

REMOTE SENSING AND GEOSPATIAL APPROACH FOR LAND DEGRADATION RISK ASSESSMENT IN THE COSTA VERDE BAY SOUTHEAST OF BRAZIL

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ABSTRACT. This study examines Olkhon Island, the largest island in Lake Baikal, located within the Pribaikalsky National Park. The research was motivated by growing tourist flows and Russia Tourism Development Strategy through 2035, which includes specially protected natural areas. To assess recreational impacts on soil cover, the authors analyzed visitation statistics, including vehicle and air transport, and described road types and their transformation. Twenty-eight soil samples were collected along an 83 km transect from the Olkhon Island ferry to Cape Khoboy. The ecological and geochemical state was assessed using the concentration coefficient (K_d), Clark concentration coefficient (K_k), and the total pollution factor (Saet index, Z_c). Results showed no critical Z_c values (<16). However, after the tourist season (August–October), a statistically significant increase in Z_c was recorded at the Buruger checkpoint, Kharantsy, Peschanaya, and Uzury settlements, indicating differentiated transport load distribution in autumn. Geochemical analysis based on K_k values revealed significant transformations for Cu, Ni, Cr, and V, with increasing trends of 0.06–0.51, possibly due to technogenic load or seasonal migration processes. Co and Zn showed stable values with minimal fluctuations (0.02–0.06), indicating geochemical stability. Benzo(a)pyrene monitoring (May–December 2024) showed significant seasonal differences. During peak tourist season (July), concentrations in Khuzhir and Kharantsy nearly doubled the maximum allowable concentration (20 $\mu\text{g/kg}$). By October, levels decreased 3–20 times. Benzo(a)pyrene inputs are presumably linked to vehicle emissions. The findings suggest localized changes in soil chemistry due to vehicle impacts, with residual anthropogenic influence from the Soviet period.

KEYWORDS: soil pollution, automobile transport, road network, polycyclic aromatic hydrocarbons, X-ray fluorescence spectrometry, pollutant element

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INTRODUCTION

Motor vehicles, as an integral part of the modern world, have a significant impact on the ecological and geochemical state of different territories worldwide (Abilov et al. 2021). Their presence not only alters the landscape but also changes the chemical composition of soils, leading to the accumulation of heavy metals and other pollutants (Vodyanitsky 2011).

The most vulnerable landscapes are steppe areas, where the road network develops rapidly. Recreational areas with access to waterfronts are subject to the greatest traffic loads. Legislative initiatives are also currently contributing to the increase in tourist flow. For example, the Russian Government signed Decree No. 2129-r of September 20, 2019, "On the Strategy for Tourism Development in the Russian Federation through 2035", which focuses on ecotourism in specially protected natural areas (SPNAs). One of the goals of ecotourism is to "increase the number of visitors to SPNAs to 16 million by 2035" of the Olkhon district are particularly vulnerable to recreational impacts. Some of these landscapes are located within the Pribaikalsky National Park (NP), the most visited protected area in the Irkutsk region, stretching for approximately 470 km. According to the electronic permitting system, the Federal State Budgetary Institution "Zapovednoye Pribaikalye" (Baikal Nature Reserve) receives over 150,000 people annually. The most visited area of the Pribaikalsky NP is Olkhon Island, which has been visited by at least 75,000 people over the past three years. High recreational loads on the island lead to the transformation of ecosystems, particularly the soil cover. The modern state of the soil cover of Olkhon Island was assessed for many years (Grebenshchikova et al. 2008; Kitaev et al. 2014; Pellinen et al. 2016; Pellinen et al. 2021; Kostyukova 2022; Ryabinina et al. 2024).

This study is a continuation of a study begun in 2016 on Olkhon Island (Pellinen et al. 2016). It examines the ecological state of the island soil cover, which was subject to agricultural impacts during the Soviet period. To assess the current ecological and geochemical state of Olkhon Island soils, an analysis of the territory's natural resource use (which enterprises were previously located on the island, what activities local residents were engaged in, etc.) and factors that may have left a geochemical trace in the soils was conducted.

The aim of this study is to assess the impact of recreational activities, including the increasing flow of tourist vehicles, on the natural environment of Olkhon Island. The main objectives of the study are:

- 1) determination of intensity of the flow of automobile and air transport on Olkhon Island and conduct an analysis depending on the season of the year;
- 2) characteristic of roads in the state under the jurisdiction of the Pribaikalsky NP;
- 3) identification of the limiting factors regulating the flow of vehicles on Olkhon Island;
- 4) definition of the pollution level of the soils examined by toxic elements, as well as their possible sources and geochemical anomalies;
- 5) determination of concentrations of benzo(a)pyrene (B(a)P) in the soil samples discussed to establish possible sources of its entry into the environment.

Materials and methods

Study Area

Olkhon Island is located in Lake Baikal and is separated from the western shore of the lake by the Olkhon Gate Strait. Administratively, the island belongs to the Irkutsk

Region, Olkhon District, and has its administrative center in the village of Khuzhir (53.1436° N, 107.28313° E). As noted above, part of its territory is included in the Pribaikalsky National Park, a specially protected natural area. Olkhon Island landscape is divided into two main classes: mountain-taiga South Siberian landscapes and steppe Central Asian landscapes. The soil component of these geosystems is represented by three main types: ordinary chernozems, chestnut soils (characteristic of steppe areas), and soddy forest soils (typical of mountain-taiga habitats) (Ubugunov et al. 2018). The soil cover of the island was formed on the rocks of the Olkhon terrane, composed of sedimentary, volcanic, and plutonic rocks that underwent metamorphism in the Early Paleozoic (Donskaya et al. 2022). The maximum soil cover thickness of 20–30 cm is present in small areas of normal sedimentary deposits of the Neogene and Quaternary periods. In the steppe and forest-steppe zones, planar deluvial, erosional, aeolian, and, to a lesser extent, karst and landslide processes are observed (Pellinen et al. 2019). The most toxic chemical elements, especially heavy metals, as well as polycyclic aromatic hydrocarbons (PAHs) are concentrated in the upper soil horizons at a depth of 0–20 cm (Dzhuvelikyan et al. 2009; Tsi bart and Gennadiyev 2013). Therefore, the upper soil horizon (depth up to 15–20 cm) along the main public and non-public roads of the Pribaikalsky NP was chosen as the object of study. The average annual amount of precipitation is 200–300 mm/year; the annual moisture coefficient is 0.34. About 83–90% of this amount falls during the period April–October, a significant part of which is in the summer. During the period January–March, the monthly amount of precipitation does not exceed 5 mm, and the snow cover averages 10–15 cm, blown either away by the winds or melting due to the large number of sunny days (Galaziy 2012).

