level of mobile potassium supply. Coefficients of variation in the content of mobile potassium in the arable horizon within individual agricultural lands range from 17.0 to 33.7%, indicating a low degree of variation in this agrochemical indicator (**Error! Reference source not found.**4).

Table 3: Grouping of soils by mobile potassium content measured by Chirikov and Machigin methods for black earths and chestnut soils

Group of soil availability levels by mobile potassium	content Mobile$_2$K2o content, mg / kg	
	according to Chirikov (in 0.5 n_{CH3}COOH) for non-carbonate black earths	according to Machigin (in 1% ($NH4_4$)$_2$$CO_3$2co3) for carbonate black earths, chestnut soils
Very low	less than 20	less than 50
Low	21-40-40	51-100100
Average	41-80-80	101-200-200
Increased	81-120-120	201-300-300
High	121-180-180	301-400-400
Very high	more than 180	more than 400

Table 4: Statistical characteristics of the variability of mobile potassium content (mg / kg) in the upper arable horizon of agricultural soils on individual agricultural lands of Kostanay region

District, soil	Economy, field	Sample size	Average	Minimum	Maximum	Coefficient of variation, %
Fedorovsky, Troyana common black earth	"Trojan"	21	327.0	165.0	458.0	23.4
Kostanay, Lugovoye southern black earths	№11704	15	293.4	218.0	399.0	19.3
	"Lugovoye", №14	13	389.6	290.0	492.0	17.0
	"Zarechnoye", No.91	39	383.3	257.0	509.0	17.2
	"Zarechnoye", №132	30	384.0	226.0	532.0	20.9
	"Zarechnoye", No.133	35	374.0	168.0	590.0	33.7

Mobile Potassium Content in Arable Soils by Districts of Kostanay Region

Agrochemical studies conducted on agricultural land in various administrative districts of Kostanay region revealed the levels of mobile potassium in the arable horizon of the main soil subtypes [8]. Based on the results of this work, statistical characteristics of the indicator were calculated for all districts of Kostanay region (fig. 44).

In the common black earth subzone, the average mobile potassium content in the arable horizon of agricultural land for all 5 districts (Fedorovsky, Uzynkolsky, Sarykolsky, Karabalyksky, Mendykarinsky) refers to a very high level of security (> 180 mg/kg). The largest variation in the mobile potassium content for the arable horizon of black earths was recorded in the Fedorovsky district, where the minimum values relate to an increased level of availability (81-120-mg/kg) (fig. 4-a).

In the southern black earth subzone, the average mobile potassium content in all districts (Karasu, Denisovsky, Kostanay, Altynsarinsky, Taranovsky) is very high (> 180 mg / kg), while in the Zhitikarinsky district this indicator is slightly lower than in other districts (Fig. 4-b). The greatest variation in the content of mobile potassium is observed in the soils of agricultural lands of the Altynsarinsky district, where the minimum values relate to a high level of security (121-180-mg/kg).

In the subzone of dark chestnut soils, the average values of mobile potassium content in the arable horizon for the soils of all three districts (Auliekolsky, Kamystynsky, and Naurzumsky) correspond to very high availability (> 180 mg / kg), while the minimum values refer to an increased and average level of availability (fig. 4-c). In the arable horizon of dark chestnut soils of the Auliekol district, the widest range of variation in the values of mobile potassium content is noted.

