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Assessment of soil properties and trace element accumulation in arid regions: A case study of Kalmykia's central dry steppe zone, Russia

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Abstract

Soil plays a pivotal role in ecosystem health and agricultural productivity. This study focuses on a critical region for soil research, Kalmykia's central dry steppe zone in southern Russia, characterized by arid conditions and unique challenges. Our investigation aimed to evaluate the current state of soil properties and assess trace element accumulation within this environment. The region's distinctive characteristics, including being home to Europe's first desert, present a complex scenario for soil conservation and management. A thorough analysis of key physicochemical properties, including organic matter content, soil texture, pH levels, and the concentrations of trace elements (V, Cr, Co, Ni, Cu, Zn, Sr, and Pb) using established methodologies, was conducted. Our findings revealed several crucial insights into the soil conditions of this arid region. Soil samples predominantly consisted of Haplic Kastanozems Sodic, characterized by low organic carbon content (0.3-1.9%). Soil texture analysis indicated a predominantly light and medium loamy granulometric composition with a prevalence of sandy fractions. Soil pH values ranged from neutral (pH = 7.6-7.9) to slightly alkaline (pH = 8.0-8.4). Furthermore, the study provided the first assessment of soil conditions in residential areas of the Caspian Lowland's arid region. Notably, trace element analysis showed elevated concentrations of several metals, with Sr having the highest levels. Co, Cr, and Zn concentrations did not significantly increase compared to the background values. The results of this soil fertility evaluation hold significance for soil restoration and conservation efforts in this unique and fragile ecosystem. In conclusion, this study underscores the urgent need for soil monitoring and management practices to address soil degradation and desertification driven by overgrazing and erosion. Understanding the physicochemical properties and trace element dynamics in arid regions is essential for developing strategies to restore and conserve these valuable soils.

Keywords: Haplic Kastanozems Sodic, humus, soil texture, soil pH, trace elements, X-ray fluorescent.

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Introduction

Being the only region of Europe with desert, the Republic of Kalmykia is one of the most important territories for research in the south of Russia (Sangadzhiev et al., 2018; Dedova et al., 2020). Kalmykia is vastly distinguished, even from neighboring federal subjects, not only by its soil, but also by a more continental climate (Degtyarev, 2019). Nowadays, the region is facing the problems of soil degradation and desertification, largely resulting from overgrazing practices (Tashninova, 2015; Lazareva et al., 2018; Bakinova et al., 2019; Shumova, 2021). Huge desert areas, limited plant cover, and strong winds give rise to such meteorological phenomena as dust and sandstorms (Sangadzhiev et al., 2021). Physical and chemical properties of soils,

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including content of organic matter, which serves as a main soil fertility factor, tend to deteriorate (Danchenko et al., 2022; Gurkova et al., 2022). In this context, soil monitoring plays an important role in soil fertility regulation, with the former consisting of observations of changes in agrochemical parameters of topsoil across rural Kalmykia (Okonov et al., 2021).

The territory of the south of Russia is characterized by efficient agricultural activities, resulting in increased anthropogenic impacts on farmlands. The key negative processes are unorganized grazing and overgrazing, degradation of natural forage lands, and water and wind erosions that give rise to multiple desert pockets and, consequently, lead to soil fertility reduction.

The soil fertility of the arid region of the Caspian Lowland was investigated and provided comprehensive insights into soil qualitative parameters in rural areas.

Material and Methods

The northwestern part of the studied area is geomorphologically located in the Ergeni upland (190-210 m above sea level) (Muev et al., 2013; Sangadzhiev et al., 2021), whereas its eastern part is in the Caspian Depression, which is a flat plain sloping towards the sea as shown in Figure 1. The numerous arroyos in the eastern parts fill up in the spring and completely dry out in the summer (Semenkov et al., 2022). The topsoil comprises Kastanozems (chestnut soils), essentially associated with solonetzes and covering arroyo watersheds and their sides. Haplic Kastanozems are dominant soils in the Ergeni upland soil cover (Klimanov et al., 2014) and can be found as associated soils along mesorelief depressions. Endosalic calcisols sodic co-dominate in flat areas of the Caspian Depression. The studied area was in the central steppe zone of Kalmykia and characterized as an arid and very arid climate with hot and moderately hot summers and moderately cold winters (Nemkeeva et al., 2019). The dry steppe zone's relatively flat landform conditions have determined an original and structurally complete plant cover dominated by perennial xerophytic plants: *Festuca valesiaca, Stipa capilláta, Stipa lessingiana, Agropyron desertorum*, *Poa bulbosa*; and xerophilous plants: *Artemisia absnthium, Artemisia pauciflora*, etc. (Fedorova, 2015; Semenkov et al., 2020; Novikova et al., 2020). The soil was sampled at the 16 settlements at 2 districts of Kalmykia: Tcelinnyy and Ketchenerovsky (Figure 1). There are 129 soil samples. The soil samples were collected during seasonal expeditions. The monitoring sites included central parts of a settlement or school yard, settlement boundaries, and at the 500 m away from the settlement boundaries (background areas) (Figure 1). At the monitoring sites (5 × 5 m), sampling was done according to ISO 18400-104:2018 guidelines. All soil samples were taken in triplicate. The weight of the sample from each monitoring site was 1500 g.

