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NATIONAL ACADEMY OF SCIENCES OF KAZAKHSTAN UNDER THE PRESIDENT OF THE REPUBLIC OF KAZAKHSTAN

ҚАЗАҚ ҰЛТТЫҚ АГРАРЛЫҚ ЗЕРТТЕУ УНИВЕРСИТЕТІ
ҚАЗАҚСТАН РЕСПУБЛИКАСЫ ПРЕЗИДЕНТІНІҢ ЖАНЫНДАҒЫ
ҚАЗАҚСТАН РЕСПУБЛИКАСЫ ҰЛТТЫҚ ҒЫЛЫМ АКАДЕМИЯСЫ

КАЗАХСКИЙ НАЦИОНАЛЬНЫЙ АГРАРНЫЙ ИССЛЕДОВАТЕЛЬСКИЙ УНИВЕРСИТЕТ
НАЦИОНАЛЬНАЯ АКАДЕМИЯ НАУК РЕСПУБЛИКИ КАЗАХСТАН
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THERMODYNAMIC MODELING OF SOLONETZ PASTURES IN THE AKMOLA REGION TO DETERMINE THE ROLE OF MAGNESIUM IN THE PROCESS OF PEDOGENESIS AND SOLONETZIZATION

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Abstract. *Introduction.* In the steppe zone of the Akmola region, low-sodium, magnesium-rich solonetz and solonetzic soils are widespread in the chestnut soil subzone. These soils are currently subject to anthropogenic degradation due to conversion to arable land. They are characterized by unfavorable hydrophysical properties, similar to classic solonetz soils. However, their solonetzic horizon B1 has low sodium and significant magnesium content. The role of magnesium in soil geochemical processes of salinization and solonetzization in the steppe zone remains insufficiently studied and has not been quantitatively substantiated. *Materials and Methods.* Therefore, thermodynamic modeling was conducted in this study to elucidate the processes of magnesian pedogenesis and solonetzization. *Results and Discussion.* A study of the aMg/aCa ion ratio revealed that the solonetzic horizon of pasture solonetz soils exhibits pronounced magnesium-rich soil solution and exchange complexes, leading to structural deterioration. *Conclusion.* The obtained results provide a theoretical basis for developing a strategy for the reclamation and restoration of solonetz soils in the steppe zone which are subject to anthropogenic degradation.

Keywords: semiarid zone, solonetz soils, magnesium, degradation, pedogenesis, geochemistry, solonetzization process, thermodynamic modeling

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АҚМОЛА ОБЛЫСЫНЫҢ ЖАЙЫЛЫМДЫҚ СОРТАҢ ТОПЫРАҚТАРЫНДА МАГНИЙДІҢ ТОПЫРАҚ ТҮЗІЛУ ЖӘНЕ СОРТАҢДАНУ ҮДЕРІСТЕРІНДЕГІ РӨЛІН АНЫҚТАУ МАҚСАТЫНДАҒЫ ТЕРМОДИНАМИКАЛЫҚ МОДЕЛЬДЕУ

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Аннотация. *Kipicne.* Ақмола облысының дала аймағындағы қара-қоңыр топырақтар таралған белдеме натрий мөлшері төмен, магнийге бай сортаң және сортаңданған топырақтар кең таралған. Қазіргі уақытта бұл топырақтар егістік мақсатында жыртылуына байланысты антропогендік деградацияға ұшырауда. Олар классикалық сортаң топырақтарға тән қолайсыз гидрофизикалық қасиеттермен сипатталады. Алайда олардың В1 сортаңды горизонты натрийдің төмен мөлшерімен және магнийдің жоғары мөлшерімен ерекшеленеді. Дала аймағындағы топырақтардың тұзденуы мен сортаңдануының геохимиялық үдерістеріндегі магнийдің рөлі жеткілікті зерттелмеген және сандық тұрғыдан негізделмеген. *Материалдар мен әдістер.* Осыған байланысты зерттеуде топырақ түзілу және сортаңдану үдерістеріндегі ролін анықтау мақсатында термодинамикалық модельдеу жүргізілді. *Нәтижелер мен талқылау.* aMg/aCa иондарының арақатынасын зерттеу жайылымдық сортаң топырақтардың сортаңды горизонтында топырақ ерітіндісі мен топырақтың сіңіру кешенінде магнийдің айқын басым екенін көрсетті, бұл жағдай топырақ құрылымының нашарлауына әкеледі. *Қорытынды.* Алынған нәтижелер антропогендік деградацияға ұшыраған дала аймағының сортаң топырақтарын мелиорациялау және қалпына келтіру стратегиясын әзірлеудің теориялық негізін қалайды.

Түйінді сөздер: жартылай құрғақ аймақ, сортаң топырақтар, магний, деградация, топырақ түзілу, геохимия, сортаңдану үдерісі, термодинамикалық модельдеу

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ТЕРМОДИНАМИЧЕСКОЕ МОДЕЛИРОВАНИЕ ПАСТБИЩНЫХ СОЛОНЦОВ АКМОЛИНСКОЙ ОБЛАСТИ ДЛЯ ОПРЕДЕЛЕНИЯ РОЛИ МАГНИЯ В ПРОЦЕССАХ ПОЧВООБРАЗОВАНИЯ И ОСОЛОНЦЕВАНИЯ

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Аннотация. *Введение.* В степной зоне Акмолинской области в подзоне каштановых почв широко распространены малонатриевые магнийсодержащие солонцы и солонцеватые почвы. В настоящее время эти почвы подвергаются антропогенной деградации вследствие их распашки. Они характеризуются неблагоприятными гидрофизическими свойствами, сходными с классическими солонцами. Однако их солонцовый горизонт В1 отличается низким содержанием натрия и значительным содержанием магния. Роль магния в геохимических процессах засоления и осолонцевания почв степной зоны остается недостаточно изученной и количественно не обоснованной. *Материалы и методы.* В связи с этим в настоящем исследовании было проведено термодинамическое моделирование для выяснения процессов магниевого почвообразования и осолонцевания. *Результаты и обсуждение.* Исследование соотношения ионов aMg/aCa показало, что солонцовый горизонт пастбищных солонцов характеризуется выраженным преобладанием магния в почвенном растворе и поглощающем комплексе, что приводит к ухудшению структуры почвы. *Заключение.* Полученные результаты создают теоретическую основу для разработки стратегии мелиорации и восстановления солонцовых почв степной зоны, подверженных антропогенной деградации.

Ключевые слова: полузасушливая зона, солонцовые почвы, магний, деградация, почвообразование, геохимия, процесс осолонцевания, термодинамическое моделирование

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Introduction.