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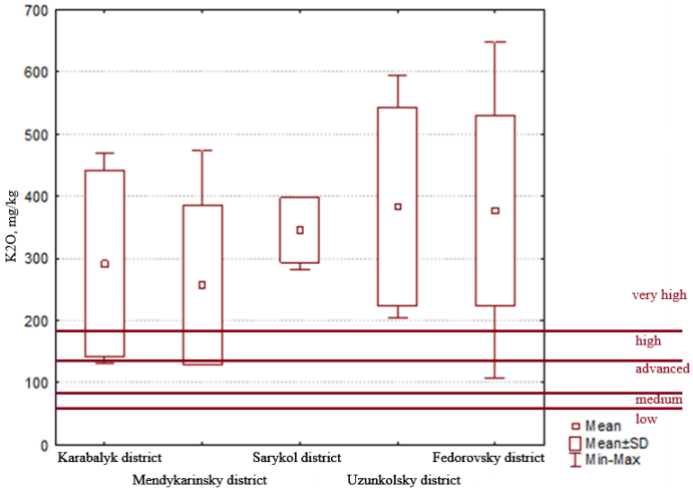
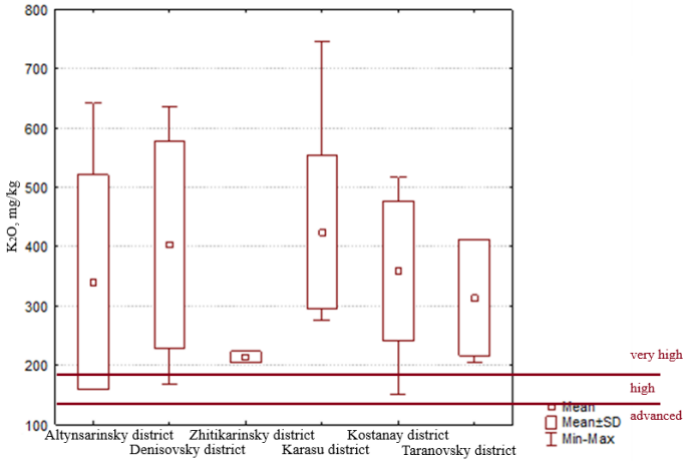
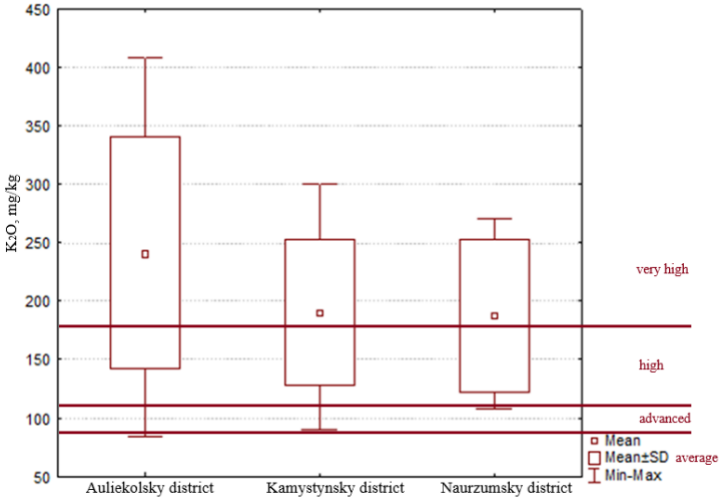


(a) Common black earths



(b) Southern black earths



(c) Dark chestnut soils

Fig. 4: Mean levels (Mean), standard deviation (SD), minimum (Min) and maximum (Max) values of mobile potassium ($_2$K2o) in the arable horizon of soils in various districts of Kostanay region: a – on ordinary black earths, b – on southern black earths, c – on dark brown soils.chestnut soils, and their comparison with the levels of security (very high, high, elevated, medium, low) (according to Ismuratov et al. [8])

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Assessment of Physical and Chemical Parameters of Soils of Agricultural Lands of Kostanay Region

Studies of the Composition of Exchange Cations in the Soils of Kostanay Region

The capacity of cation exchange (EC) and the composition of exchange cations have a great influence on the physical properties of soils and plant growth conditions.

In common and southern black earths and chestnut soils of non-saline genera that are undifferentiated in terms of silt content, the EC usually decreases down the profile along with the humus content [10, 11]. The structure of exchange cations is dominated by the calcium ion. In such soils, the reaction of the medium is close to neutral, colloids are in a state of irreversible gels and do not undergo peptization with an excess of moisture, which causes a good structure of these soils and favorable physical properties for plants [12].