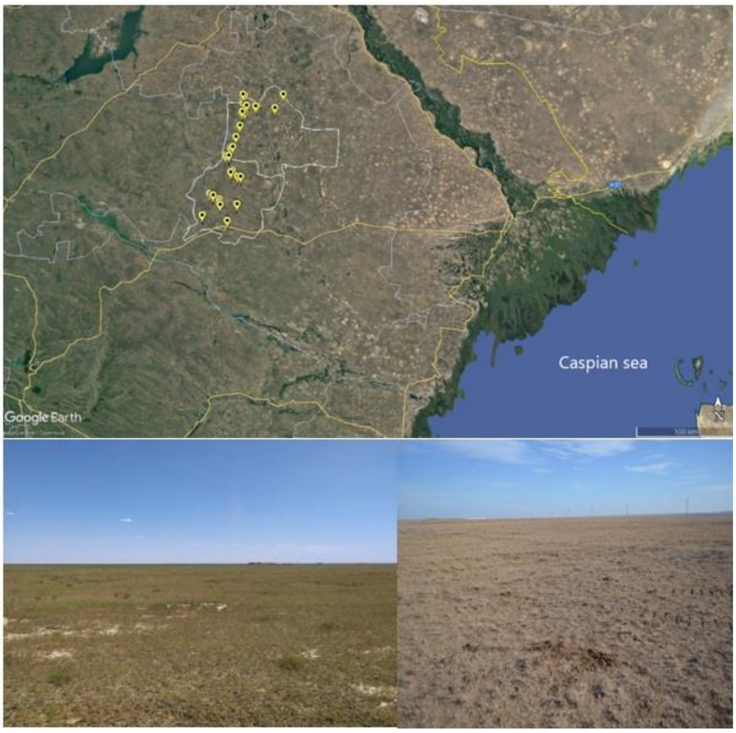

Figure 1. The monitoring sites of soil sampling.

The soil samples were air-dried in the laboratory, cleaned from root remains, grinded and sieved to 1.0 mm. The physicochemical properties of collected soil samples were determined by the following methods: pH in H_2O using a glass electrode in a 1:5 (volume fraction) suspension of soil in water (ISO 10390:2005); organic matter content by the sulfochromic oxidation, ISO 14235:1998 and carbonate content by the volumetric method, ISO 10693:1995. The pipette method with the pyrophosphate procedure preparation was used to determine the soil particle size distribution (ISO 13317-2:2001; Shein, 2009). The total elemental composition (Si, Al, Fe, Ca, Mg, S, and Na) in the soils was determined by an X-ray fluorescent scanning spectrometer "Spectroscan Makc-GV" (Spectron, Saint-Petersburg, Russia).

The statistical processing of the obtained results was carried out using the Microsoft Excel computer software package. The standard error was determined for each arithmetic mean. To assess the accumulation processes of each element, the following indicators were calculated: the concentration coefficient (Kk), the coefficient of relative accumulation of trace elements in the soil (Kkr), and the background concentration coefficient (Kkf). The calculation of the indicators was carried out according to the method of Glazovskaya (1999).

Results and Discussion

The soil in the studied area is represented by Haplic Kastanozems Sodic. The average pH was showed the values of 7.6–8.7. The pH values of the monitoring sites were close and vary slightly (V=3%) from 7.7-8.7 (Ketchenerovsky district) and 7.6-8.4 (Tcelinnyy district), i.e., they have an alkaline and highly alkaline reaction (up to 8.7 units). The soil organic carbon (C_{org}) contents ranged between 0.67 and 1.89%, and the average C_{org} was noted at 1.39% (Table 1). The average value with C_{org} in the Ketchenerovsky district was 0.94%, in the territory of the Tselinsky district - 1.40%. The maximum values of C_{org} (1.89%) coincide both on the territory of the Ketchenerovsky district (Kegult village, background) and on the territory of the Tcelinsky district (Verkhny Yashkul, background) (Table 1). Carbonates are almost equally represented by calcium and magnesium salts. The Ca content of the topsoil in Haplic Kastanozems Sodic was 0.60-0.98%, and the Mg content was 0.53-0.79% (Table 1). Their content in the soil fine-grained soil on the territory of the Ketchenerovsky district ranged from 0.55%-0.90%, the content of $CaCO_3$ was in the range (V=7%) from 1.60% to 2.30% (Ketchenery village, school), $MgCO_3$ (V=7%) - from 1.93% to 2.52% (Kegult village, edge locality). In the Tcelinsky district, the content of carbonates in soils varies (V=12%) from 1.6 to 2.7% ($CaCO_3$) and 1.9 to 2.7% ($MgCO_3$).

Table 1. Statistical parameters of physico-chemical properties of soils

Parameter	M (average)	SD (standard deviation)	Med	Min	Max	SE (standard error)	CV
Ketchenerovsky district							
C_{org}, %	0.94	0.44	0.90	0.31	1.89	0.10	47
pH in water	8.21	0.27	8.20	7.70	8.70	0.06	3
Ca, %	0.80	0.11	0.86	0.60	0.90	0.02	14
Mg, %	0.61	0.04	0.60	0.55	0.72	0.01	7
$CaCO_3$, %	2.10	0.15	2.12	1.60	2.30	0.03	7
$MgCO_3$, %	2.14	0.14	2.10	1.93	2.52	0.03	7
Tcelinnyy district							
C_{org}, %	1.40	0.40	1.37	0.67	1.89	0.08	29
pH in water	8.10	0.21	8.20	7.60	8.40	0.04	3
Ca, %	0.82	0.08	0.80	0.64	0.98	0.02	10
Mg, %	0.66	0.06	0.67	0.53	0.79	0.01	9
$CaCO_3$, %	2.07	0.24	2.10	1.60	2.70	0.05	12
$MgCO_3$, %	2.35	0.23	2.35	1.85	2.77	0.04	10