Soil salinization is a major cause of declining agricultural productivity in many arid and semi-arid regions of the world [Qadir et al., 2000: 501–521]. According to the FAO Salt-Soil Map, it covers 8 5 % of the world's land area or more than 424 million hectares of topsoil (0–30 cm) and 833 million hectares of subsoil (30–100 cm) are affected by salinization [Global Map of Salt Affected Soils, 2021]. Among these saline solonetzic soils occupy a special place and are also widespread worldwide. The main areas of solonetzic soil distribution are in Ukraine, the Russian Federation, Kazakhstan, Hungary, Bulgaria, Romania, China, the USA, Canada, South Africa, Argentina and Australia [Miller & Brierley, 889–902]. The total area of solonetzic soils worldwide is approximately 135 million hectares. They are characterized by a dense structure and the presence of a clay horizon B where the proportion of adsorbed sodium is relatively high. Solonetz soils containing free soda (Na_2CO_3) have a highly alkaline reaction (pH> 8.5) [IUSS Working Group WRB, 2015]. In Kazakhstan, the main areas of solonetz soils and solonetzic soils are concentrated in the central and northern regions. According to the Agency for Land Management of the Republic of Kazakhstan solonetzic soils occupy 61.5 million hectares [Committee for Land Resources Management, 2023]. They were formed among the most fertile zonal soils of Northern Kazakhstan and in comparison with them are distinguished by very low fertility. In the Akmola region where the area of solonetz soils is about 3.2 million hectares, low-sodium solonetz soils and solonetzic soils are widespread. In the chernozem zone of Northern Kazakhstan, their area amounts to 0.528 million hectares [Mikhailichenko, 1979]. They, like all solonetz soils, have poor water-physical and physicomechanical properties but in their dense and clayey horizon B, the proportion of adsorbed (exchangeable) sodium is very low and the proportion of absorbed magnesium is significant. Similar soils were found in the Canadian Prairies [Miller & Brierley, 2011: 889–902] and North Dakota (USA) which had a sodic morphology but did not meet the chemical criteria and the requirement for a sodium adsorption coefficient ≥13. Although magnesium has a lower dispersion capacity than sodium (magnesium dispersion in clay soils is ~5 % of that of sodium), its high concentrations still contribute to the deterioration of soil structure. A Mg/Ca ratio of >1 in irrigation water and a proportion of exchangeable Mg^{2+} of >25 % in soils are considered sufficiently high to lead to soil degradation and negatively impact crop yields [Qadir et al., 2018: 1108–1117]. In Kazakhstan along with typical solonetz and solonetzic soils, they provide an additional source of increased feed production for growing livestock.

High magnesium content was found in more than 30 % of irrigated lands in southern Kazakhstan which were characterized by low infiltration and hydraulic conductivity. This resulted in a gradual decline in cotton (Gossypium hirsutum L.) yields. Unsustainable irrigation methods in the irrigation zone of the Arys Turkestan Canal led to the formation of sierozem soils with poor physicochemical properties containing high concentrations of Mg^{2+} in the cation exchange complex. Therefore, in the context of increasing climate change and growing anthropogenic load on solonetzic pastures, the problem of restoring their fertility is of particular importance. Moreover, the role of magnesium as an independent pedogenetic factor remains insufficiently quantitatively substantiated, despite a significant volume of research devoted to sodium-dominant solonetzes. Therefore, this paper clarifies the existing model of solonetz formation, which allows us to consider magnesian solonetzism as an independent geochemical mechanism for the evolution of solonetzs in the steppe zone of Kazakhstan.

The objective of this study was to study the role of magnesium in the soil-geochemical processes of salinization and alkalinization of pasture solonetz soils in the Akmola region based on thermodynamic analysis.

Main research objectives:

- to study the material composition of solonetz soils in pasture areas in the Akmola region and assess their spatial distribution along the profile;
- to study the comparative activity of the ratio of major cations (aMg/aCa, aMg/aNa) in the soil solution of solonetz soils in pasture areas;
- to assess the preferential absorption of cations from solution by the soil absorption complex of solonetz soils in pasture areas based on the Gapon selectivity coefficient (KG);
- to model the chemical composition of the soil solution of solonetz soils in pasture areas to determine the saturation indices (SI) of key minerals;
- to determine the direction and intensity of salinization, alkalinization and magnesium content based on a comprehensive analysis of the chemical composition, ion activity, KG and SI of solonetz soils.

The study was conducted in the Akmola Region of Kazakhstan which is located in the steppe zone in

the northwestern part of the Central Kazakhstan Uplands and occupies a vast area of the upper Ishim River basin, the lower reaches of the Nura and Selety rivers and the vast endorheic basin of Lake Tengiz-Kurgaldzhin. The region is characterized by basement-denudation and stratigraphic-denudation plains, river valleys and lacustrine-alluvial plains. The study region is part of the chloride-sulfate salt accumulation province in the Kara Sea drainage basin with inversion of salt belts which encompasses the entire West Siberian Lowland and the northern slope of the Kazakh folded country. Kazakhstan occupies a very small southwestern part of this vast region [Issanova et al., 2017: 243–250]. These plains of the southern part of the West Siberian Lowland were formed as a result of epeirogenic subsidence of the earth's crust and are composed of strata of Paleogene, Neogene and Quaternary marine sediments, saline with residual marine salts and gypsum. They are overlain on the surface by a mantle of thin alluvial-deltaic deposits. Extensive watershed plains are characterized by increased salinity and swampiness. The most common parent rocks are Quaternary deposits which almost completely overlie earlier sediments. They are represented by mantle loess-like loams, alluvial, eluvial-deluvial and ancient alluvial (fluvial and lacustrine) deposits. Loess-like loams occupy elevated watershed plains and are characterized by considerable thickness (15–25 m), a heavy texture, high carbonate content and a finely porous and weakly stratified structure in the lower horizons.

To study and evaluate the current state of subsurface halogenesis and alkalization processes in sodium-magnesian solonetz soils in the Akmola region we selected two sites (Nos. 21 and 24) located in the Astrakhan and Sandytau districts. In these districts these sites are used as distant pastures.

Table 1. Characteristics of the locations of solonetzic soils of pastures in the Akmola region

Plot No.	District, point	Location coordinates	Absolute height, m
21	Astrakhan, Ornek	N 51° 313' 935», E 070° 209' 884»	387
24	Sandyktau, Vladimirovka	N 52° 323' 206», E 068° 611' 116».	307

The Akmola Region is located in the dry steppe zone of the West Siberian temperate climate zone. Due to its vast territory and the presence of highly dissected, hilly terrain, the region's climate is highly variable. The abrupt transition from harsh winters to hot summers and low precipitation result in a sharply continental climate. According to the Kazhydromet weather station, the average monthly temperature in July is 18.5–21.5°C and in January, -13–18°C. On some hot days the temperature rises to 39–42°C (absolute maximum) while in very harsh winters on flat, open areas it drops to -49°C to -52°C (absolute minimum). The warm period with temperatures above 0°C averages 200 days. The central part of the region receives approximately 350 mm of precipitation annually while in the east of the region it reaches 400 mm. Precipitation peaks in July and during the summer months (June, July, and August) it mostly occurs in the form of showers. Summer is generally dry, despite the relatively high precipitation. The precipitation regime necessitates the implementation of measures to accumulate and retain soil moisture. A characteristic and unfavorable climatic feature of the region is its strong spring and summer wind activity, as well as early spring drought. Average annual wind speeds range from 3.4 to 5.4 m/s. The annual maximum wind speed within the region is 20–34 m/s, with gusts up to 30–48 m/s. The prevailing wind direction is southwesterly with a frequency of 4–55 % [https://www.kazhydromet.kz/uploads/files/69/file/5ec14594bbfb0-oblast.pdf].

The formation of stable snow cover begins in late October and early November. The final snowmelt occurs in mid-April. Since the Akmola region grows its main grain crops under rainfed, fallow conditions they are extremely sensitive to climate change.