In ordinary black earths of the common and carbonate types, the share of exchangeable calcium decreases down the profile from 70-80% in the humus horizon to 30-40% of the total of exchangeable cations in the rock against the background of an increase in the share of exchangeable magnesium. The proportion of the sum of exchangeable sodium and potassium within the soil profile does not exceed 2.5% and only in the soil-forming rock increases to 6-7% of the sum of exchangeable cations (Fig5) [10].

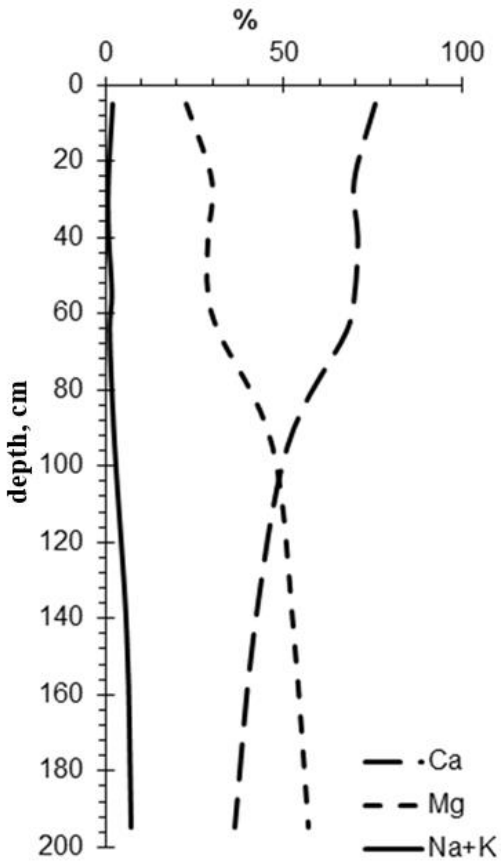

Fig. 5: Profile distribution of exchange cations in ordinary black earth of the Karabalyksky district of Kostanay region, % of the amount of exchange cations [10]

In the southern black earths of the common and carbonate types, the profile distribution of exchangeable calcium and magnesium is similar (fig. 626) [11]. The share of exchangeable sodium in the soil profile, as in ordinary black earths, does not exceed 2.5% of the total of exchangeable cations, but in the soil-forming rock it increases to 10-11%.

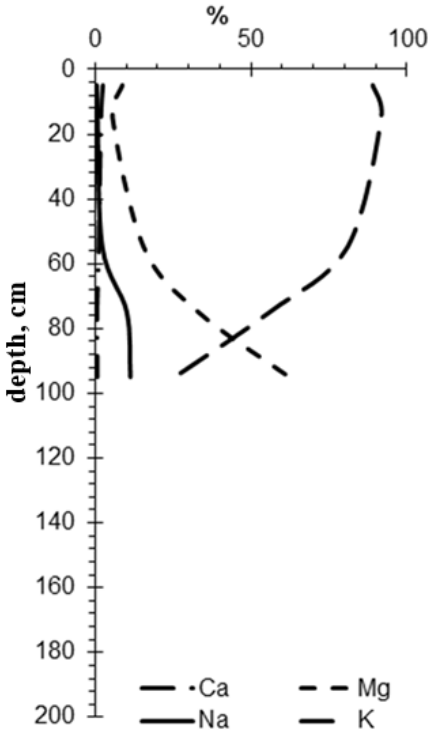

Fig. 62: Profile distribution of exchange cations in the southern black earth of Kostanay district, Kostanay region, % of the amount of exchange cations [11]

Common black earths, southern and chestnut soils of solonets genera are widely distributed in the soil cover of Kostanay region. They are usually formed in complexes with solonets mainly near rivers and lakes in poorly drained areas with a close occurrence of underlying saline rocks. The proportion of sodium in the soil absorbing complex of such soils is higher than 5% of the total exchange cations already within the soil profile, usually in the transition horizon to the rock [12, 13].