The contents of clay vary in a wide range from 6.84 to 64.88, with minimum values observed in the schoolyards of Ovata, Arshan-Bulg, Baga-Chonos, and Voznesenovka (Figures 2, 3, Table S2). Low content of P was noted, i.e., 0.09–0.18%, while P exchange content is medium - 1.37–2.98% (Table 3). In Ovata, the former's medium value is 0.14%, and that of exchange potassium is 2.98%. A determination of metals was performed, and the high content of these toxic metals was observed. According to Table 2, the total content of the accumulated metals is categorized as follows:

Arshan-Bulg : Sr > V > Cr > Zn > Cu > Pb > Ni > Co
Baga-Chonos : Sr > Cr > Cu > Zn > V > Co > Ni > Pb
Voznesenovka : Sr > Cr > V > Zn > Ni > Cu > Pb > Co
Verkhny Yashkul : Sr > Cr > V > Zn > Ni > Cu > Pb > Co
Iki-Chonos : Sr > Cr > V > Zn > Ni > Cu > Pb > Co
Ovata : Sr > Cr > V > Zn > Ni > Cu > Pb > Co
Troitskoye : Sr > Cr > Zn > V > Ni > Cu > Pb > Co
Khar-Buluk : Sr > Zn > Cr > V > Ni > Cu > Pb > Co

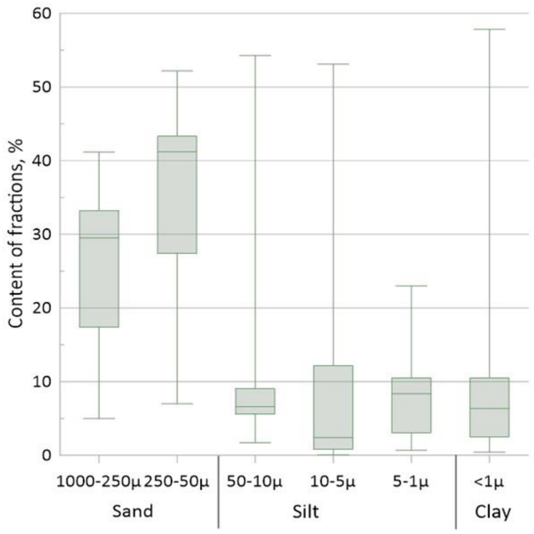

Figure 2. Variation of granulometric fractions. The central line is the median, the borders of the box are quartiles, the ends of the whiskers are the minimum and maximum

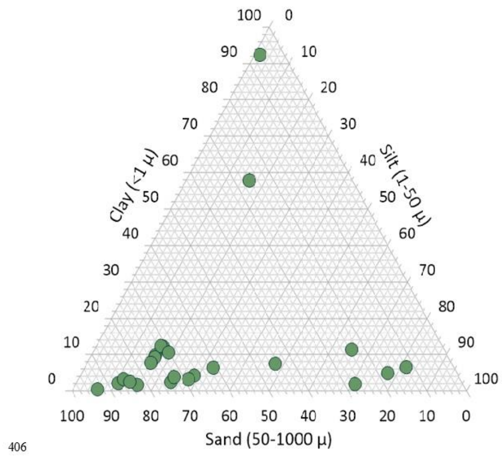

Figure 3. The ratio of granulometric fractions

Table 2. Average total content of macro- and microelements in soil samples

Soil Sampling Site	P_2O_5, %	K_2O, %	V, mg/kg	Cr, mg/kg	Co, mg/kg	Ni, mg/kg	Cu, mg/kg	Zn, mg/kg	Sr, mg/kg	Pb, mg/kg
Arshan-Bulg	0.18±0.02	2.24±0.16	91.22±0.52	86.85±0.41	11.37±0.23	48.01±1.75	32.29±1.25	70.60± 1.35	213.27±1.75	24.44±0,95
Baga-Chonos	0.17±0.02	1.37±0.17	22.90±0.85	75.43±0.85	14.76±2.06	10.07±0.46	15.17±1.46	45.04±1.46	83.13±1.95	6.42±0.42
Voznesenovka	0.10±0.02	2.43±0.17	88.31±0.19	138.25±0.70	14.27±2.01	54.73±1.75	35.94±2.06	66.72±1.61	180.91±1.50	17.35±0.86
Verkhny Yashkul	0.09±0.01	2.42±0.16	82.56±1.07	117.59±5.42	13.31±1.80	43.14±2.21	29.06±1.95	54.95±1.40	181.28±1.00	15.27±0.75
Iki-Chonos	0.17±0.03	2.44±0.16	83.47±1.70	96.90±0.70	9.99±2.48	61.34±2.21	40.72±2.26	75.38±1.25	235.15±1.00	26.75±0.75
Ovata	0.14±0.01	2.98±0.16	88.97±0.35	117.33±0.64	10.14±1.96	76.37±1.61	48.83±1.95	83.95±1.06	185.58±1.00	15.94±0.75
Troitskoye	0.17±0.01	2.15±0.16	74.33±0.27	99.92±2.65	8.30±0.06	36.22±2.05	30.91±1.20	83.94±1.07	196.88±1.25	16.30±0.70
Khar-Buluk	0.15±0.01	2.43±0.16	89.46±2.00	94.86±3.22	14.84±0.58	55.45±1.95	38.13±1.20	102.33±1.61	190.20±1.15	22.58±0.75
Maximum allowable concentration (SanPiN, 2021)	-	-	150	100	5.0	85.0	55.0	100.0	600	30.0
Substance hazard category	-	-	1	1	1	1	1	2	3	2
Clarke according to Vinogradov (Semenkov and Konyushkova, 2022)	-	-	100.0	200.0	18.0	58.0	14.7	83.0	340	16.0
Haplic Kastanozems of the Ergeni Upland	-	-	125.0	60.0	7.7	28.0	17.0	38.0	116.0	-
Background matter content in soils worldwide	-	-	-	200.0	10.0	40.0	20.0	50.0	-	10.0