In the Akmola Region, a combination of soil-forming factors has contributed to the formation and distribution of some of the most fertile soils in the world: chernozems and chestnut soils. Since the reclamation of virgin and fallow lands (1954–1955), these soils have been used for growing grain crops (e.g., spring wheat). The chernozem zone is divided into two subzones: ordinary chernozems and southern chernozems. The chestnut zone within the region is divided into three subzones: dark chestnut, chestnut and light chestnut soils. However, among these soils solonetzic soils and solonetz soils are widespread in patches, confined to steppe depressions, lake basins, plains between hills, lowlands and other relief depressions. The widespread occurrence of solonetzic soils is due to the natural and historical conditions of the region's development. In the steppe zone where our research was conducted, steppe, meadow-steppe and meadow solonetz soils are found depending on the hydrological regime. In automorphic steppe solonetz soils groundwater is quite deep (deeper than 8-10 m) and does not significantly influence soil formation processes. Steppe solonetz soils are rarely found in homogeneous massifs. They are most often found in association with chernozems or chestnut

soils, significantly reducing the quality of the latter.

According to the classification system of Kazakhstan which was largely inherited from the Soviet Union, solonetz soils in the Akmola region are divided into three types based on their water regime and the complex of associated properties: automorphic, semihydromorphic and hydromorphic. At the species level according to the thickness of the humus horizon A they are divided into "crust" (Ah≤5 cm), "shallow" (Ah=6–10 cm), "medium" (Ah=11–18 cm) and "deep" (Ah≥18 cm) [Rayment & Lyons, 2011]. According to WRB 2014 the Solonetz group includes soils with a dense, well-structured, clayey horizon B which is characterized by a high proportion of adsorbed (exchangeable) Na+ and in some cases also Mg2+. Soils in which free soda (Na_2CO_3) is present have a strongly alkaline reaction (field pH>8.5) [IUSS Working Group WRB, 2015]. However, most automorphic solonetz soils in the Akmola region have morphological properties that allow them to be classified as solonetzic but their exchangeable cation is predominantly represented by absorbed magnesium, not sodium. Therefore, based on the principles of WRB (2014) and the domestic soil classification, the names of the soils in this study and their qualifiers were determined (Table 2).

Table 2. Classification of solonetz soils of pasture areas of the Akmola region

Plot No.	District, point	Soil classification Kazakhstan system, WRB, 2014	
		Name	Qualifiers
21	Astrakhan, Ornek	Solonetz (SN): automorphic cortical	magnesic (mg); natric (na); salic (sc); calcic (cc); chloridic (cl); sulfatic (sf)
24	Sandyktau, Vladimirovka	Solonetz (SN): small meadow	magnesic (mg); salic (sc); calcic (cc); chloridic (cl); sulfatic (sf)

Soil Sample Collection and Chemical Analysis.

Full-profile pits were established in the field on solonetzic soils of the two aforementioned pasture plots and the morphogenetic characteristics of their genetic horizons were described. Typical pit locations on solonetz soils were determined based on the nature of the main landforms (meso- and microrelief), vegetation and soil surface. The coordinates of the soil pits were determined using a global positioning system. The surface character and main plant species are described.

Monitoring Site No. 21 is located in the Astrakhan District of the Akmola Region, 300 meters south of the Astana-Atbasar highway and 600 meters north of the village of Ornek. The soil type is crusted solonetz, the topography is flat, the landscape aspect is grayish-greenish and the water regime is atmospheric.

Monitoring Site No. 24 is located in the Sandytau District of the Akmola Region, 4 km southeast of the Atbasar-Kokshetau highway and 1.5 km southeast of the village of Vladimirovka. The soil type is shallow meadow solonetz, the topography is gently rolling plain, the landscape aspect is green and the water regime is groundwater.

Sampling from the pits was conducted in the fall, during the peak of soil salinity and solonetzization, according to standard protocol [Food and Agriculture Organization of the United Nations, 2006]. These soil samples taken from all genetic horizons were prepared and submitted to the laboratory for chemical analysis. To study solonetz soils of pasture areas at the ion-molecular level, the following indicators were used reflecting the manifestation of magnesium content: cation exchange capacity (CEC), CO_2, the composition of exchangeable cations in the SEC, SARact, ESP, pH of the soil solution and soluble ions (HCO_3^-, CO_3^{2-}, Cl^-, SO_4^{2-}, Ca^{2+}, Na^+, Mg^{2+}, K^+) of the aqueous extract (Table 3).

Table 3. Methods for determining the chemical composition and physicochemical properties of solonetz soils

Indicators	Unit of measurement	Methods	Sources
HCO_3^-, CO_3^{2-}, Cl^-, SO_4^{2-}, Ca^{2+}, Mg^{2+}, Na^+, K^+	mg-eq/100 g of soil	soil:water extract (1:5)*	[Rayment & Lyons, 2011]
Absorbed Ca^{2+}, Mg^{2+}, Na^+, K^+	mg-eq/100 g of soil	replacement of exchangeable cations with a solution BaCl$_2$	[Bazilevich & Pankova, 1968]
CEC, cation exchange capacity	mg-eq/100 g of soil	forced exchange method of barium chloride	[Bazilevich & Pankova, 1968]
Sum of salts	%	sum of ions of aqueous extract	[Rayment & Lyons, 2011]
pH water		pH meter for soil and water extract analysis	[Thomas, 1996: 475–490]
CO_2 carbonates	%	volumetric method	[Loeppert & Suarez, 1996: 437–474]
Granulometric composition	%	pipette method	[Gee & Or, 2002: 255–293]

* A clear aqueous extract obtained from water in a soil to water ratio 1:5.

The dynamics of these indicators indicate changes in the processes of interphase interactions occurring at the boundaries: solid phase of the soil - soil solution - gas phase [Rhoades, 1996: 417–435]. Saline solonetzic

soils were identified based on several key indicators: the sodium adsorption coefficient (SAR_{act}), exchangeable magnesium (Mg saturation) and sodium (ESP) which reflects the proportion of exchangeable Mg^{2+} and Na^{+} relative to the total cation exchange capacity (CEC) of the soil [U.S. Salinity Laboratory Staff, 1954].

$$\text{ESP } (\%) = \frac{\textbf{Exchangeable Na+, meq}}{\text{CEC, meg}} \times 100 \text{ESP } (\%) = \frac{\textbf{Exchangeable Na+, meq}}{\text{CEC, meg}} \times 100 \quad (1)$$

$$\text{Mg saturation } (\%) = \frac{\text{exchangeable } Mg^{2+}, \text{ meq}}{\text{CEC, meg}} \times 100 \text{Mg saturation } (\%) = \frac{\text{exchangeable } Mg^{2+}, \text{ meq}}{\text{CEC, meg}} \times 100 \quad (2)$$

where:

ESP = Percentage of exchangeable sodium.

Mg saturation = percentage of exchangeable magnesium

Na^{+}, Mg^{2+} = measured exchange Na^{+} и Mg^{2+}

CEC = Cation exchange capacity calculated as the sum of exchangeable cations [Thomas, 1996: 475–490].

Geochemical Modeling.

The PHREEQC program [Parkhurst & Appelo, 2013] was used to assess the geochemical equilibrium of soil solutions in solonetz pasture plots. The model was used to calculate the activities of ions in the soil solution, mineral saturation indices (calcite, dolomite, magnesite, gypsum) and the Gapon selectivity coefficient for the ratio of magnesium, calcium and sodium ions (KG_MgCa, KG_MgNa, KG_NaCa). Ion concentrations from a 1:5 aqueous extract and exchangeable cation data for the adsorption complex for each soil horizon were entered into the model. For example, for the Mg/Ca pair, the coefficient was calculated using the following formula:

$$KG_{Mg/Ca} = \frac{Mg_{excangeable}/Ca_{exchangeable}}{\sqrt{aMg / aCa}} KG_{Mg/Ca} = \frac{Mg_{excangeable}/Ca_{exchangeable}}{\sqrt{aMg / aCa}} \quad (3)$$

$KG_{Mg/Ca}$ - Gapon coefficient for the pair Mg–Ca

$Mg_{excangeable}$, $Ca_{excangeable}$ — exchange cations (cmol(+)/kg or mEq/100 g);

aMg/aCa — activity of ions in the soil solution.