Study Design

The study utilized both in situ and laboratory research methods, as well as geographic information systems for the preparation of cartographic material. In-situ methods included the selection of key points and sampling. The expedition research was conducted in two stages. The initial stage of soil sampling was carried out during the peak tourist season, which generally extends from late July to August 25. During this stage, in August 2023, a total of 28 sampling sites were tested. Key points were selected based on road classification (public or private), main traffic points, and tourist attractions (Fig. 1).

Sampling points were located 10 meters from the impact source (the road) on both sides. The reference site was located 10 km from the public road, away from tourist routes and any infrastructure. It should be noted that this study represents the first stage of monitoring aimed at identifying general patterns and hot spots of the pollution. These sampling sites were tested based on logistical constraints and the objective of a primary assessment of the zone of direct transport impact, where the maximum concentration of pollutants is expected. The sampling depth (0–20 cm) corresponds to standard practice for assessing surface pollution accumulating in the upper, most biologically active soil horizon (Saet 1990; Vodyanitsky 2011). Sampling was carried out using the route method. The transect was 83 km long, and a plot with an area of 1 m² was laid out in advance; soil samples were collected using the envelope method (Cherkashina and Pellinen 2022).

The second stage of soil sampling was conducted in October 2023 at the same locations, one and a half months after the tourist season ended. By this time, traffic on

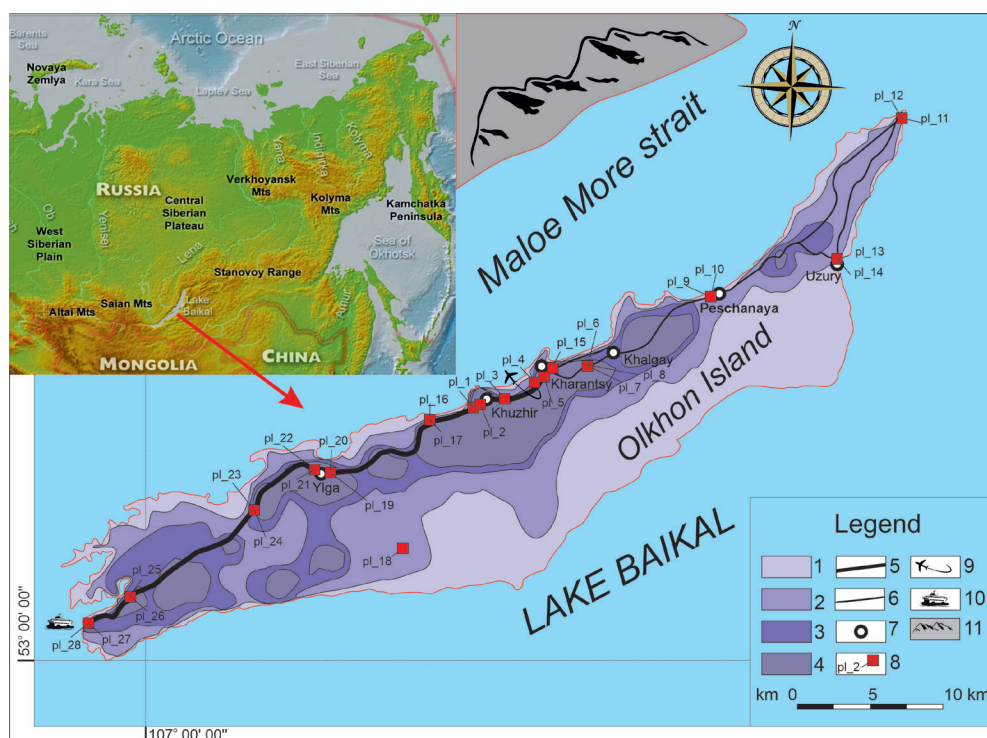


Fig. 1. Map of soil sampling sites and road density. Legend: 1 – road density no more than 0.2 km/km² (single, forest roads); 2 – road density from 0.2 to 0.6 km/km²; 3 – road density from 0.6 to 1.6 km/km²; 4 – road density from 1.6 to 2.2 km/km²; 5 – public road; 6 – non-public road (North of Olkhon Island route); 7 – settlement; 8 – sample site; 9 – airport; 10 – ferry; 11 – the Baikal Ridge

public roads had decreased by 54.2%, and on the “North of Olkhon Island” tourist route, by ~94.4%. Non-public roads (forest roads, with the exception of two tourist routes) are not shown on the map, as they are mainly used by state inspectors (Fig. 1). The same sites were also sampled in July and October 2024 to assess contamination with highly toxic organic compounds. This work utilized information on bedrock from a 1:200,000 geological map (Konoplev 1959), monographs (Vinogradov 1957; Grebenshchikova et al. 2008). Data on nature management were taken from a popular science essay (Kalikhman et al. 2017). Statistical data on vehicles transported to Olkhon Island by ferry were analyzed. Additionally, a request was made to Siberian Light Aviation LLC, which operates flights from Kharantsy Airport, Khuzhir municipal formation (53.221058° N, 107.418467° E), to provide information on the number of flights and aircraft refueling at the airport.

Laboratory methods include sample preparation for X-ray fluorescence (XRF) spectrometry, which consists of the following steps: drying soil samples in a drying oven to an air-dry state, sifting through a coarse sieve (0.25 mm size) to remove organic and stony inclusions, grinding 50 g samples each in an agate mortar to a fine fraction of 0.1 mm, taking a 1±0.001 g sample of the fine fraction powder to determine light components (V, Cr, Co, Ni, Cu, Zn) and 5±0.001 g for heavy components (Pb, As). The quality control of the measurements was carried out using a set of certified standard samples of soils and sediments of different chemical compositions. All the measurements were carried out by using a XRF-spectrometer S8 TIGER (Germany), located at the Center for Geodynamics and Geochronology, Institute of the Earth's Crust, SB RAS, Irkutsk. Concentrations of the elements to be determined were computed using the SPECTRA software connected to this device, using a previously authored method developed (Cherkashina and Pellinen 2021).