In soil samples, the highest levels are registered for Sr, the lowest ones for Co and Pb. In order to assess the distribution and accumulation of trace elements in soils, an analysis of variance (ANOVA) was carried out (Table 3). The results obtained were compared with the lithosphere Clark according to Vinogradov (Kk), with the coefficient of relative accumulation of trace elements (Kkr), and with the regional background concentration (Kkf).

Table 3. Analysis of variance of the results of the determination of metals

Element	Kk	Kkr	Kkf	Shares of MPC
V	0.77	0.62	-	0.55
Cr	0.52	1.73	0.51	1.03
Co	0.67	1.58	1.21	2.42
Ni	0.83	1.72	1.20	0.57
Cu	0.72	1.99	1.69	0.62
Zn	0.88	1.92	1.46	0.72
Sr	0.54	1.58	-	0.31
Pb	1.13	-	1.81	0.60

All elements Kk < 1, except Pb, had an increased value of -1.13 in comparison with the lithosphere Clark (Table 3). The lowest concentrations Clarks relative to the litho-sphere were obtained for Cr (Kk = 0.52) and Sr (Kk = 0.54). A comprehensive evaluation of soil indicators showed damage to the central dry steppe zone of Kalmykia. The physiochemical characteristics of soils play a major role in restricting fertility, while high metal contents restrict growth and impose a risk on the food chain. The pH of the soil solution is an essential parameter to characterize soil conditions and formation processes. Soil acidity influences plant nutrition, and even soils rich in organic matter may be barren. Soil acidity analyses of samples from the settlements of Tcelinnyy District reveal faintly alkaline reactions of soil solutions, with pH equal to 8.0–8.4, while samples from Arshan-Bulg, Iki-Chonos, and Voznesenovka show neutral values of 7.6–7.8, which are environmentally optimal for the growth and development of agricultural plants (Figure 4; Table S1).

The soil of the Ketchenerovskiy district was characterized by more alkaline reaction (pH > 8) of the soil solution than in soil of the Tcelinnyy district (Figure 4). On the territory of the school and the boundary of the Ketchenery settlement, areas with a highly alkaline reaction of the medium (pH 8.5-8.7) were observed (Table 1). Most likely, the highly alkaline environment the school grounds are associated with the use of carbonate crushed stone layed on road surfaces, building materials, as well as due to the sprinkling of anti-icing agents in the winter season in the school yard. Dordzhiev et al. (2018) mentioned that it was the decent Ca content in soils that pro-vided the most favorable conditions for the majority of plants and aerobic microorganisms. The highest levels of cation exchange are inherent in soils with clay granulometric composition and increased organic matter (Ovata), while low ones are observed in sandy soils (Arshan-Bulg). Studies of the content of exchangeable cations of the Ketchenerovsky district had shown that the content of exchangeable Mg didn't exceed 0.67%, Ca - 0.90% (Table 1).

Soil organic matter (humus) is a regulator of the most important physiological and biological properties of the soil, which determine the water-air and nutrient regimes of soils. One of the key soil-forming processes is humus accumulation, which occurs during the humification and mineralization of incoming plant residues (Semenov et al., 2008). The content of soil organic carbon is the main indicator for assessing the soil's tolerance toward degradation and for predicting the possibility of restoring the fertility of degraded soil. Wind erosion is the main factor in the degradation of soil in the Caspian lowlands. It promotes the removal of fine particles and humus, lowering the soil fertility. As a result, there are sharp fluctuations in the total humus content of the soil, which affects the soil fertility (Gurkova, 2022). An increase in this parameter results in better physical and physicochemical properties and higher biological activity (Post et al., 1990; Davidson et al., 2000; Gurkova, 2022). Soil monitoring results attest to the fact that the prevailing share of Russia's soils is characterized by organic matter contents of 3% to 6% and 41 million ha, i.e., 48.6% of soils. Analysis of soil samples from Tselinny District shows humus levels are evaluated as low (less than 3%). So, organic carbon contents in settlement territories range between 0.67 and 1.89%, with the highest (1.89%) recorded in Verkhny Yashkul and Ovata background areas and the lowest (0.67% and 0.79%) in Baga-Chonos and Voznesenovka schoolyards in Haplic Kastanozems Sodic (Figure 5). In Ovata, carbon contents in topsoil (1.81–1.89%) slightly exceed those from other settlements. Low humus content losses in analyzed soil samples can be explained by the destruction of the humus horizon resulting from agricultural activities.