Visualization of spatial data on the distribution of ions in water extract and the absorption complex along the profile of solonetz pasture areas was performed in the Python environment using specialized statistical libraries [Python Software Foundation, 2023].

Results and Discussion.

Morphological and Genetic Characteristics of Na-Magnesium Solonetzes.

In the semiarid subzone of dark chestnut soils in the Akmola region, the structural features of the steppe automorphic solonetzes used as pastures were studied. These solonetzes formed under conditions of deep mineralized groundwater (deeper than 6 m) and the close proximity of saline soil-forming rocks (sandy loams of alluvial-lacustrine and deluvial-proluvial origin) and underlying rocks (Tertiary variegated clays, marine sediments, etc.) to the surface. Their salinization is due to the salinity of the parent rocks which is in most cases associated with hydromorphic conditions in the past. Research has shown that in the pasture crusted solonetz soils of pasture plot No. 21, the solonetz horizon B1 is characterized by a columnar structure, a dense structure and a heavy loamy texture (Table 4). In these soils, a vigorous reaction to hydrochloric acid is observed in the subsolonetz horizons where carbonate deposits appear. These deposits become more numerous with depth. Their maximum accumulation in the form of deposits is achieved in the parent rock where gypsum clusters also appear.

On pasture plot No. 24, the meadow shallow solonetz soils are characterized by the presence of dark brown natric and subnatric horizons. The natric horizon is distinguished by a columnar structure, dense consistency and a heavy loam texture. Unlike the previous plot, effervescence with hydrochloric acid is observed throughout the entire soil profile, indicating the carbonate nature of the studied soils. Carbonates occur as patches and their abundance increases with depth, reaching a maximum in the parent material (Fig. 1).

Thus, the external characteristics of solonetz soils in pasture areas reveal a clear differentiation of the profile and the formation of a dense illuvial horizon. Their solonetz horizon is characterized by a dark brown

color, a columnar structure, high compactness and a heavy loamy texture. These characteristics, taken together, indicate unfavorable physicochemical properties of the soil and its limited agronomic value. Improvement of these properties is based on reclamation measures.

Table 4. Main morphological features of solonetz pastures in the Akmola region

Horizon	Depth (cm)	Color matrix	Structure	Class of granule composition	composition	Reaction to 10% HCl
Pasture area 21 - Crusted solonetz (SN):						
A	0-4	dark gray	layered-lumpy	loamy	dry, poorly compacted	does not effervesce
B_1	5-22	dark brown	columnar	heavy loam	dry, dense	does not effervesce
B_2	23-40	brown	lumpy	loamy	wet, compacted	effervesces vigorously; isolated carbonate patches are present
BC	41-74	dark brown	structureless	clayish	wet, compacted	effervesces vigorously; carbonate patches occur
C	75-120	dark brown with a white tint	structureless	clayish	wet, compacted	Abundant carbonate patches and gypsum druses
Pasture plot 24 - Solonetz meadow (SN):овый (SN):						
A	0-12	brown	granular-lumpy	loamy	wet, compacted	effervesces
B1	13-32	dark brown	columnar	heavy loam	fresh, dense	effervesces; carbonate patches present
B2	33-56	darker than the previous one with a grayish tint	lumpy	loamy	wet, compacted	effervesces; scattered carbonate patches
BC	57-78	grayish-dark	structureless	loamy	wet, compacted	effervesces; carbonate patches
C	79-120	light brown	structureless	clayish	damp, slightly compacted	effervesces vigorously



(А) (Б)

Fig. 1. Profile structure of automorphic crusted (A) and meadow shallow solonetz (B) soils of pasture plots in the Akmola region.

Characteristics and nutritional value of vegetation.

To assess the condition of the natural vegetation on the solonetz pasture plots, we studied their forage value. Research showed that the projective vegetation cover in pasture plot No. 21 is 65 % of the total area. The pasture type is wormwood-feather grass-fescue. The botanical composition of plants in this plot consists of wormwood (60 %), feather grass (20 %), fescue (10 %), and izyon (10 %). Single specimens of wheatgrass,

alyssum and kermek are also found. The pasture yield is 6.1 c/ha. The coordinates of the boundaries of study point No. 21 are N 51º18’50.2”; E 070º12’35.7”. Analysis of the obtained data when determining the chemical composition of plants growing on solonetz soils, shows that the air-dry protein content is 12.52 %, fat – 6.32 %, fiber – 32.23 %, BEF – 34.04 %, and ash – 12.21 %. Moreover, on these types of pastures, the yield of feed units at natural plant moisture is 0.51 per kilogram of feed, and the metabolizable energy is 8.23 MJ.



(А) (Б)

Fig. 2. The state of vegetation of automorphic crust (A) and meadow small solonetz (B) pasture areas of the Akmola region

In the meadow solonetz pasture plot No. 24 the projective vegetation cover is 85 % of the total area. The pasture type is grass and forbs. The botanical composition of plants in this plot consists of couch grass – 30 %, alkali grass – 16 %, brome grass – 15 %, yarrow – 10 %, wormwood – 10 %, knotweed – 10 % and fescue – 9 % of the area. The pasture mass yield is 17.0 c/ha. The coordinates of the boundaries of the contour of survey point No. 24 are N 52º19’23.4”; E 068º36’40.1”. A study of the chemical composition of plants growing on meadow solonetz soils revealed that the air-dry protein content was 16.63 %, fat 3.93 %, fiber 32.72%, BEF 33.42% and ash 10.14 %. The yield of feed units at natural plant moisture was 0.50 per kilogram of feed and the metabolizable energy was 6.91 MJ.

Chemical composition and physicochemical properties of sodium-magnesium solonetz soils.

Solonetzes in the Akmola region with high exchangeable magnesium content like high-sodium solonetzes are characterized by low fertility. In many respects, low-sodium (magnesium) solonetzes are very similar to typical solonetzes.

Chemical composition data for crusted solonetzes at monitoring site No. 21 in the Astrakhan district of the Akmola region show a humus content of 2.20 % in the humus horizon and 1.64% in the subhumus horizon (Table 5). From a depth of 10 cm downwards, the soil pH ranges from moderate to highly alkaline.

Table 5. Chemical composition and physical properties of solonetz soils in pasture areas

Plot №	Depth, см	Total humus, %	Gross nitrogen, %	Movable forms, мг/кг			Physical clay, <0,01мм
				Nitrogen	Phosphorus	Potassium	
Pasture plot 21 - Crusted solonetz (SN):							
21	0-4	2,20	0,140	50,4	62	600	22,000
	10-20	1,64	0,098	36,4	20	330	74,428
	25-35	0,93	0,070	25,2	6	250	54,257
Pasture plot 24 - Meadow solonetz (SN):							
24	0-10	5,03	0,336	53,2	62	1000	62,077
	20-30	4,66	0,322	39,2	6	260	64,289

Compared to the previous soils, the meadow solonetz soils of Monitoring Site No. 24 in the Sandytau District of the Akmola Region are characterized by high humus levels, reaching 5.03 % and 4.66 % in the upper horizons, respectively (Table 4). The soils of the two pasture plots studied have a coarse texture, beginning with the solonetzic horizon. While the crusted solonetz soils have a physical clay content of 74.4 %, the shallow meadow solonetz soils have a physical clay content in the solonetzic horizon reaching 64.29 % (Table 5).