To assess the level of pollution of roadside soils with a highly toxic organic compound (B(a)P, C₂₀H₁₂), which belongs to the PAH group and has high carcinogenic

activity, a measurement technique was used (Kovalev 2007). The concentration of B(a)P was measured by using a gas chromatograph model 7890 B with a mass selective detector 7000 C (Agilent Technologies Inc., USA). The internal surrogate standard method, which uses a mixture of deuterated naphthalene-d₈, acenaphthene-d₁₀, phenanthrene-d₁₀, chrysene-d₁₂, and perylene-d₁₂, was applied. The relative error in the measurement of B(a)P in the soil was 15%, with a confidence level of P = 0.95.

For the assessment of the level and degree of chemical contamination in the soil samples examined, the following indicators were used: the chemical concentration index (K_c), the Clark concentration index (K_k), and the total pollution factor Z_c (Saet index). Data processing was performed for each component being determined. The K_c index is an indicator of the level of abnormality in the pollutant element content. The intensity of accumulation of these elements was assessed using the ratio of the actual average content of the pollutant in the soil (C_i) to its regional background value (C_r) (Eq. 1): $K_c = C_i / C_r$. According to the level of relative values of the K_c index, pollutant elements are divided into three groups: $K_c < 1$ (low level of pollution), $1 < K_c < 2$ (moderate level), $K_c > 2$ (critical level) (Vodyanitsky 2008). The K_k index is defined as the ratio of the element content at a specific sampling point to its Clark value, where C_i is an element content at a specific sampling point and K_i is the Clark value of the element in the earth's crust in accordance with (Wedepohl 1995) (Eq. 2): $K_k = C_i / K_i$. The following categories based on the K_k index were recognized: $K_k < 1$ – the element is less concentrated than the average in the earth's crust; $K_k = 1$ – the element concentration corresponds to the Clark value; $K_k > 1$ – the element is concentrated relative to the average level of its content; $K_k \gg 1$ (e.g., 10, 100, and more) – significant enrichment in the element, which may indicate ore formation (Saukov 1975). The Saet index (Z_c) was expressed (Saet et al. 1990) as the sum of the concentration coefficients, K_c , of the i -th pollution component, with values of $K_c > 1.5$, taking into account the number of anomalous

elements (n). The obtained critical values characterizing the total pollution (Z) of the area studied were classified according to the degree of danger (Vodyanitsky 2008).

RESULTS AND DISCUSSION

Characteristics of the road conditions in the Pribaikalsky National Park

As of 2024, there are 25 tourist routes operating on the territory of the Pribaikalsky NP (Federal State Budgetary Institution "Zapovednoye Pribaikalye", 2024). These are classified by movement type as water, hiking, or combined (hiking, cycling, and car). The most popular routes are on Olkhon Island, located on the western side of Lake Baikal, 142 km from Irkutsk (611,215 permanent residents as of 2023). Between 2021 and 2023, the share of tourist visits to Olkhon Island was nearly equal to that of the mainland part of this park, averaging 52.1%. This is 4.2% higher than the mainland visitor numbers. Most tourists prefer to travel by car because of the long travel distances (e.g., "South of Olkhon Island" – 48 km, "North of Olkhon Island" – 61 km). Visitors' numbers and travel types depend on the season. Combined routes account for 66.67% of summer traffic, compared to 16.67% in winter, when car routes became dominant (58.33%). In addition to the tourist flow, the island has a permanent population. It contains nine settlements within the Khuzhir Municipal Formation (Khuzhir MF), concentrated along the western coast of the Small Sea. As of January 1, 2024, the permanent population was 1,967. According to the regional register of collective accommodation, as of December 2020, there were 70 recreation centers within the settlements, offering 2,355 places, with an additional 3,262 places available in cottages. An assessment of land use on Olkhon shows that only 1.7% of its territory is developed by humans, though 29.61% on the steppe landscapes are used as pastures for grazing cattle (Solovieva et al. 2024).

High tourist demand – 94,833 people visited Olkhon Island in 2023 – has subjected the island's soil cover to intense anthropogenic impact. A major source of this impact is motor transport, evidenced by an extensive road network (405 km of authorized public and non-public roads; 575 km of unauthorized roads) (Solovyeva et al. 2024) and traffic flow dynamics (Fig. 2).

According to the Ministry of Transport and Road Management of the Irkutsk Region, visits to Olkhon Island peaked in July and August 2023 (see Fig. 2). From May 9 to December 4, 2023, 118,225 vehicles were delivered via the

ferry, with the peak load (44,555 vehicles) occurring from July 15 to August 25. State inspectors from the Island Forestry Service of the Pribaikalsky NP confirm that August was the busiest month for transport on the island. Of the total traffic flow, 8.34% travels the "North of Olkhon Island" route from the Khuzhir village towards Cape Khoboy and the village of Uzury. This route is used by both locals and tourists, leading to a summer vehicle flow of approximately 8,000 units, which constitutes the main load. According to 2023 data, the permanent populations of the villages along this route are small: Khalgay (48 people), Peschanaya and Uzury, with seven residents each. During the summer, tourist transport along these routes is mainly provided by UAZ SGR vehicles (running on AI-92 gasoline), whose exhaust gases contain nitrogen, carbon dioxide, carbon monoxide, nitric oxide, B(a) P, non-carcinogenic hydrocarbons, and solid particles (soot) (Baybarin 2014).

Heavy vehicle traffic is transforming the roadbed and adjacent terrain, particularly along the "North of Olkhon Island" route. In some sections, the roadbed is overcompacted. Excessive moisture and vertical loads from vehicles lead to various defects such as deep ruts, plastic deformations (ridges), and heaving depressions. Drivers attempting to avoid these depressions create new unauthorized roads. The impact of vehicles on roadside landscapes in the park was studied by Yurkova and Filippova (2013), who showed that roadside landscapes experience a distinct impact of motor vehicles, expressed in an increase in the level of heavy metal pollution in local soils such as Pb, Zn, Ni, Co, Cr, and Cu. The problems of soil degradation of the road network in the forest zone were studied in (Atucha et al. 2013; Yousefi et al. 2016). These studies showed that roads in forest areas lead to a decrease in soil infiltration and increase the potential runoff, even at low-intensity precipitation loss, resulting in a decrease in soil fertility in erosion zones around forest dirt roads.