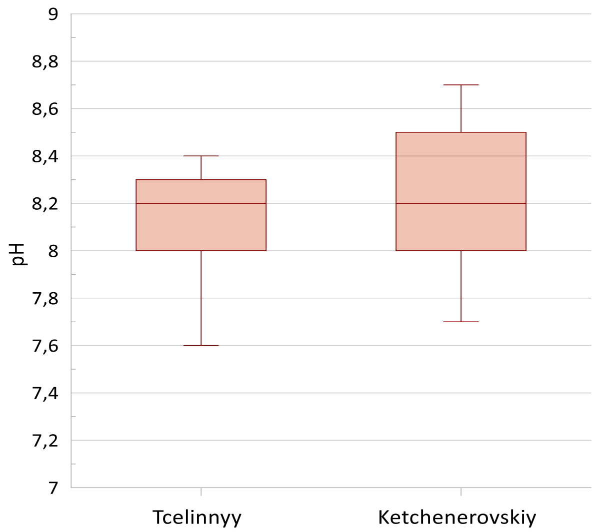

Figure 4. Variation of pH in soil samples. The central line is the median, the borders of the box are quartiles, the ends of the whiskers are the minimum and maximum.

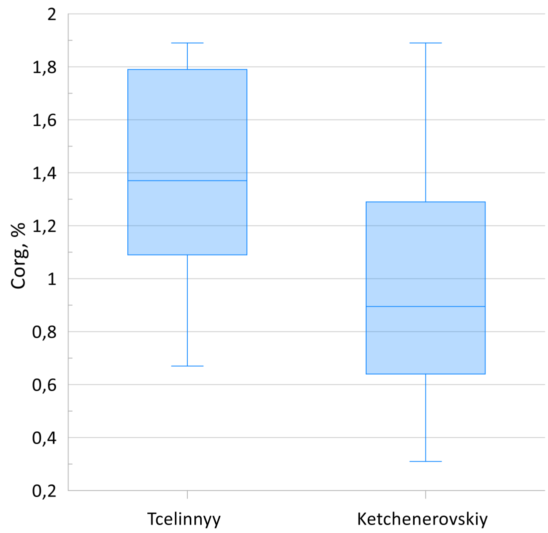

Figure 5. Variation of Corg content in soil samples. The central line is the median, the borders of the box are quartiles, the ends of the whiskers are the minimum and maximum.

According to the humus content, the soils of the Ketchenerovsky district differ slightly from the soils of the Tcelinnyy district, they belong to weak and low humus. The C_{org} content varies in the range from 0.31 to 1.89% (Table 1). Its lowest content was noted on the territory of the settlement of Gojur (0.31-0.34%). In the vicinity of the settlements of Gashun-Burgusta (center) and Kegult (background), the maximum values of 1.87 and 1.89%, were noted respectively (Table 1). Soil texture is another important parameter affecting soil fertility. Granulometric analysis concludes the dominant soils of the studied district are loamy ones. The contents of physical clay vary in a wide range from 6.84 to 64.88, with minimum values observed in the schoolyards of Ovata, Arshan-Bulg, Baga-Chonos, and Voznesenovka (Figure 2; Table 2). The investigated soils cluster with medium and light silty sandy loams since the prevailing fractions are those of medium sand (up to 41.18) and fine sand (up to 51.18). Such soils are characterized by a strong clod structure and the air and water holding capacities of their topsoil. As a result, the soil in Ovata is Haplic Kastanozems Sodic, medium loamy, cloddy silty, and loose. The schoolyard topsoil sample contains less silt (1.44) than the background and boundary ones. Values of physical clay vary from 23.84 to 29.84.

Phosphorus (P) and potassium (K) are of utmost importance for plant mineral nutrition. So, labile P and exchangeable K levels are also essential to soil fertility. In our study, labile P values in topsoil samples from examined localities are basically very low, between 0.09 and 0.18%, while K exchange content is medium, at 1.37 to 2.98% (Table 2). In Ovata, the former's medium value is 0.14%, while that of the exchange potassium was noted at 2.98%. Organic matter content is related not only to clay minerals but also to total microelements. For example, an increase in humus content facilitates a decreased migration of zinc and copper, resulting in a slight reduction in the values of these metals.

One of the main indicators of the anthropogenic load on the soil is the content of trace elements. They are accumulating in the upper fertile layer of the soil, where they have a negative impact on agricultural crops and can also enter animal and human bodies through food chains. In this regard, there is a need to conduct monitoring studies of soils to control the level of trace elements. Metal accumulation in soil can significantly alter the soil ecosystem by lowering soil quality and fertility due to their non-biodegradable properties. In the present study, the maximum value of V was registered in Arshan-Bulg, while the minimum was in Baga-Chonos (Table 2 and 3). These values are below the current maximum allowable concentration and background element content in soils worldwide, as well as the corresponding Clarke number according to Vinogradov (Korte et al., 1975; Dordzhiev et al., 2018). High levels of Cr were traced in Voznesenovka (138.25 mg/kg) and low ones in Baga-Chonos (75.43 mg/kg). These exceed the established maximum allowable concentration but not the background element content in soils worldwide or the Clarke number, according to Vinogradov (1962).

Total content of Co exceeds maximum allowable concentrations in all investigated settlements, with average values for this element traced in the district being 1.5-2 times higher than regionally established background levels, though they remain below the Clarke number, according to Vinogradov (1962). Ni and Cu contents from analyzed samples lie in a wide range, and maximum values for these elements were registered in Ovata (Ni: 76.37 mg/kg, Cu: 48.83 mg/kg). The concentration values did not exceed maximum allowable concentration ones but tended to increase as compared to background parameters and Clarke numbers, according to Vinogradov (1962). Zn content was below maximum allowable concentrations, the only and slight exception being that of 102.33 mg/kg in Khar-Buluk. The maximum (235.15 mg/kg) and minimum (83.13 mg/kg) Sr contents were found in Iki-Chonos and Baga-Chonos, respectively. Average content levels of the element are below the maximum allowable concentration. Pb concentration analysis of soil samples from the studied district attests to the fact that values vary from 6.42 mg/kg to 26.75 mg/kg, with the maximum in Iki-Chonos (26.75 mg/kg) and the minimum in Baga-Chonos (6.42 mg/kg). Pb content is below the maximum allowable concentration but exceeds background content levels in soils worldwide and the Clarke value. The Pb concentration in the sample from Baga-Chonos is below the regionally established background value. In soil samples, the highest levels are registered for Sr, the lowest ones for Co and Pb. High levels of these elements not only reduce soil fertility and plant growth, but they may also pose a threat to humans through the food chain.