In solonets, the profiles of which are usually sharply differentiated in terms of silt content, the maximum EC value is characteristic of the illuvial horizon, and in the overlying solonets horizon, depleted in the silty fraction, it is less. The share of exchangeable sodium exceeds 10% of the total of exchangeable cations (fig7) [1]. An increase in the proportion of sodium in the composition of exchange cations leads to the manifestation of an alkaline reaction, which negatively affects the state of colloids and plant growth. Sodium-saturated colloids are easily peptized, and the soils containing them are usually poorly structuredand have unfavorable water-physical properties: increased density, poor water permeability, poor water recovery, and low availability of soil moisture to plants [14].

To prevent salinization of land in Kostanay region, it is important to control the rational use of land [15]. Reclamation of solonetzic soils should be accompanied by appropriate tillage, herbage (sowing sweet clover or wheat grass) or application of fertilizers (primarily phosphorous). The experience of reclamation of solonets in the southern steppe subzone with dark chestnut soils in the Kostanay region has shown that as a result of deep reclamation treatments, salts are not completely washed out of the soil profile. At the same time, soil vaporization led to a decrease in the salt content in the upper 50 cm layer [16].

Research of Acid-Base Properties of Arable Black Earths of Kostanay Region

In the vertical profiles of the studied common black earths of the Karabalyk and Fedorovsky districts of Kostanay region, the soil reaction measured using the pHvalue H2ovaries from neutral (6.6-7.0) in the upper horizon and slightly alkaline (7.1-7.5) in the sub-arable horizons to alkaline (7.6-8.0) and strongly alkaline (> 8.1) in the middle horizons. and lower horizons (fig) [1, 10]. In the southern black earths, the slightly alkaline reaction of the soil is characteristic starting from the upper arable horizon, and in the sub-arable and underlying ones it becomes strongly alkaline [11].

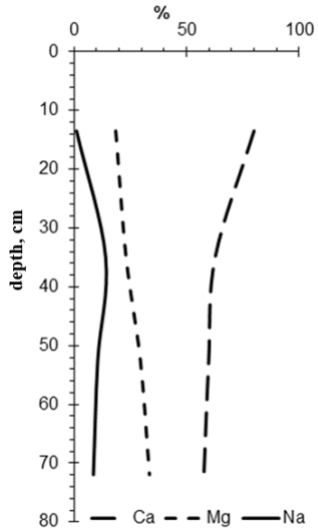

Fig. 7: Profile distribution of exchange cations in black earth solonets of the Fedorovsky district of Kostanay region, % of the amount of exchange cations [1]

The indicator of actual acidity pHH2oin the arable horizon on individual agricultural lands of the farm "Lugovoye" in the pre-sowing period varied from 7.0 to 8.1 [6] (Tulkubaeva et al., 2022), that is, from neutral to highly alkaline, while the average values of 7.4-7.5 refer to a slightly alkaline reaction of the soil environment. The coefficients of variation in the pHof H2owere 4.1-4.8%, indicating a low degree of variation in this indicator. On the studied agricultural lands, the spatial distribution of the pHvalue H2oin the arable horizon satisfies the normal law; the verification was carried out using the Wilk-Shapiro criterion (at the significance level p = 0.05).

The total alkalinity index studied in ordinary black earth of the Karabalyksky hospital was about 0.022% in the upper arable horizon, it decreased to 0.015% in the sub-arable horizon, and increased to 0.040% in the underlying horizons (horizon B2) and 0.051% (horizon C). In the black earth profile of the southern Talapker station, the total alkalinity index gradually increased from 0.022% in the upper layer of 0-10 cm and 0.034% in the sub-arable layer of 20-40 cm to 0.052% at a depth of 90-100 cm [11]. In brackish black earths, the total alkalinity increases to 0.06-0.08% or more, impairing the potential fertility of such soils.