The combination of natural soil-forming factors and the hydromorphic conditions of the steppe zone in historical times determined the current salt regime of the automorphic solonetz soils of the above-mentioned plots. Their salinization is largely due to the salinity of the parent material. In meadow analogues of solonetz soils, the main source of readily soluble salts is, in most cases, groundwater which is located close to the surface and influences soil formation processes. This is clearly demonstrated by the total salt content which increases with depth. For example, the crusted solonetz soils of pasture plot No. 21 are both solonchakous and solonchakous. The maximum mass of readily soluble salts is concentrated in the underlying layers, amounting

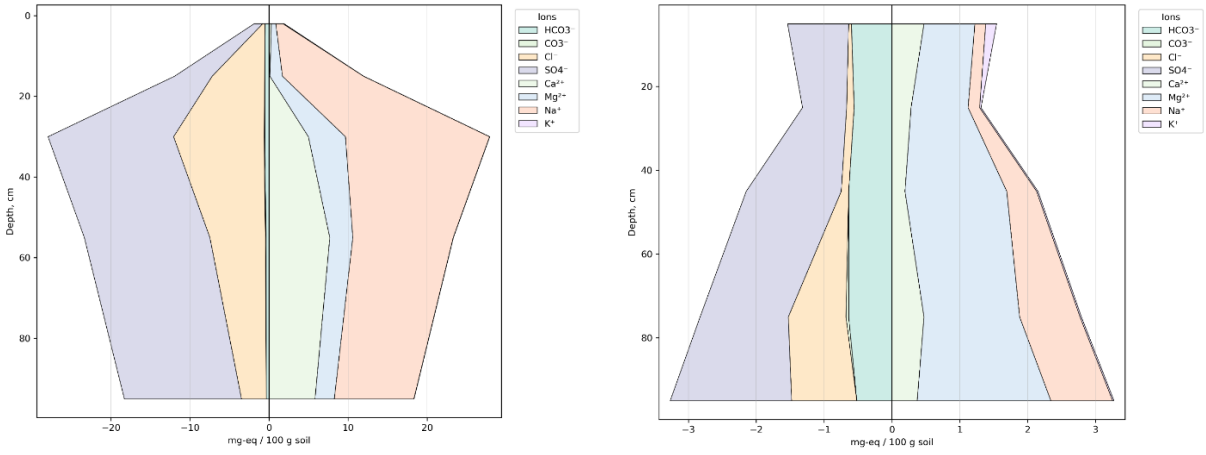
to 1.2–1.8 % (Table 6).

Table 6. Main parameters of salinity and solonetzization of magnesian solonetz soils in pasture plots in the Akmola region.

Depth, см	Sum of salts, %	SAR_{act}	pH	ESP %	Mg sat, %	Ca sat, %	CEC, mg-eq per 100 g of soil
Pasture plot 21 - Crusted solonetz (SN):							
0-4	0,133	0,10	7,70	1,40	29,40	65,80	13,61
10-20	0,755	0,90	8,32	18,03	56,57	25,36	23,31
25-35	1,779	0,72	8,83	41,65	16,94	41,39	52,89
50-60	1,517	0,48	8,63	45,62	24,71	29,65	40,27
90-100	1,222	0,43	8,50	31,89	35,67	32,41	30,70
Pasture plot 24 - Meadow solonetz (SN):							
0-10	0,109	0,01	8,24	0,27	22,27	74,30	33,49
20-30	0,090	0,02	8,22	0,10	44,20	55,56	48,36
40-50	0,143	0,04	8,45	1,61	41,77	56,46	44,07
70-80	0,179	0,07	8,34	3,53	42,93	53,39	47,52
90-100	0,205	0,06	8,34	4,92	35,19	59,67	32,51

The energy (rate) of solonetzization (the incorporation of sodium into the soil-extracting complex) is determined not only by the concentration of the solution but also by its composition. It increases according to the following series: NaCl<Na2SO4<NaHCO3<Na2CO3 [Mikhailichenko, 1979]. The potential ability of the soil solution to soda salinization (SARact) throughout the solonetz profile is very low. The SARact parameter in these soils does not exceed 1. Soils are usually subject to soda salinization when they are exposed to water (e.g., capillary water) with a high SAR>5 value and a high NaHCO3 content. Such soils can form with surface wetting or under the influence of capillary ascending solutions [Bower, 1971: 53–57]. In solonetz, soda usually causes plant death at a content of 0.005 %.

The high salt content in the automorphic solonetz soils of pasture plot № 21 is due to both sodium chlorides and sulfates (Fig. 3). The latter predominates in the anionic composition. The absolute maximum of sulfate ion in the soil solution was established at depths of 25–35, 50–60 and 90–100 cm, where it constituted 15.88, 15.88 and 14.81 mg-eq per 100 g of soil, respectively. Harmful chloride ion content begins already at 10 cm and covers almost the entire meter-thick layer. Its concentration within these limits fluctuates from 3.14 to 11.45 mg-eq per 100 g of soil. Sodium dominates in the cationic composition, varying from 10.06 to 18.23 mg-eq per 100 g of soil in the depth range from 10 to 100 cm. Magnesium deserves special attention as its concentration should also be considered significant. In the above-mentioned soil layer, it ranges from 1.59 to 4.69 mg-eq per 100 g of soil. These soils are virtually devoid of normal carbonates. However, traces of it (0.08 mg-eq per 100 g of soil) are found in the 25–35 and 50–60 cm layers. Therefore, in the crusted solonetz soils of pasture plot No. 21, the subsolonetz horizons located at depths of 25–35 and 50–60 cm should be considered salic.



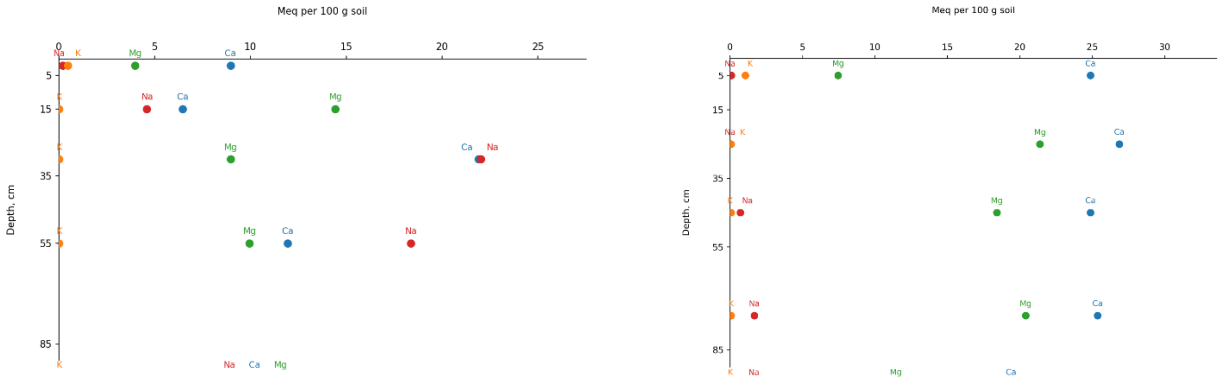
Pasture plot 21 - Solonetz (SN) crusted *Pasture plot 24 – Solonetz (SN) meadow*

Fig. 3. Spatial differentiation of ions in aqueous extracts of solonetz pasture areas

The shallow meadow solonetz soils of pasture plot No. 24 are virtually free of salinity on the surface. Salt content in the first half-meter varies from 0.090 to 0.109 % (Table 5). However, in the underlying horizons, salt levels gradually increase, reaching slightly saline levels (0.205 %) in the parent rock. The soil pH in the solonetz soils of the first pasture plot ranges from slightly to strongly alkaline (pH 7.7–8.8) while in the second plot it is moderately alkaline (pH 8.22–8.45).