Conclusion

For the first time, an assessment of the soils condition in residential areas of the arid region of the Caspian Lowland was carried out. The average levels of organic carbon in Haplic Kastanozems Sodic were low. A stable decrease in humus reserves (less than 3%) suggested deterioration in soil nutritional content. It was established that the soil acidity was neutral to faintly alkaline. The variable contents of P and K in studied soil were shown. The soil texture was mainly loamy in nature and belonged to dusty-sandy medium and light loams. Since the fractions of medium sand (up to 41.18%) and fine sand (up to 51.18%) dominate, heavy loam is less common. In the soil of studied area Co, Cr, and Zn contents exceed maximum allowable concentrations. The Co values in all settlements were higher than maximum allowable concentrations up to 2–3 times. The varia-tions of soil quality parameters in the different areas of the Caspian lowland were re-vealed. The results are important evidence for necessity of protecting or restoring the soil fertility at the central dry steppe zone of Kalmykia by reasonably utilizing soil resources.

Table S1. Chemical and Physical Properties of Arid Region Soils (0–20)

Settlements	pH	C_{org}, %	Calcium: Ca (meq/100 g in the numerator, in the denominator –%)	Calcium: $CaCO_3$ (%)	Magnesium: Mg (meq/100 g in the numerator, in the denominator – %)	Magnesium: $MgCO_3$ (%)
Arshan-Bulg, background	8.3 ± 0.03	1.24 ± 0.17	0.054 ± 0.005 / 0.980 ± 0.080	2.70 ± 0.28	0.056 ± 0.001 / 0.672 ± 0.016	2.35 ± 0.06
Arshan-Bulg, schoolyard	8.2 ± 0.03	1.09 ± 0.17	0.038 ± 0.005 / 0.760 ± 0.080	1.90 ± 0.28	0.060 ± 0.001 / 0.720 ± 0.016	2.52 ± 0.06
Arshan-Bulg, boundary	8.3 ± 0.03	1.66 ± 0.17	0.036 ± 0.005 / 0.720 ± 0.080	1.80 ± 0.28	0.060 ± 0.001 / 0.720 ± 0.016	2.52 ± 0.06
Baga-Chonos, schoolyard	8.2 ± 0.12	0.67 ± 0.22	0.044 ± 0.002 / 0.880 ± 0.048	2.20 ± 0.12	0.056 ± 0.001 / 0.672 ± 0.016	2.35 ± 0.06
Baga-Chonos, boundary	7.8 ± 0.12	1.25 ± 0.22	0.042 ± 0.002 / 0.840 ± 0.048	2.10 ± 0.12	0.056 ± 0.001 / 0.672 ± 0.016	2.35 ± 0.06
Baga-Chonos, background	7.9 ± 0.12	1.37 ± 0.22	0.036 ± 0.002 / 0.720 ± 0.048	1.80 ± 0.12	0.060 ± 0.001 / 0.720 ± 0.016	2.52 ± 0.06
Voznesenovka, boundary	7.8 ± 0.17	0.79 ± 0.28	0.048 ± 0.001 / 0.960 ± 0.013	2.40 ± 0.03	0.052 ± 0.001 / 0.624 ± 0.001	2.18 ± 0.00
Voznesenovka, background	8.4 ± 0.17	1.45 ± 0.28	0.046 ± 0.001 / 0.920 ± 0.013	2.31 ± 0.03	0.052 ± 0.001 / 0.624 ± 0.001	2.18 ± 0.00
Voznesenovka, schoolyard	8.0 ± 0.17	1.75 ± 0.28	0.046 ± 0.001 / 0.920 ± 0.013	2.30 ± 0.03	0.052 ± 0.001 / 0.624 ± 0.001	2.18 ± 0.00