During winter, traffic on the official ice crossing across Kurkutsy and Irkutskaya bays is not counted. To estimate it, tourist data was used: from February to April 2021–2023, 24,566 people visited Olkhon Island via organized routes. Assuming four people per vehicle, it amounts to about 6,141 vehicles over three months, which is 7.4 times fewer than during the ferry season. This accounting period was based on data from the official ice crossing, which has operated annually since 2015, opening in February and functioning for an average of 42 days.

Limiting factors for visiting Olkhon Island are the seasonality of the ferry crossing across the Olkhon Gate

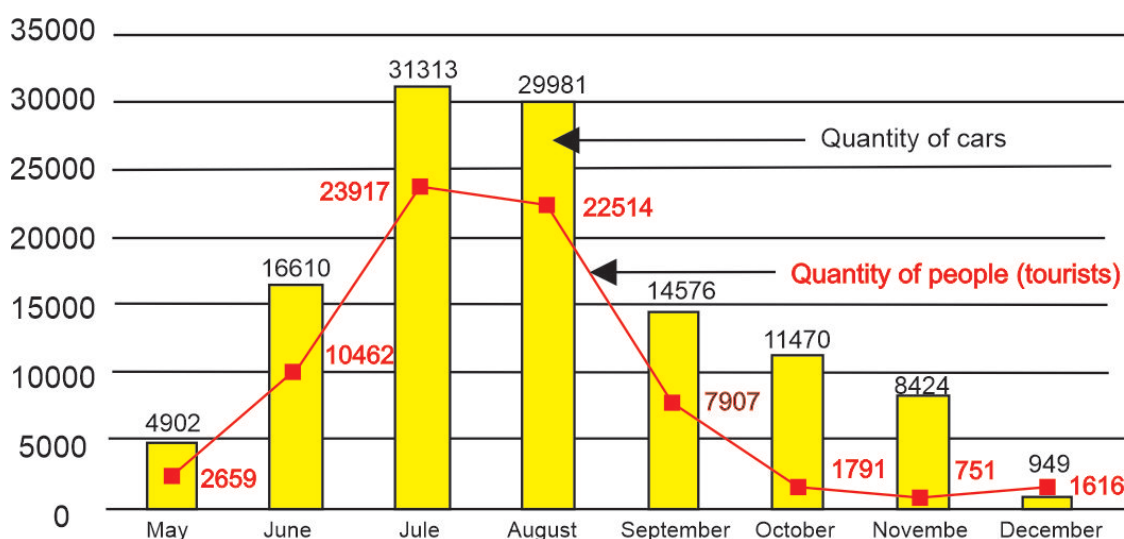


Fig. 2. Traffic dynamics congestion on the ferry, including the cars of local residents, as well as the number of tourists, 2023

Strait, as well as weather conditions (storms), during which the ferry suspends operations. According to open internet data sources, between 2015 and 2024, the water crossing operated 239 days and the ice crossing 49 days in 2017. Thus, over the past 9 years, the island has been inaccessible to the public for an average of 90 days. The data does not include days when the ferry did not sail due to weather conditions.

In the work (Pellinen et al. 2019), the distribution of heavy metals and fluorine in the soils of Olkhon Island was analyzed. Applying the K_k index, a geochemical row was established, revealing low contamination levels of F, Zn, Pb, and V. Subsequent monitoring by Pellinen et al. (2021) and Cherkashina et al. (2025) identified Pb, Cd, and Hg as significant pollutants. These studies examined the extent of anthropogenic soil pollution, migration pathways of the heavy metals examined in surface soils, and their potential origin sources.

The study (Yurkova and Filippova 2013) was focused on the assessment of the vehicles impact on roadside areas of the Pribaikalsky NP, except for Olkhon Island. The average content of Pb, Zn, Cu, Cr, and F in roadside soils near Sarma exceeded regional background levels by 2–5 times. The highest exceedances of maximum allowable concentrations (MAC) in local areas were recorded for Mo, Pb, Ag, and Cu, with concentrations decreasing further from the road. The Malomorskaya recreational zone is clearly affected by vehicle emissions, with anthropogenic pollution of roadside soils primarily driven by Pb, Cu, Zn, and As. Our study aims to address this gap by analyzing traffic flow directly to Olkhon Island. We found a significant impact of vehicles on natural systems of the island.

Geochemical analysis of the soil cover within the road network of Olkhon Island

The general ecological and toxicological state of the island soil cover was assessed by using geochemical indicators, which included rare and trace elements of hazard classes I–III in accordance with (Popova 2021): As, Pb, Zn – highly hazardous; Co, Cr, Cu, Ni – moderately hazardous; V – low-hazard. The regulatory framework for assessing the current ecological and geochemical state of roadside soils using the obtained element concentrations was based on their contents in the Earth's crust and regional background in the soil (Wedepohl 1995; Pellinen et al. 2016) (Table 1).

As a result of geochemical analysis, values of the Z_c

index were assessed by using Eq. 1 and the formula from (Saet et al. 1990) for all sampling points. It was found that these values for all heavy metals examined in the observed period of August–October did not exceed the 8-unit mark (Fig. 3). However, it was established that for this period, the total volume of traffic flow on the roads of Olkhon Island was 26,046 units. Analysis of the dynamics of this indicator revealed heterogeneity in changes in the anthropogenic load during the final period of the tourist season. As is obvious from Fig. 4, in certain areas of Olkhon Island, such as the Kharantsy, Peschanaya, and Uzury settlements; the Buruger checkpoint; and the public road to the ferry crossing to Olkhon Island (monitoring points pl 4–pl 9, pl 14, and pl 26), a statistically significant increase in the Z_c values was recorded at the end of the tourist season, while in other areas, a steady downward trend in the obtained values was observed. In the background area in the Tashkiney hollow (point pl 18), the value of the Z_c factor did not exceed the 2-unit mark (see Fig. 3). The obtained results indicate a differentiated nature of the distribution of transport loads on the island in the autumn period, which is probably due to changes in the intensity of tourist flows and the peculiarities of the organization of the road network.