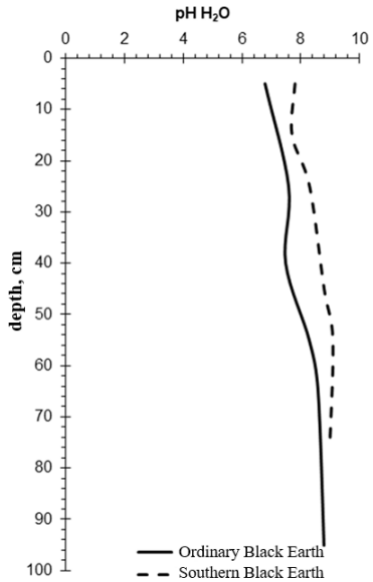

Fig. 8: Profile distribution of H_2O pH in ordinary black earth and southern black earth of Kostanay region [10, 11]

Discussion

Long-Term Dynamics of Phosphate Content in Soils of Kostanay Region

In the study of the dynamics of agrochemical indicators of black earths of Kostanay region [3] for a 32-year period (from 1989 to 2021), a decrease in the content of mobile forms of phosphorus in the arable horizon by 2.0-2.5 mg/kg was noted. Insufficient mobile phosphorus content in the arable soils of many farms is due to the fact that mineral and organomineral fertilizers are not applied on most agricultural land [17]. The reduction of nutrients leads to low productivity of agricultural crops. It is necessary to bring the phosphorus content to an optimal level in the arable soils of the Kostanay region, this will help to even out the diversity of the soil cover on individual lands, stabilize and improve their fertility [1].

Studies conducted at the Karabalyk agricultural experimental station showed that the introduction of superphosphate increases the content of mobile forms of phosphorus in the arable horizon of ordinary black earth and improves the field germination of wheat seeds, as well as increases the amount of gluten in grain [18]. The positive effect of nitrogen and phosphorous fertilizers on the grain yield can be traced both in the variants with traditional tillage and with zero technology.

Based on the data of the Ministry of Agriculture of the Republic of Kazakhstan on the agrochemical state of soils of Kostanay region for the period 2019-2022 [19-22], it is possible to trace the 4-year dynamics of the average mobile phosphorus content and land area with various categories of this indicator, noted according to the results of periodic agrochemical surveys (Table 5). The weighted average value of mobile phosphorus content in the arable horizon of agricultural lands of Kostanay region in 2019 was 18.0 mg/kg. In 2020-2021, the weighted average value decreased to 14.2-15.0 mg/kg, and in 2022 again slightly increased to 15.7 mg/kg. During the entire presented period of 2019-2022, the occupied area in Kostanay region is dominated by land with a low supply of arable soils with mobile phosphorus.

Table 5: Dynamics of mobile phosphorus content and land area with different levels of arable soil availability according to agrochemical surveys of Kostanay region for 2019-2022 [20-23]

Year					2019	2020	2021	2022
Surveyed area, thousand ha					1173.51	804.24	809.16	826.42
Grouping by mobile phosphorus content	low	Group boundaries, mg / kg of soil	no more than 15 mg / kg	thousand ha	534.76	524.71	541.94	480.54
				%	45.6	65.2	67.0	58.1
	average		16-30 mg / kg	thousand ha	499.48	235.15	245.58	301.15
				%	42.6	29.2	30.4	36.4
	high		more than 30 mg / kg	thousand ha	139.27	44.38	21.64	44.73
				%	11.9	5.5	2.7	5.4
Weighted average mobile phosphorus content, mg / kg					18.0	15.0	14.2	15.7

Long-Term Dynamics of Mobile Potassium Content in the Soils of Kostanay Region

In the study of the dynamics of agrochemical indicators of black earths of Kostanay region for a 32-year period (from 1989 to 2021), there were no changes in the gradation of a very high content of mobile potassium in their arable horizon [3]. The potash regime of arable black earths and dark chestnut soils of Kostanay region is quite favorable due to the high content of exchangeable potassium in soils on loess-like loamy soil-forming rocks.

Based on the data of the Ministry of Agriculture of the Republic of Kazakhstan on the agrochemical state of soils of Kostanay region for the period 2019-2022 [19-22], it is possible to trace the 4-year dynamics of the average mobile potassium content and land area with various categories of this indicator, noted according to the results of periodic agrochemical surveys (**Error! Reference source not found.**). The weighted average value of mobile potassium content in the arable horizon of agricultural lands of Kostanay region in 2019 was 483.7 mg/kg. In 2020, the weighted average value increased to 633.6

mg/kg, and in 2021-2022 it sharply decreased to 366.0-384.5 mg/kg. During the entire presented period of 2019-2022, the occupied area in Kostanay region is dominated by land with a high supply of arable soils with mobile potassium.