Verkhny Yashkul, boundary	8.2 ± 0.20	0.83 ± 0.32	0.040 ± 0.001 / 0.800 ± 0.013	2.00 ± 0.03	0.054 ± 0.002 / 0.648 ± 0.034	2.27 ± 0.12
Verkhny Yashkul, boundary	8.2 ± 0.20	0.83 ± 0.32	0.040 ± 0.001 / 0.800 ± 0.013	2.00 ± 0.03	0.054 ± 0.002 / 0.648 ± 0.034	2.27 ± 0.12
Verkhny Yashkul, schoolyard	8.2 ± 0.20	1.62 ± 0.32	0.038 ± 0.001 / 0.760 ± 0.013	1.90 ± 0.03	0.050 ± 0.002 / 0.600 ± 0.034	2.10 ± 0.12
Background area between Verkhny Yashkul and Tarata	7.6 ± 0.20	1.89 ± 0.32	0.040 ± 0.001 / 0.800 ± 0.013	2.10 ± 0.03	0.060 ± 0.002 / 0.720 ± 0.034	2.52 ± 0.12
Iki-Chonos, schoolyard	8.3 ± 0.08	0.83 ± 0.12	0.038 ± 0.002 / 0.760 ± 0.046	1.90 ± 0.12	0.050 ± 0.003 / 0.600 ± 0.041	2.10 ± 0.27
Iki-Chonos, boundary	8.2 ± 0.08	1.14 ± 0.12	0.046 ± 0.002 / 0.920 ± 0.046	2.30 ± 0.12	0.056 ± 0.003 / 0.672 ± 0.041	2.77 ± 0.27
Iki-Chonos, background	8.0 ± 0.08	1.21 ± 0.12	0.042 ± 0.002 / 0.840 ± 0.046	2.11 ± 0.12	0.044 ± 0.003 / 0.528 ± 0.041	1.85 ± 0.27
Ovata, schoolyard	8.3 ± 0.10	1.85 ± 0.02	0.040 ± 0.002 / 0.800 ± 0.048	2.00 ± 0.12	0.062 ± 0.001 / 0.744 ± 0.013	2.60 ± 0.05
Ovata, background	8.0 ± 0.10	1.81 ± 0.02	0.032 ± 0.002 / 0.640 ± 0.048	1.60 ± 0.12	0.060 ± 0.001 / 0.720 ± 0.013	2.52 ± 0.05
Ovata, boundary	8.0 ± 0.10	1.89 ± 0.02	0.038 ± 0.002 / 0.760 ± 0.048	1.90 ± 0.12	0.064 ± 0.001 / 0.768 ± 0.013	2.69 ± 0.05
Troitskoye, schoolyard	8.0 ± 0.08	1.79 ± 0.24	0.040 ± 0.001 / 0.800 ± 0.013	2.00 ± 0.03	0.066 ± 0.005 / 0.648 ± 0.057	2.60 ± 0.16
Troitskoye, boundary	8.1 ± 0.08	1.80 ± 0.24	0.042 ± 0.001 / 0.840 ± 0.013	2.10 ± 0.03	0.066 ± 0.005 / 0.792 ± 0.057	2.52 ± 0.16
Troitskoye, background	8.3 ± 0.08	1.08 ± 0.24	0.042 ± 0.001 / 0.840 ± 0.013	2.10 ± 0.03	0.050 ± 0.005 / 0.600 ± 0.057	2.10 ± 0.16
Khar-Buluk, background	8.3 ± 0.10	1.79 ± 0.25	0.042 ± 0.002 / 0.840 ± 0.040	2.11 ± 0.05	0.052 ± 0.012 / 0.624 ± 0.012	2.18 ± 0.04
Khar-Buluk, schoolyard	7.8 ± 0.10	1.29 ± 0.25	0.038 ± 0.002 / 0.760 ± 0.040	1.90 ± 0.05	0.050 ± 0.012 / 0.600 ± 0.012	2.10 ± 0.04
Burgsun, center	7.7 ± 0.25	0.85 ± 0.20	0.04 ± 0.01 / 0.84 ± 0.03	2.10 ± 0.07	0.05 ± 0.01 / 0.58 ± 0.01	2.02 ± 0.04
Burgsun, background	8.2 ± 0.25	1.21 ± 0.20	0.04 ± 0.01 / 0.90 ± 0.03	2.10 ± 0.07	0.05 ± 0.01 / 0.60 ± 0.01	2.10 ± 0.04
Gashun-Burgusta, schoolyard	8.2 ± 0.06	1.87 ± 0.39	0.04 ± 0.01 / 0.90 ± 0.02	2.12 ± 0.01	0.05 ± 0.01 / 0.60 ± 0.01	2.10 ± 0.03
Gashun-Burgusta, boundary	8.0 ± 0.06	0.85 ± 0.39	0.04 ± 0.01 / 0.90 ± 0.02	2.13 ± 0.01	0.05 ± 0.01 / 0.60 ± 0.01	2.10 ± 0.03
Gashun-Burgusta, background	8.0 ± 0.06	0.58 ± 0.39	0.05 ± 0.01 / 0.85 ± 0.02	2.12 ± 0.01	0.05 ± 0.01 / 0.57 ± 0.01	2.02 ± 0.03
Godzhur, center	7.9 ± 0.20	0.31 ± 0.03	0.04 ± 0.01 / 0.86 ± 0.01	2.20 ± 0.01	0.05 ± 0.01 / 0.62 ± 0.01	2.18 ± 0.01

Table S1. (continued)