The K_k index as geochemical method allows one to estimate the level of accumulation of chemical elements in rocks, ores, or soils compared to their average content in the Earth's crust (Clark). Analysis of geochemical rows constructed based on the computed K_k values enables one to identify possible geochemical anomalies, determine potentially ore-bearing zones, and study the migration processes of polluting elements. The following geochemical rows were obtained for heavy metals in soil samples collected in August and October 2023, respectively: Cu (3.89) > Ni (3.25) = Cr (3.25) > As (3.24) > V (2.71) > Co (2.47) > Zn (2.39) > Pb (1.11); Cu (3.95) > Cr (3.45) > Ni (3.39) > V (3.22) > Co (2.49) > Zn (2.45) > As (2.09) > Pb (0.94). Comparative analysis revealed significant changes in the geochemical composition of the studied system. Significant transformations were found for elements with an increasing trend in the K_k values for Cu, Ni, Cr, and V in the range of 0.06–0.51 (Fig. 4). Thus, the maximum K_k values were 3.89 in August and 3.95 in October for Cu, which demonstrates a stable upward trend. Such dynamics may be caused by several factors: an increase in technogenic load, or seasonal changes in the conditions of migration and sorption of the element (Saet et al. 1990).

Table 1. The obtained and reference contents of heavy metals in soils within the road network of Olkhon Island and the earth's crust

Element	Average content, August/October, mg/kg	Standard deviation (σ), August/October, mg/kg	Clark in the earth's crust, mg/kg	Regional background, mg/kg
			Soils of deluvial deposits, horizon A	
V	144/171	18/22	53	171
Cu	56/57	7/8	14.3	44
Cr	114/121	14/16	35	101
Co	29/29	4/4	11.6	19
Ni	61/63	8/9	18.6	46
As	6/4	1/0.5	2	2.5
Zn	124/128	15/17	52	109
Pb	19/16	3/2	17	17

Of particular interest is the synchronous behavior of Cr and Ni, which demonstrate comparable growth dynamics in their concentrations: an increase in the K_k index of 0.15 for Cr and 0.14 for Ni. For vanadium, the positive increase in the K_k value was 0.51, which deserves special attention and requires a study of its speciation. Such behavior may be related to its input into the soil from petroleum products (exhaust gases, lubricants) or from terrigenous rocks enriched in organic matter, which is relevant for road networks and arable lands. Such a change in the geochemistry of these metals is characteristic of ferruginous massifs, for which they are typomorphic. Further isotope-geochemical studies are required to definitively identify the source of V. A decrease in the K_k value (−1.15) for As towards the end of the summer season is noted, which can be explained by seasonal leaching of mobile forms of this metal from the upper soil horizon by precipitation or by active biogenic migration, namely accumulation by vegetation or soil microorganisms.

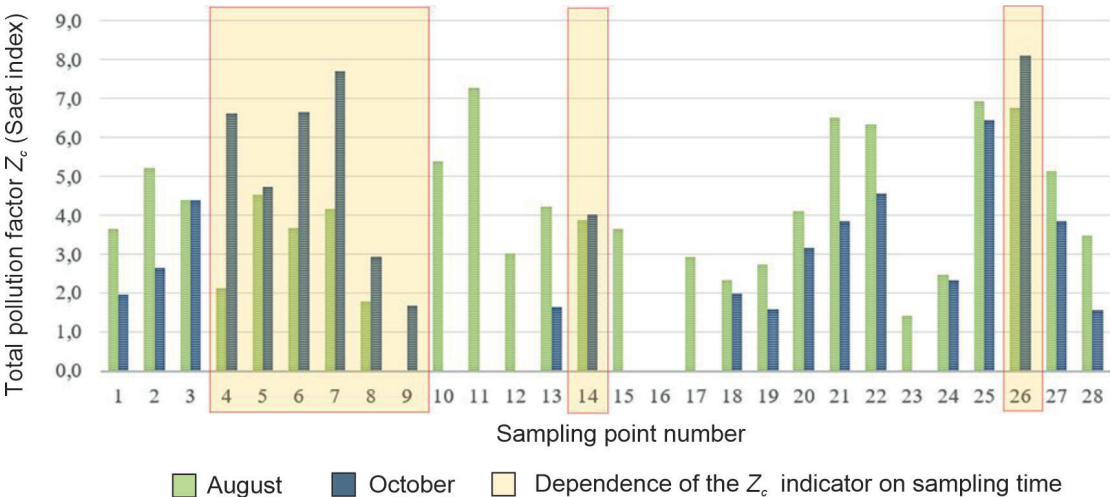
A group of elements with stable values, including Co and Zn, is characterized by minor fluctuations in their Clark concentration coefficients in the range of 0.02–0.06. This inert behavior indicates the stability of their geochemical characteristics in this ecosystem and may be related to the characteristics of their migratory forms and sorption properties. The behavior of Pb is indicative: by the end of the tourist season in October, the obtained values of the K_k index were decreased from 1.11 to 0.94, indicating the

removal of this element from the ecosystem, possibly due to a combination of natural and anthropogenic factors.

Benzo(a)pyrene in roadside soils of Olkhon Island and its possible sources

The monitoring results of the B(a)P levels in the samples examined, obtained in the period from May to December 2024, revealed significant differences between July and October readings. Concentrations of B(a)P, elevating the maximum allowable permissible (MAC) value for B(a)P, were recorded in soils in various settlements and arable lands. The values of B(a)P recorded in the Khuzhir village in July were as follows (Fig. 1, 5): 37 µg/kg near the pharmacy (point pl 1) and 39 µg/kg at the exit towards the Yalga village (point pl 2), which exceeded its MAC value (B(a)P = 20 µg/kg) by 1.85 and 1.95 times, respectively (Popova 2021). The B(a)P concentration at the maximum permissible level (21 µg/kg) was detected in the pl 3 sample point, located at the exit from the Khuzhir village towards the Kharantsy village in front of the forest (see Figs. 1, 5).