Table Error! Bookmark not defined.**: Dynamics of mobile potassium content and land area with different levels of arable soil availability according to agrochemical surveys of Kostanay region for 2019-2022**

Year					**2019**	**2020**	**2021**	**2022**
Surveyed area, thousand ha					1173.51	804.24	809.16	826.42
Grouping by mobile potassium content	low	Group boundaries by content, mg / kg soil	no more than 200 mg / kg	thousand ha	11.30	0.53	0.63	1.11
				%	1.0	0.1	0.1	0.1
	average		201-300 mg / kg	thousand ha	89.42	13.27	102.57	167.01
				%	7.6	1.6	12.7	20.2
	high		more than 300 mg / kg	thousand ha	1072.79	790.44	705.96	658.30
				%	91.4	98.3	87.2	79.7
Weighted average value of mobile potassium content, mg/kg					483.7	633.6	366.0	384.5

In general, the content of mobile forms of phosphorus and nitrate nitrogen are the limiting factors of fertility in most areas of Kostanay region, the soil cover of which is represented by ordinary and southern black earths (**Error! Reference source not found.**). Arable dark chestnut soils are severely deficient in nitrate nitrogen. The content of mobile forms of potassium in the arable horizon of black earths and dark chestnut soils in all districts of Kostanay region is very high.

For decades, ordinary and southern black earths, as well as chestnut soils on many agricultural lands of Kostanay region, have been subjected to dehumification, wind and water erosion, salinization, and deterioration of nitrogen and phosphorus nutrition of agrocenotic plants.

Table 1: Prevailing levels of soil fertility indicators on agricultural land in 14 districts of Kostanay region

Subtype, soil type	Districts of Kostanay region	Level of humus content in the arable horizon	Level of plant nutrient supply in the arable horizon		
			$N\text{-}NO_3$	P_2O_5	K_2O Common
black earths and common solonetzic black earths	Karabalyksky	medium	low	medium	very high
	Uzunkolsky	medium	high	low	very high
	Mendykarinsky	low	low	low	very high
	Sarykolsky	medium	medium	medium	very high
	Fedorovsky	medium	low	medium	very high
Southern black earths and southern solonetzic	black earths Altynsarinsky	low	low	low	very high
	Denisovsky	low	very low	very low	very high
	Zhitikarinsky	low	low	medium	very high
	Karasu	low	medium	medium	very high
	Kostanay	low	very low	low	very high
	Taranovsky	low	very low	medium	very high
Dark chestnut and Dark Brownchestnut salty	Auliekolsky	low	very low	low	very high
	Kamystinsky	low	very low	medium	very high
	Naurzumsky	low	low	medium	very high

According to the Ministry of Agriculture of the Republic of Kazakhstan, in Kostanay region for the period from 2019 to 2022, there was an increase in the share of arable land with negative fertility indicators: with a low level of humus content (2-4%) from 45.0 to 48.6%, with a low supply of easily hydrolyzable nitrogen (less than 40 mg / kg) from 27.3 to 47.7% , with a low availability of mobile phosphorus (less than 15 mg / kg) from 45.6 to 58.1%.

This study, underpinned by robust field data and multi-methodological analyses, uncovers nutrient imbalance and degradation in Kostanay's agricultural soils, offering critical insights for sustainable arid-zone soil management. Enhancing

data coverage and exploring biotic-soil interaction mechanisms will significantly reinforce the translation of research findings into practical agricultural applications. To further optimize the paper, the following considerations are pivotal:

1) The soil pore structure exerts a substantial influence on mobile phosphorus and potassium dynamics, analogous to its role in porous concrete systems. As demonstrated in the study by He et al. pore architecture governs ion mobility and retention [23].

2) Pore structure can be effectively modeled using two-scale fractal dimensions, as outlined in He and Liu's research [24]. This framework may facilitate quantitative analysis of how pore complexity affects nutrient availability in soils, bridging mechanistic understanding between material science and soil fertility research.