Settlements	pH	C_{org}, %	Calcium: Ca (meq/100 g in the numerator, in the denominator –%)	Calcium: $CaCO_3$ (%)	Magnesium: Mg (meq/100 g in the numerator, in the denominator – %)	Magnesium: $MgCO_3$ (%)
Godzhur, background	8.3 ± 0.20	0.37 ± 0.03	0.03 ± 0.01 0.88 ± 0.01	2.22 ± 0.01	0.05 ± 0.01 0.62 ± 0.01	2.17 ± 0.01
Ergeninskii, schoolyard	8.1 ± 0.12	0.64 ± 0.12	0.04 ± 0.01 0.89 ± 0.01	2.14 ± 0.01	0.05 ± 0.01 0.60 ± 0.01	2.10 ± 0.03
Ergeninskii, background	8.1 ± 0.12	1.02 ± 0.12	0.04 ± 0.01 0.88 ± 0.01	2.13 ± 0.01	0.05 ± 0.01 0.60 ± 0.01	2.10 ± 0.03
Ergeninskii, background	8.3 ± 0.12	0.94 ± 0.12	0.04 ± 0.01 0.90 ± 0.01	2.15 ± 0.01	0.05 ± 0.01 0.62 ± 0.01	2.18 ± 0.03
Kegul'ta, schoolyard	8.2 ± 0.12	1.02 ± 0.29	0.06 ± 0.01 0.67 ± 0.06	2.10 ± 0.03	0.05 ± 0.01 0.60 ± 0.05	2.10 ± 0.18
Kegul'ta, boundary	8.0 ± 0.12	0.96 ± 0.29	0.05 ± 0.01 0.60 ± 0.06	2.20 ± 0.03	0.06 ± 0.01 0.72 ± 0.05	2.52 ± 0.18
Kegul'ta, background	7.8 ± 0.12	1.89 ± 0.29	0.05 ± 0.01 0.60 ± 0.06	2.18 ± 0.03	0.05 ± 0.01 0.55 ± 0.05	1.93 ± 0.18
Ketchenery, schoolyard	8.7 ± 0.06	0.79 ± 0.21	0.04 ± 0.01 0.86 ± 0.03	2.30 ± 0.07	0.06 ± 0.01 0.67 ± 0.02	2.35 ± 0.07
Ketchenery, boundary	8.6 ± 0.06	0.58 ± 0.21	0.03 ± 0.01 0.88 ± 0.03	2.10 ± 0.07	0.05 ± 0.01 0.65 ± 0.02	2.27 ± 0.07
Ketchenery, background	8.5 ± 0.06	1.30 ± 0.21	0.04 ± 0.01 0.79 ± 0.03	1.90 ± 0.07	0.05 ± 0.01 0.60 ± 0.02	2.10 ± 0.07
Tugtun, schoolyard	8.2 ± 0.15	0.40 ± 0.15	0.04 ± 0.01 0.74 ± 0.05	2.11 ± 0.01	0.05 ± 0.01 0.58 ± 0.01	2.10 ± 0.01
Tugtun, background	8.5 ± 0.15	0.69 ± 0.15	0.05 ± 0.01 0.85 ± 0.05	2.10 ± 0.01	0.05 ± 0.01 0.60 ± 0.01	2.11 ± 0.01
Shin-Mer, schoolyard	8.4 ± 0.05	1.29 ± 0.02	0.03 ± 0.01 0.66 ± 0.01	1.90 ± 0.07	0.05 ± 0.01 0.55 ± 0.06	1.93 ± 0.21
Shin- Mer, boundary	8.5 ± 0.05	1.33 ± 0.02	0.03 ± 0.01 0.64 ± 0.01	1.60 ± 0.06	0.06 ± 0.01 0.67 ± 0.06	2.35 ± 0.21

Table S2. Characteristics of soil samples (topsoil) texture

Soil Sampling Site	1-0.25	0.25-0.05	0.05-0.01	0.01-0.005	0.005-0.001	< 0.001 silt	< 0.01 physical clay	Soil type by granulometric composition
Arshan-Bulg, background	31.90	41.90	7.20	12.40	4.20	2.40	19.00	Sandy Loam
Arshan-Bulg, schoolyard	37.70	47.70	7.80	2.40	1.20	3.20	6.84	Loamy Sand
Arshan-Bulg, boundary	31.10	41.20	7.70	4.00	12.20	3.80	20.0	Sandy Loam
Baga-Chonos, schoolyard	29.50	39.40	6.50	12.20	9.20	3.20	24.60	Light Loamy
Baga-Chonos, boundary	25.50	35.50	8.84	18.20	5.60	6.40	30.20	Medium Loamy
Baga-Chonos, background	28.50	38.46	7.64	12.40	8.80	4.20	25.40	Light Loamy
Voznesenovka, boundary	31.90	42.06	6.28	0.08	9.88	9.80	19.76	Light Loamy
Voznesenovka, background	39.36	43.32	6.40	0.76	8.52	5.60	18.88	Light Loamy
Voznesenovka, schoolyard	37.03	47.03	9.04	1.40	3.00	2.50	16.90	Light Loamy
Verkhny Yashkul, boundary	37.62	49.62	5.60	1.96	3.08	2.12	17.16	Light Loamy
Verkhny Yashkul, schoolyard	33.20	43.06	6.36	2.28	7.40	7.70	17.38	Light Loamy
Background area between Verkhny Yashkul and Tarata	30.50	40.42	5.92	0.16	10.84	12.16	23.16	Light Loamy
Iki-Chonos, schoolyard	5.00	7.00	23.12	53.10	5.28	6.48	64.88	Heavy Loamy
Iki-Chonos, boundary	10.70	12.78	53.76	10.76	0.68	11.32	22.76	Light Loamy
Iki-Chonos, background	17.36	27.36	42.32	2.56	2.96	7.44	12.96	Light Loamy
Ovata, schoolyard	41.18	51.18	3.80	0.32	2.08	1.44	23.84	Medium Loamy
Ovata, background	8.10	18.02	5.04	2.64	8.36	7.84	29.84	Medium Loamy
Ovata, boundary	32.20	42.20	1.72	3.48	11.20	9.20	28.88	Medium Loamy
Troitskoye, schoolyard	29.14	41.14	6.60	0.80	11.80	10.52	23.10	Light Loamy
Troitskoye, boundary	29.17	42.20	5.20	0.91	10.20	10.69	23.12	Light Loamy
Troitskoye, background	29.32	43.32	4.96	0.96	10.52	10.92	22.40	Light Loamy
Khar-Buluk, background	9.68	17.68	52.96	13.52	4.28	1.88	19.68	Light Loamy
Khar-Buluk, schoolyard	5.78	11.78	54.28	0.28	23.00	4.88	29.16	Medium Loamy

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