As shown in Fig. 5, at the end of the tourist season in October, when the intensity of vehicle traffic significantly decreases, a significant decrease in B(a)P concentrations was detected at some observation points. In the sampled points of pl 1– pl 3 in the area of the Khuzhir village, the B(a)P content was decreased and became equal to 1.7, 3.3, and 1.6 µg/kg, respectively. Similar dynamics can be



Note: The yellow color shows the areas where an increase in the Z_c values was detected

Fig. 3. The distribution of the computed values of the Saet index (Z_c) for all key soil-sampling sites within the public road

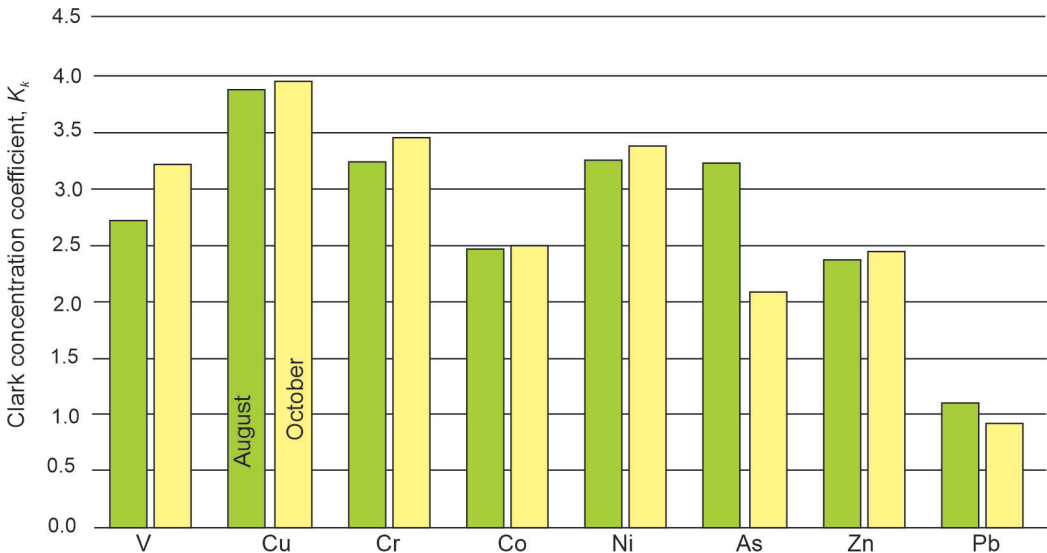


Fig. 4. The comparison of the K_k index values for the soil samples collected in August and October 2023

observed at other sampling points (see Fig. 1, 5): in the area of the Kharantsy village, near the Khuzhir airport, at point pl 5 there was a decrease from 9.5 to 1 $\mu\text{g/kg}$; in the hollow near the road (point pl 6) – from 5.9 to 1.9 $\mu\text{g/kg}$; at the observation platform (point pl 15) – from 5 to 1.3 $\mu\text{g/kg}$; in front of the Maly Khuzhir village, at point pl 16, – from 8.3 to 1.4 $\mu\text{g/kg}$; and at point pl 17 – from 10 to 1.2 $\mu\text{g/kg}$; as well as at the Yalga settlement, in the area of the pier, – from 7.7 to 1.5 $\mu\text{g/kg}$ (point pl 25), and from 6.5 to 0.5 $\mu\text{g/kg}$ (point pl 26).

Within such areas as the Buruger checkpoint, Cape Khoboy, and the Uzury village (Fig. 1), the B(a)P concentrations in the range of 0.3–0.8 $\mu\text{g/kg}$ were recorded during the peak tourist season in July, which is significantly lower than its MAC value of 20 $\mu\text{g/kg}$. Then, in October, a further decrease to values of 0.3–0.6 $\mu\text{g/kg}$ was noted in these areas (see Fig. 5). These areas are similar to the background site in the Tashkiney Valley (point pl 18) in terms of the B(a)P content. The obtained B(a)P values for the background site were 0.18 $\mu\text{g/kg}$ in July and 0.1 $\mu\text{g/kg}$ in October.

Note that sources of the elevated B(a)P concentrations in the studied roadside soils can be both natural and anthropogenic factors. This issue requires careful additional study, but, in this case, it is possible to assume that the release of B(a)P into the soil is associated with emissions from motor vehicles during the combustion of petroleum products in internal combustion engines (Kosheleva et al. 2023). In addition, the source of B(a)P can also be pyrogenic sources – any combustion products such as coal, peat, and wood (Gennadiev et al. 1996), which is typical for large villages. In the same way, B(a)P production occurs during the combustion of household waste or as a result of the release of polluted water into the soil (Labana et al. 2007).

The significant decrease in the B(a)P concentrations observed in some roadside soil samples from July to October may be due to the increased acidity ($\text{pH} < 7$) of some soil types on Olkhon Island, where B(a)P decomposes. Noted that the loss of concentrations of this highly toxic pollutant in one of its locations may be due to its migration through leaching from the upper soil layers due to seasonal precipitation, as well as a threefold decrease in vehicle traffic.

Thus, the identified seasonal dynamics of the content of elements such as As and Pb, as well as B(a)P, indicate active migration processes in the soil profile. The main factors responsible for the decrease in their concentrations

by autumn are likely: 1) leaching of mobile forms by atmospheric precipitation; 2) biogenic migration; 3) microbiological degradation in the case of B(a)P. The acidity of the island soils may be a catalyzing factor for some of these processes.

CONCLUSION

An ecological and geochemical assessment of Olkhon Island revealed that the impact of modern motor vehicles on the geochemical composition of soils is localized. Residual influences from the Soviet period of management remain in the steppe soils, creating a specific background of anthropogenic pressure. The main findings of the study are as follows:

1. The total pollution factor (Z_c) for Pb, Zn, Cu, Cr, Ni, Co, V, and As did not exceed the 8-unit mark. This indicates the absence of critical contamination during the observation period (August–October 2023). 71.5% of the studied soil samples were characterized as moderately hazardous, indicating the need for continued monitoring. A significant increase in the Z_c values by the end of the tourist season was revealed in the villages of Kharantsy, Peschanaya, and Uzury, the Buruger checkpoint, and the approaches to the ferry crossing. In other areas, a downward trend was observed, reflecting the uneven distribution of traffic flows during the autumn.

2. Analysis using the K_k method revealed multidirectional migration processes of the examined elements. The increase in the K_k values by an average of 0.06–0.51 for Cu, Ni, Cr, and V indicates their continued input from anthropogenic sources. Simultaneously, the removal of Pb and As from the ecosystem was recorded (a decrease in the K_k values for As by 1.15, and for Pb from 1.11 to 0.94), due to seasonal leaching and biogenic migration. Co and Zn demonstrate stable behavior, with minor fluctuations in the K_k values from 0.02 to 0.06.

3. A pronounced seasonal dynamic of the B(a)P levels in roadside soils was revealed. During the peak tourist season (July), in areas of heavy traffic (Khuzhir and Kharantsy), concentrations exceeding the MAC value by 1.85–1.95 times were recorded. By October, concentrations had decreased by 3–20 times, confirming the influence of motor vehicles as the main source of this pollutant.