While this study highlights the dynamics of mobile phosphorus (P) and potassium (K) in Kostanay's agricultural soils, several limitations and unresolved challenges warrant attention. Methodological inconsistencies pose a significant constraint: the use of divergent extraction methods (Chirikov vs. Machigin) for P and K across studies complicates data comparability. For instance, the Chirikov method (applied to non-carbonate soils) likely overestimates P availability in Kostanay's carbonate-rich, alkaline soils compared to the more appropriate Machigin method. This inconsistency obscures accurate fertility assessments and undermines recommendations for fertilizer application. This aligns with the study of Gomes (2025), who emphasized that soil properties like particle size distribution, porosity, and water content significantly influence particle movement and cannot be adequately modeled by the Chirikov method when studying non-carbonate soils [25]. The Machigan method is also not without flaws and can also pose the risk of overestimating P contents. Future research should focus on employing more than two or more extraction methods to bolster comprehensibility [26]. Additionally, spatial sampling biases are evident. Data aggregation across districts in Figure 2 and Table 2 masks micro-scale variability within fields, where coefficients of variation for P reach 58.5%. Such heterogeneity necessitates precision agriculture tools such as GIS mapping and remote sensing to tailor interventions, yet these approaches remain underutilized [27].

The research also overlooks mechanistic drivers of nutrient depletion. While declining P trends (Table 5) are attributed to insufficient fertilizer use, the study does not quantify historical application rates or evaluate crop-specific nutrient extraction [28]. For example, wheat-dominated rotations may exacerbate P mining without balanced replenishment [29]. Furthermore, salinization's impact on nutrient bioavailability is insufficiently explored. Alkaline conditions (pH > 8.0) reduce P solubility via calcium phosphate precipitation, yet the study does not correlate spatial P deficits with salinity hotspots (e.g., solonetzic soils in Fedorovsky). This gap impedes targeted reclamation.

Divergences from global analogues are equally instructive. Unlike temperate chernozems in Ukraine or Russia, where integrated manure-mineral fertilization sustains P, Kostanay's low organic inputs exacerbate depletion. Similarly, salinization here parallels trends in dryland steppes (e.g., Inner Mongolia), but Kazakhstan's slower adoption of phytomeliorants (e.g., salt-tolerant cover crops) delays remediation [30].

Conclusion

Agricultural lands and arable lands of Kostanay region cover significant areas in the steppe zone. In the central and southern regions of the region, the share of land used as pastures is growing, and they also belong to agricultural land.

The main zonal soils of Kostanay region are represented by subtypes of black earths, chestnut soils and brown desert soils. Saline soils are widely distributed, which are distinguished during diagnostics at the genus level within the types of black earth and chestnut soils. The soil cover in many territories of Kostanay region is characterized by complexity. In addition to zonal soils, intrazonal soils are common in the regions of the region: Solonets, meadow-black earth, meadow alluvial. Salt marshes are common in many districts of Kostanay region, but these soils are practically impossible to use in agriculture, they need to be reclaimed.

Analysis of long-term data, including our own research, has shown that the availability of phosphorus forms available for plants in the soils of croplands of Kostanay region varies significantly in different administrative districts of Kostanay region, but many field lands are deficient in plant mineral nutrition elements, which indicates the development of degradation processes of agricultural depletion. At the same time, the natural potential of potash reserves in arable black earths and chestnut soils is a high element supply.

Unfavorable conditions for agriculture are created by the processes of salinization, which often complement the main processes of soil formation in black earths and chestnut soils. With intensive cultivation of land, they can increase, which is quite often noted in agrochemical surveys of soils in Kostanay region. Salinization of soils is often accompanied by a shift in their acid-base balance to the alkaline side, which is also unfavorable for soil fertility.

Thus, for the sustainable development of the region, it is extremely important to conduct a comprehensive assessment of agricultural soils, on the basis of which in the future it is possible to develop optimal and balanced solutions for land management in Kostanay region.

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