The crusted solonetz soils of pasture plot No. 21 in the Astrakhan district of the Akmola region are characterized by high levels of exchangeable magnesium and especially, sodium. Their content in the solonetzic horizon (10–20 cm) is 14.43 and 4.60 mg-eq per 100 g of soil, respectively (Fig. 4), and the share

reaches 56.67 and 18.03 % of the cation exchange capacity (25.51 mg-eq per 100 g of soil). However, in the subsolonetzic horizon at a depth of 25–35 cm, exchangeable magnesium gives way to sodium in the absorption complex. The latter in this layer reaches a maximum (22.03 mg-eq) and is 41.65 % (ESP) of CEC (Table 6). Even deeper, in the layers of 50-60 and 90-100 cm, the magnesium content increases slightly compared to the overlying horizon and is 9.95 and 10.95 mg-eq per 100 g of soil. The concentration of exchangeable sodium, on the other hand, decreases with depth from 22.03 to 9.79 mg-eq per 100 g of soil (Fig. 4). Despite this, a high proportion of exchangeable sodium (ESP 31.89–45.62 %) relative to other cations remains in the 25–100 cm soil layer.



Пастбищный участок 21 - Солонец корковый (SN): *Пастбищный участок 24 - Солонец луговый (SN):*

Fig.4. Composition of absorbed bases of solonetz pasture areas

Exchangeable sodium and hydrolytically alkaline salts cause solonetz formation indirectly (through changes in the zeta potential and increased solvation of the sodium ion), but indirectly through hydrophilic molecular plasma. This plasma is present in solonetzes with both low and high exchangeable sodium contents and acts as a peptizer and stabilizer for hydrophobic systems. Some of this plasma is not precipitated by magnesium and calcium cations.

The shallow meadow solonetzes of pasture plot No. 24 in the Sandytau district of the Akmola region are characterized by magnesium dominance and possibly solonetzic properties. This is due to the high content of absorbed magnesium which in the solonetzic and supra-solonetzic horizons ranges from 18.41 to 21.39 mg-eq per 100 g of soil, accounting for 41.77% and 44.2 % of the total electrolyte content, respectively (Table 6). Therefore, the possibility of the modern formation of low-sodium solonetzes and the active role of magnesium in the solonetz process should not be denied. It is noteworthy that despite the clear manifestation of physical solonetzism, the content of exchangeable sodium in these soils is very low and does not exceed 5.0 % of the CEC. The reason for its low content in the solonetzic horizon is apparently the leaching of a significant amount of sodium into the depths by the descending water flow, i.e., at present, its amount has decreased in the process of desalination. Therefore, they began to be called relict solonetzes, i.e., formed at some point under the influence of sodium salts. Meadow solonetzes in the process of self-development are in the initial stage of transition to meadow-steppe, and then to steppe solonetzes as the steppeification process of the Northern Kazakhstan plain develops.

Geochemical role of magnesium in the processes of pedogenesis and solonetzization of solonetzic pastures in the semi-arid zone of the Akmola region

To assess the geochemical processes of solonetz pedogenesis and the role of magnesium in the solonetzization process, a study was conducted of the activity of the aMg/aCa and aMg/aNa ion ratios in the soil solution, the Gapon selectivity coefficient describing the Mg–Ca–Na exchange reactions in the soil adsorption complex (KGMgCa, KGMgNa, KGNaCa), the sodium adsorption coefficient (SARact) calculated using ionic activity, the proportion of exchangeable magnesium in the soil adsorption complex expressed as a percentage of the cation exchange capacity (Mg saturation, %) and mineral saturation indices (SI). The results of the studies showed that in the solonetz soils of pasture plot No. 21, the influence of magnesium in the surface horizons is observed. This is clearly evidenced by the activity of the aMg/aCa ion ratio in the soil solution. Its value in the humus horizon (0–4 cm) is 1.91, indicating magnesium dominance and the risk of magnesium depletion in this layer. In the underlying solonetzic horizon, the aMg/aCa ratio increases very sharply and significantly, reaching 16.32. This ratio provides a pronounced magnesium depletion in the soil solution which leads to deterioration of the solonetzic horizon structure. In the latter, the saturation of the magnesium adsorbing complex reaches 56.57 % of the CEC. Meanwhile, the calcium saturation is reduced to

25.36 % of the CEC. However, a strong sodium hazard cannot be ruled out in the aforementioned solonetzic and supra-alonetzic horizons. Since the aMg/aNa activity ratio in the soil solution of these horizons is 0.22 and 0.04, respectively, that is below unity. In the solonetzic horizon, the ESP is 18.03 % of the CEC. As one moves deeper into the underlying horizons, the Ca2+ content begins to dominate over magnesium. For example, at depths of 25–35, 50–60 and 90–100 cm, the aMg/aCa ion activity ratios in the soil solution were 0.84, 0.33, and 0.36, respectively (Table 7). It should also be noted that in the underlying horizons, a strong sodium hazard in the soil solution still persists.

Table 7. Soil solution ion activity ratios in solonetzic pasture plots according to PHREEQC data.

Plot	Depth, см	aMg	aCa	aNa	aMg/aCa	aMg/aNa	SAR_{act}
21	0-4	3,640000E-04	1,910000E-04	1,670000E-03	1,905759	0,217964	0,10
	10-20	6,840000E-04	4,190000E-05	1,720000E-02	16,324582	0,039767	0,90
	25-35	1,390000E-03	1,660000E-03	2,830000E-02	0,837349	0,049117	0,72
	50-60	8,630000E-04	2,620000E-03	1,990000E-02	0,329389	0,043367	0,48
	90-100	7,350000E-04	2,050000E-03	1,600000E-02	0,358537	0,045938	0,43
24	0-10	5,020000E-04	3,240000E-04	2,960000E-04	1,549383	1,695946	0,01
	20-30	5,890000E-04	2,000000E-04	3,160000E-04	2,945000	1,863924	0,02
	40-50	9,270000E-04	1,220000E-04	8,040000E-04	7,598361	1,152985	0,04
	70-80	8,670000E-04	2,990000E-04	1,610000E-03	2,899666	0,538509	0,07
	90-100	1,150000E-03	2,260000E-04	1,640000E-03	5,088496	0,701220	0,06

A somewhat different situation was observed in the meadow solonetz soils of pasture plot № 24. Unlike the solonetz soil of the previous plot, these soils exhibit a noticeable magnesium content in the soil solution throughout the entire profile. This state is demonstrated by the aMg/aCa ion activity ratio, which varies from 1.55 to 7.59 within a meter of the meadow solonetz soil. Despite the low salinity of this soil, Mg^{2+} predominates in the soil solution (aMg/aNa>1) in the upper three horizons, particularly in the A, B1 and B2 horizons. However, the horizons located at depths of 20–30, 40–50 and 70–80 cm are characterized by high exchangeable magnesium saturation of the adsorption complex. In the latter horizons, magnesium saturation was 44.20, 41.77 and 42.93 % of the SEC, respectively. A significant sodium hazard is established only in the deepest parent and supra-parental horizons where the aMg/aNa ratio in solution is 0.54 and 0.70, respectively (Table 7). These soils have a relatively low ESP value throughout the profile but it gradually increases with depth from 0.27 to 4.92 % of the SEC. This suggests that in the underlying horizons (70–80 and 90–100 cm) of meadow solonetzic soils, the sodium hazard in the soil solution is consistent with its hazard in the adsorption complex.