To assess long-term trends, continued monitoring is necessary, increasing the number of observation points and taking into account the historical legacy (former

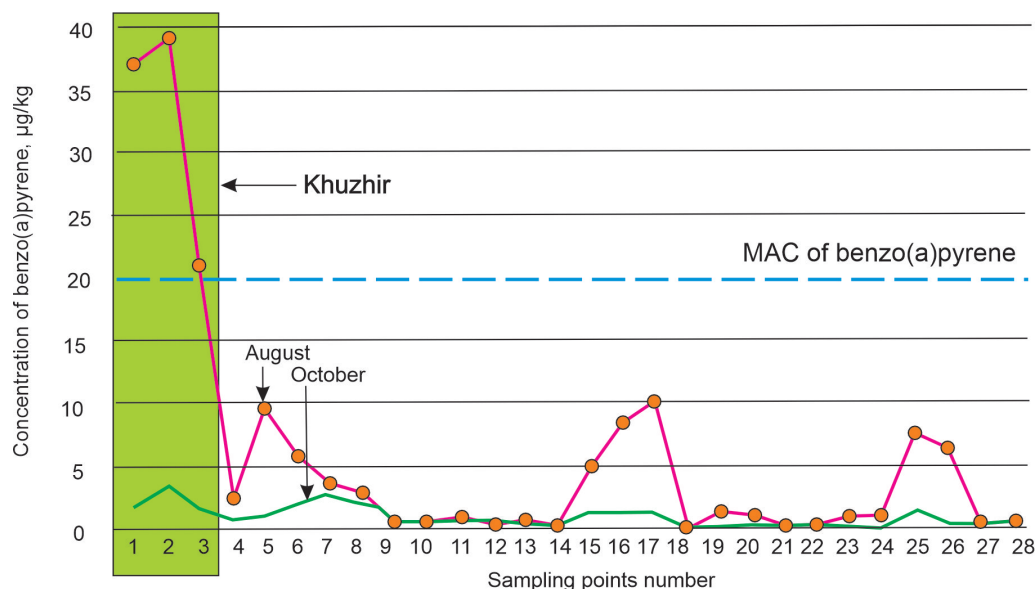


Fig. 5. The distribution of the B(a)P contents in roadside soil samples collected in July and October 2024

agricultural lands from the Soviet era). This study is relevant for revealing changes in the environment of the Pribaikalsky NP protected area as a part of the development of tourism and recreational activities. It is necessary to

continue monitoring the geochemical state of roadside soils during the tourist season and clarify the location of former agricultural lands in the island study area. ■