To determine the role of magnesium in the pedogenesis and solonetzization of solonetzic soils in pasture areas, we determined the Gapon coefficient (KG) of the Mg/Ca, Mg/Na, and Na/Ca ratios. This indicator demonstrates the preference (selectivity) of the adsorption complex (AC) for exchanging one cation for another at equilibrium between the soil solution and the AAC. Since KG takes into account the activity of ions, not their concentrations, it is a thermodynamic indicator and reflects the actual equilibrium in the system. The data showed that on the automorphic solonetz soils of pasture plot #21, the soil-absorbing complex of the upper horizons prefers Ca^{2+}. The KGMg/Ca parameter at depths of 0–4, 10–20 and 25–35 cm was 0.32, 0.55 and 0.45, respectively. However, in the lowest horizons at depths of 50–60 and 90–100 cm, Mg accumulates in the absorbing complex, indicating moderate magnesium content. In these horizons, the KGMg/Ca values reach 1.45 and 1.84, respectively (Table 8).

The Gapon coefficient for Mg/Na showed that the automorphic solonetz soils of pasture plot #21 are superficially resistant to sodium. This is due to the predominance of Mg^{2+} in the absorption complex which reaches 56.57 % of the SEC in the solonetzic horizon. In the solonetzic horizon of the studied soil, the KGMg/Na value was 2.06, likely indicating strong suppression of sodium by exchangeable magnesium and to some extent, calcium. Below the solonetzic horizon B1 (10–20 cm), this parameter drops sharply to 0.3–0.4 and then rises again to 0.66 in the parent rock. In this part of the crustal solonetz, exchangeable sodium is well retained in the absorption complex where it predominates and through competition, creates a high risk of sodium solonetzation. Thus, the shallow, shallow humus horizon of the crustal solonetz retains calcium well, reaching 65.80% of the SEC in the SEC. However, magnesium becomes dominant in the solonetzic horizon, suppressing sodium. However, it should be noted that exchangeable magnesium is not the primary cause of the solonetzic nature of this horizon. Its impact on the soil is closer to that of calcium than to sodium. Exchangeable

magnesium reduces the rate of water filtration at a ratio of one to calcium. Meanwhile, Na+ significantly reduces filtration even at a Ca:Na absorption ratio of 94:4. In the deeper layers of the automorphic solonetz, there is a risk of sodium solonetzization and moderate magnesium content. Therefore, even at minimal levels, exchangeable sodium can be the primary cause of soil solonetzic nature. In the meadow solonetz soils of pasture plot No. 24, the Mg/Ca and Mg/Na ion ratios indicate strong calcium retention throughout the profile and, along with it, surface magnesium retention in the SEC. For example, KGMg/Ca varies across the profile from 0.26 to 0.47, i.e., does not exceed unity (Table 8). This dominance of calcium and magnesium over sodium is also demonstrated by KGNa/Ca, which does not exceed unity throughout the profile and fluctuates between 0.05 and 0.76. In this soil, the risk of solonetzization manifests itself primarily in horizons located deeper than the solonetzic horizon. This is evidenced not only by the ESP values which increase to 1.61–4.92 % but also by the KGMg/Na value (0.35–0.68). To determine the direction and intensity of soil-geochemical processes in solonetz soils of pasture plots, we studied mineral saturation indices (SI). This indicator indicates the degree of deviation of a system from equilibrium, potentially leading to undersaturation (dissolution) or precipitation into the mineral phase. It was found that in the automorphic crusted solonetz soils of pasture plot No. 21, carbonate minerals (calcite and aragonite) are precipitated primarily in the three underlying horizons at depths of 25–35, 50–60, and 90–100 cm. Within these horizons, the saturation indices (SI) of calcite and aragonite (CaCO3) range from 0.70 to 1.08 and from 0.56 to 0.93, respectively (Table 9).

Table 8. Selectivity coefficient of cation exchange of Gapon solonetz soils in pasture areas.

Plot	Depth, см	√aMg	√aCa	KG_MgCa	KG_MgNa	KG_NaCa
21	0-4	1,907878E-02	1,382027E-02	0,321767	1,741882	0,184724
	10-20	2,615339E-02	6,473021E-03	0,552002	2,063046	0,267567
	25-35	3,728270E-02	4,074310E-02	0,447310	0,308726	1,448893
	50-60	2,937686E-02	5,118594E-02	1,451991	0,366912	3,957331
	90-100	2,711088E-02	4,527693E-02	1,837910	0,660097	2,784303
24	0-10	2,240536E-02	1,800000E-02	0,240885	1,095056	0,219975
	20-30	2,426932E-02	1,414214E-02	0,463874	9,283654	0,049967
	40-50	3,044667E-02	1,104536E-02	0,268438	0,684718	0,392041
	70-80	2,944486E-02	1,729162E-02	0,472211	0,663953	0,711211
	90-100	3,391165E-02	1,503330E-02	0,261414	0,345781	0,756012

Table 9. Thermodynamic state of carbonate and soda minerals in solonetz soil solutions by saturation indices (SI)

Plot	Depth, см	Carbonates				Soda		
		Calcite	Aragonite	Dolomite	Magnesite	Natron	Nahcolite	Na_2CO_3
21	0-4	-0,890	-1,030	-0,310	-1,050	-10,480	-5,670	-12,060
	10-20	-0,930	-1,070	0,530	-0,160	-7,840	-4,670	-9,420
	25-35	1,080	0,930	3,260	0,550	-7,010	-4,550	-8,570
	50-60	0,950	0,810	2,600	0,020	-7,640	-4,830	-9,210
	90-100	0,700	0,560	2,130	-0,190	-7,970	-4,940	-9,540
24	0-10	-0,040	-0,190	1,280	-0,300	-11,380	-6,360	-12,950
	20-30	-0,300	-0,450	1,040	-0,280	-11,370	-6,360	-12,940
	40-50	-0,240	-0,380	1,580	0,190	-10,280	-5,910	-11,850
	70-80	0,040	-0,110	1,710	0,050	-9,790	-5,610	-11,360
	90-100	-0,180	-0,330	1,520	0,080	-9,870	-5,690	-11,450

Dolomite saturation indices ($CaMg(CO_3)_2$) are characterized by higher values compared to calcite and aragonite, reflecting the more intense kinetics of its formation. Unlike these minerals, the positive SI value for dolomite also covers the solonetzic horizon. The relief fluctuation of dolomite's SI ranges from 0.53 to 3.26. Magnesite ($MgCO_3$) is characterized somewhat differently with positive values (SI>0) established at depths of 25–35 and 50–60 cm, at levels of 0.55 and 0.02, respectively. This indicates that magnesite is in a precipitated state and its excess in solution leads to magnesium depletion. Thus, elevated or positive SI values indicate magnesium accumulation in the system and can be considered an indicator of the development of magnesium depletion in soils. While negative SI values for magnesite indicate its presence in the solution predominantly in a mobile state. In our case, the surface solonetzic and supra-solonetzic horizons of the automorphic solonetz

have negative SI values for almost all carbonate minerals. This indicates that the latter are in a dissolved equilibrium state. For example, the SI values of calcite and aragonite in the surface soil horizons vary from –0.89 to -0.93 and from –1.03 to –1.07 (Table 8). A negative saturation index of dolomite is shown only by the humus horizon (SI = –0.31). Magnesite deserves special attention, for which negative SI values were established not only in the surface horizons (–1.05 and –0.16) but also in the parent rock (–0.19). Magnesite is characterized by significantly higher solubility than calcite. Its solubility increases in the presence of carbon dioxide through the formation of sodium bicarbonates.

The meadow solonetz soils of pasture plot No. 24 exhibit a somewhat different character of carbonate minerals in the system. Dolomite [$CaMg(CO_3)_2$] is a virtually insoluble form of magnesium compound. In the soils under consideration, it is present in a precipitated state throughout the entire profile. The SI parameter of dolomite within a meter of soil thickness ranges from 1.04 to 1.71 (Table 8). Calcite and aragonite do not form a mineral form separately since their saturation indices have negative values, varying from –0.04 to –0.24 and from –0.11 to –0.45. The lower horizons of the meadow solonetz are characterized by a high magnesia content due to the presence of magnesium and the formation of a precipitated form of magnesite. In this part of the meadow solonetz, the SI of magnesite has positive values, varying from 0.05 to 0.19. Thus, it can be cautiously concluded that magnesium minerals may be the source of magnesium in automorphic crustose and meadow shallow solonetz soils. Their decomposition will yield significant amounts of exchangeable magnesium. Like sodium, magnesium, when incorporated into the absorption complex, although to a lesser extent, increases the hydrophilicity of colloids, disrupting the bonds between aggregates and making the rock unstable to alkaline hydrolysis.

In addition to carbonate minerals, we identified and studied soda compounds which in both soils had negative SI values throughout the profile. This suggests that soda minerals such as natron ($Na_2CO_3 \cdot 10H_2O$), nahcolite ($NaHCO_3$) and soda ash (Na_2CO_3) are dissolved. Moreover, the more negative the SI value, the more intense the potential dissolution processes. A relatively high degree of solubility for soda and sodium carbonate was observed in meadow solonetzes. The SI value for soda within a meter of soil depth in automorphic solonetzes varies from –7.0 to –10.48, while in meadow solonetzes it ranges from –9.7 to –11.38 (Table 9). The degree of soda saturation in the former soils ranges from –8.57 to –12.06, and in the latter, from –11.36 to –12.95.

The thermodynamic state of neutral chloride and sulfate compounds in soil solutions of automorphic and semihydromorphic solonetzes at various sites indicates their active dissolution. This is primarily due to their high solubility in water. As Table 10 shows, among the sulfate minerals, epsomite ($MgSO_4 \cdot 7H_2O$) and thenardite (Na_2SO_4) have higher solubility than gypsum ($CaSO_4 \cdot 2H_2O$) and anhydrite ($CaSO_4$). Magnesium sulfate (epsomite) is a typical magnesium-containing compound found in saline soils. Its solubility is 252 g/L, making it extremely toxic and the most poisonous and harmful to plants. It never accumulates in soils in its pure form.

Table 10. Thermodynamic state of sulfate and chloride minerals in solonetz soil solutions by saturation indices (SI)

Plot	Depth, см	Sulfates				Chlorides
		gypsum	anhydrite	epsomite	thenardite	halite
21	0-4	-2,330	-2,510	-4,620	-8,340	-7,600
	10-20	-2,520	-2,700	-3,880	-5,840	-5,280
	25-35	-0,570	-0,750	-3,220	-5,060	-4,850
	50-60	-0,350	-0,530	-3,400	-5,340	-5,210
	90-100	-0,440	-0,620	-3,460	-5,520	-5,650
24	0-10	-2,190	-2,370	-4,570	-9,930	-9,220
	20-30	-2,530	-2,710	-4,630	-10,010	-8,750
	40-50	-2,460	-2,640	-4,150	-8,910	-8,350
	70-80	-2,120	-2,300	-4,230	-8,350	-7,170
	90-100	-2,130	-2,310	-3,990	-8,230	-7,110

Comparing solonetz soils from individual pasture plots reveals differences in the dissolution rates of the aforementioned minerals. For example, in meadow solonetz soils which are naturally wetter, virtually all sulfate minerals are in a more intense state of dissolution and exhibit increased environmental aggressiveness. Automorphic solonetz soils, however, are somewhat inferior in this regard. Epsomite exhibits somewhat similar SI values in the studied soils, ranging from -3.22 to -4.62 in automorphic solonetz soils and from -3.99 to -4.57 in a meter-thick layer. The chloride mineral we studied was halite (NaCl). It is characterized by the

highest water solubility among minerals found in saline soils. In the studied soils, the SI of halite is negative, indicating undersaturation in the soil solution. $MgCl_2$ is significantly more prevalent in saline soils and due to its high solubility (353 g/L), is exceptionally toxic. Its accumulation is possible only at the highest levels of salinity. In the upper horizons of solonchaks, $MgCl_2$, like $CaCl_2$, can form as a result of exchange reactions between the ascending NaCl solution and the absorbed magnesium in the soil. $MgCl_2$ and $CaCl_2$ are highly hygroscopic salts, absorbing water vapor from the atmosphere at low air temperatures. During this process their crystalline precipitate quickly liquefies and turns into a concentrated solution.

Conclusion.

In the flat semiarid zone of the Akmola region, saline, low-sodium solonetz soils with high exchangeable magnesium contents are widespread. They exhibit the full range of negative hydrophysical properties typical of classic sodium solonetz soils. However, in these soils, the morphological characteristics of solonetzic soils do not correlate with the low content of absorbed sodium. These soils in the Akmola region are actively used as distant pastures. Therefore, they are currently subject to anthropogenic degradation. Their formation is associated with saline parent materials in conditions of deep groundwater. To elucidate the role of magnesium in pedogenesis and solonetzization processes, we modeled solonetz soils in two pasture plots using thermodynamic analysis (PHREEQC). A study of the aMg/aCa and aMg/aNa ion ratios in soil solution and the potential for mineral formation (SI), as well as the selectivity of cation exchange between the solution and the adsorbing complex, revealed localized magnesium enrichment in automorphic crustal solonetzes with a general predominance of sodium in both the solution and the adsorbing complex. Based on the SI of carbonate minerals, it was established that they form sediments only in the lower horizons. The KG value confirms the sodium-magnesium exchange type in the solonetzic horizon while in the lower horizons, sodium exchange increases, characterizing the development of sodium solonetzization.

In meadow solonetzes, the carbonate equilibrium shifts toward dolomite oversaturation throughout the profile. Furthermore, localized magnesite oversaturation was observed in the lower horizons while soda, sulfate and chloride minerals remained undersaturated. Sodium selectivity (KGNa/Ca<1) is absent throughout virtually the entire meadow solonetz profile, except in the lower horizons, indicating weak development of sodium solonetzation processes. The ion activity ratio aMg/aCa>1 throughout the profile and aMg/aNa>1 only in the upper horizons indicates a pronounced magnesium content in meadow solonetz with a limited dominance of calcium over magnesium.

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