REFERENCES

- Abilov Zh.A., Anzorova M.A., Bityukova V.R., Makhrova A.G., Khojnikov A.V., and Yaskevich V.V. (2021). Planning structure as a road traffic pollution differentiation factor: A case study of Nur-Sultan. *Geography, Environment, Sustainability*, 14(3), 6-13, DOI: 10.24057/2071-9388-2021-061.
- Atucha A., Merwin I.A., Brown M.G., Gardiazabal F., Mena F., Adiazola C., and Lehmann J. (2013). Soil erosion, runoff and nutrient losses in an avocado (*Persea americana* Mill) hillside orchard under different groundcover management systems. *Plant and Soil*, 368(1), 393-406, DOI: 10.1007/s11104-012-1520-0.
- Baybarin V.A., Bozhko A.V. (2014). The influence of exhaust gases of MES engines on the ecology and their composition. *Bulletin of agricultural science of the Don*, 4(28), 81-86. (in Russian with English summary)
- Cherkashina T.Yu. and Pellinen V.A. (2022). Assessment of soil pollution level using environmental indices in Olkhon Island, Lake Baikal, Russia: Primary data. *International Journal of Environmental Analytical Chemistry*, 102(12), 2766-2777, DOI: 10.1080/03067319.2020.1759567.
- Cherkashina T.Yu., Pellinen V.A. (2021). Applicability of X-ray fluorescence spectrometry for assessing geochemical features and heavy metal contamination of soils: Primary data. *International Journal of Environmental Analytical Chemistry*, 101(14), 2272-2287, DOI:10.1080/03067319.2019.1700971.
- Cherkashina T.Yu., Svetlakov A.A., Pellinen V.A., and Cherkashin E.A. (2025). Relationships between heavy metal migration in soils and landslide dynamics under conditions of modern climate change: A case study of Lake Baikal, Olkhon Island. *Science of the Total Environment*, 975, 179285, DOI: 10.1016/j.scitotenv.2025.179285.
- Donskaya T.V., Gladkochub D.P., Mazukabzov A.M., Sklyarov E.V., Khubanov V.B., Demonterova E.I., and Motova Z.L. (2022). Metaterrigenous rocks of the Olkhon terrane of the Central Asian folded belt: U-Pb age of zircons, geochemical characteristics and models of sedimentary protolith formation. *Geodynamics & Tectonophysics*, 13(3), 1-30 (in Russian with English summary), DOI: 10.5800/GT-2022-13-3-0635.
- Dzhuvelikyan H.A., Shcheglov D.I., and Gorbunova N.S., eds. (2009). *Pollution of Soils with Heavy Metals. Methods of Soil Pollution Monitoring and Regulation*. Voronezh: State University Press. (in Russian)
- Galaziy G.I. (2012). *Baikal in questions and answers*. Irkutsk: OOO "Forward". (in Russian)
- Gennadiev A.N., Pikovsky Yu.I., Florovskaya V.N., Alekseeva T.A., Kozin I.S., Ogloblina A.I., Ramenskaya M.E., Teplitskaya T.A., and Shurubor E.I. (1996). *Geochemistry of polycyclic aromatic hydrocarbons in rocks and soils*. Moscow: University Publishing House. (in Russian)
- Grebenshchikova V.I., Lustenberg E.E., Kitaev N.A., and Lomonosov I.S. (2008). *Environmental Geochemistry of the Baikal Region (Baikal Geoeological Test Site)*. Novosibirsk: Geo Academic Publishing House. (in Russian)
- Kalikhman A.D., Bencharova N.V., and Kalikhman T.P. (2017). *Olkhon: Nature and People*. Irkutsk: Sochava Institute of Geography SB RAS.
- Kitaev N.A. and Grebenschikova V.I. (2014). *Rare and Ore Elements in the Environment of the Baikal Region (Bedrocks, Bottom Sediments, Soils)*. Irkutsk: Irkutsk State University Publishing House. (in Russian)
- Konoplev S.P., ed. (1959). *Map of Mineral Resources: N-48-XXX. Map of Mineral Resources of the USSR. Baikal Series. Scale 1:200000*. Moscow: Irkutsk Geological Administration. (in Russian)
- Kosheleva N.E., Nikiforova E.M., Timofeev I.V., and Zavgorodnyaya Yu.A. (2023). Polycyclic aromatic hydrocarbons in soils of Severobaikalsk. *Geography and natural resources*, 4, 77-89 (in Russian with English summary), DOI: 10.15372/GIPR20230408.
- Kostyukova M.S. (2022). Assessment of the current ecological state of soils on the western coast of Lake Baikal (based on the example of soils in the coastal part of the lake, delta and Goloustnaya River basin). *The Bulletin of Irkutsk State University. Series "Earth Sciences"*, 41, 77-93 (in Russian with English summary), DOI: 10.26516/2073-3402.2022.41.77.
- Kovalev A.V., ed. (2007). *M-MVI-202-07. Methodology for measuring the mass fraction of polynuclear aromatic hydrocarbons (PAH) in samples of soil, bottom sediments and solid waste using chromatograph mass spectrometry with isotope dilution*. FR.1.31.2011.09357. St. Petersburg: Monitoring Press.
- Labana S., Kapur M., Malik D., Prakash D., and Jain R. (2007). Diversity, biodegradation and bioremediation of polycyclic aromatic hydrocarbons. In: Singh S.N., Tripathi R.D., eds., *Environmental Bioremediation Technologies*. New York: Springer Berlin Heidelberg, P. 409-443, DOI: 10.1007/978-3-540-34793-4_18.
- Pellinen V.A., Cherkashina T.Yu., Pashkova G.V., Gustaytis M.A., Zhurkova I.S., Shtel'makh S.I., and Panteeva S.V. (2016). Assessment of Soil Cover Ecological State of Olkhon Island (from the Obtained Experimental Data). *The Bulletin of Irkutsk State University. Series "Earth Sciences"*, 16, 79-90 (in Russian with English summary).
- Pellinen V.A., Shtel'makh S.I., and Cherkashina T.Yu. (2019). Chemical composition of soils of the piedmont steps of Olkhon Island. *The Bulletin of Irkutsk State University. Series "Earth Sciences"*, 27, 90-110 (in Russian with English summary), DOI: 10.26516/2073-3402.2019.27.90.
- Pellinen V.A., Cherkashina T.Yu., and Gustaytis M.A. (2021). Assessment of metal pollution and subsequent ecological risk in the coastal zone of the Olkhon Island, Lake Baikal, Russia, *Science of the Total Environment*, 786, 147441, DOI: 10.1016/j.scitotenv.2021.147441.
- Popova A.Y. (2021). *Sanitary rules and regulations 1.2.3685-21. Hygienic standards and requirements for ensuring the safety and (or) harmlessness of environmental factors for humans*. St. Petersburg: Lema Press. (in Russian)
- Ryabinina O.V., Ponomarenko E.A., and Lopatovskaya O.G. (2024). Analysis of the relationship of the physical and chemical properties of the soil with its anti-erosion stability and recreational capabilities of the west coast of Olkhon Island, *Scientific and practical journal "Vestnik IrGSHA"*, 3(122), 70-82 (in Russian with English summary), DOI: 10.51215/1999-3765-2024-122-70-82.
- Saet Yu.E., Revich B.A., Yanin E.P., Smirnova R.S., Basharkevich I.L., Onishchenko T.L., Pavlova L.N., Trefilova N.Ya., Achkasov A.I., and Sargsyan S.Sh. (1990). *Geochemistry of the environment*. Moscow: Nedra. (in Russian)
- Saukov A. A. (1975). *Geochemistry*. Moscow: Nedra. (in Russian)
- Solovyova E.N., Podlipsky I.I., and Stronskaya A.M. (2024). The state and limiting factors of the use of the territory of Olkhon Island (Baikal National Park). *The Bulletin of the Baikal State University*, 34(1), 122-133 (In Russian), DOI 10.17150/2500- 2759.2024.34(1).
- Tsibart A.S. and Gennadiev A.N. (2013). Polycyclic aromatic hydrocarbons in soils: Sources, behavior, indicative value (review). *Eurasian Soil Science*, 46(7), 788-802 (in Russian), DOI: 10.1134/S1064229313070125.

Ubugunov L.L., Ubugunova V.I., Belozertseva I.A., Gyninova A.B., Sorokovoi A.A., and Ubugunov V.L. (2018). Soils of the Lake Baikal drainage basin: Results of research for 1980–2017. *Geography and Natural Resources*, 4, 76-87 (in Russian with English summary), DOI: 10.21782/GIPR0206-1619-2018-4(76-87).

Vinogradov A.P. (1957). *Geochemistry of rare and trace chemical elements in soils*. Moscow: Publishing house of the USSR Academy of Sciences.

Vodyanitsky Yu.N. (2008). *Heavy metals and metalloids in soils*. Moscow: State Scientific Institution V.V. Dokuchaev Soil Science Institute, RAAS. (in Russian)

Vodyanitsky Yu.N. (2011). On hazardous heavy metals/metalloids in soils. *Bulletin of the V.V. Dokuchaev Soil Science Institute*, 68, 56-82 (in Russian), DOI: 10.19047/0136-1694-2011-68-56-82.

Wedepohl K.H. (1995). The composition of the continental crust. *Geochimica Cosmochimica Acta*, 59(7), 1217-1232.

Yousefi S., Moradi H., Boll L., and Schonbrodt-Stitt S. (2016). Effects of road construction on soil degradation and nutrient transport in Caspian Hyrcanian mixed forests. *Geoderma*. 284, 103-112, DOI:10.1016/j.geoderma.2016.09.002.

Yurkova I.V. and Filippova L.A. (2013). The influence of motor transport on the roadside territories of the Baikal National Park (using the example of the Western Volga region). *The Bulletin of Irkutsk State Technical University. Series "Earth Sciences"*, 9(80), 118-123 (in Russian with English summary).