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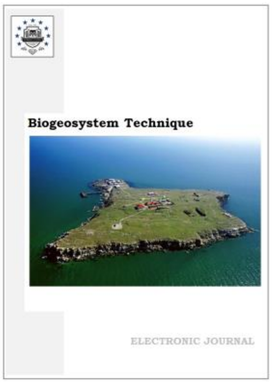

Assessment of Pollution of the Oilfield Territories in Mongolia

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Abstract

For balanced approach to Sustainable Development Goals, the physical and chemical degradation of soils in result of oil pollution were studied. The data on the particle-size distribution and the content of chemical components in the soils of the Tamtsagbulag and Zuunbayan oil-producing areas are presented. Due to arid and could climate and geographical location of inland and mid-latitude highlands the studied soils are characterized by similar physical and chemical properties: high content of physical sand (particle size > 0.01 mm) up to 86-91 %, alkaline reaction pH up to 8.7-8.8, density of the solid phase 2.63-2.64 g/cm^3. However, the total carbon content is much higher in Tamtsagbulag soils (kastanozem soils of dry steppe zone) than in Zuunbayan soils (semi-desert brown soils) – 1.07 and 0.24 % respectively. The content of petroleum hydrocarbons (HC) in the Zuunbayan soils varies from 9 to 60 mg/kg, in the Tamtsagbulag soils – from 7 to 670 mg/kg with a maximum in the vicinity of the operating wells. According to the level of hydrocarbon pollution, Zuunbayan soils can be attributed to uncontaminated ("background" concentration of HC, less than 100 mg/kg), Tamtsagbulag soils – from "background" concentration of HC up to "moderate level" of pollution (locally, near the well). Despite the locality and "moderate level" of oil pollution of Tamtsagbulag soils, a study conducted using remote sensing methods showed that pollution has a certain effect on vegetation cover. The maximum vegetation index value is some but reliably lower in an oilfield (within a radius of 4 km) than adjacent territory.

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For sustainable solutions planning of the oil production, transportation, and pollution prevention the transcendental Biogeosystem Technique methodology will be helpful for Land Degradation Neutrality implementation.

Keywords: oil production, soils, hydrocarbons, pollution, Mongolia.

1. Introduction

To date, daily oil production in Mongolia reaches 23 Kbbl, although intensive geological investigation began only in the 1940s. By 1948, the first Zuunbayan oilfield was explored and put into operation. In the same year, the first oil exploration in the Tamtsag Basin began. Since 1960 for 30 years the research has stopped and since 1990 new stage of development in the given area has begun. Further geological exploration work has shown that the most prospective areas for oil exploration are the Mesozoic sedimentary basins (Figure 1A). After the resumption of upstream petroleum activities in the early 1990s, oil production steadily increased. Circa 65 Mbbl of oil have cumulatively been produced in Mongolia between 1996 and 2019. As of 2020, there are a total of 33 petroleum blocks (Figure 1B). Three of these blocks have advanced to production, while exploration is being conducted on 17 blocks under 18 PSCs (Production Sharing Contracts). Today two deposits of the East Mogolia (Tamtsagbulag and Zuunbayan) are intensively explored. More than 90 % of the country's annual production has been solely from Blocks XIX and XXI in Tamtsag basin in eastern Mongolia in recent years. Mongolia in difficult economic conditions supports the foreign investment in geological investigation of oil and conclusion of a bilateral sharing of production. There are two companies PetroChina Daqing Tamsag" LLC and "Dongsheng petroleum Mongolia" LLC currently operating in these oilfields. PetroChina's subsidiary – "PetroChina Daqing Tamsag" LLC is one of them and leading in oil production and export. In 2019, about 6,9 Mbbl of petroleum was sold and 6,5 Mbbl were exported (Oil in Mongolia; Mongolia..., 2020).

Physical and chemical degradation of soils, biological degradation of soil organic matter in result of oil pollution in oil-producing regions are the worldwide environment and high cost problems (Villacís et al., 2016). In Mongolia, as in most oil-producing regions of the world, the decline in reserves and production volumes of "light" oils has recently caused increased interest in the resources of hard-to-recover oils and the production of heavy and high-viscosity oils. Such oils have a high content of paraffins and resins (Shirchin et al., 2003; Golovko et al., 2004; Khongorzul et al., 2007; Sugimoto et al., 2012; Serebriakov, Kondratiev, 2012; Myagmargerel et al., 2021), which leads not only to technological complications during oil production, transportation and processing, but also to serious environmental problems. Contamination of soils in oil production areas with "heavy" oils, the destruction of which in situ proceeds extremely slowly, causes serious violations of their functioning and self-purification.

According to the zoning map of Mongolian soils (Figure 2), the main acting and potential oil production facilities are concentrated in the dry steppe zone with kastanozem soils and brown semi-desert soils zone. The soils are very different from similar soils of the same latitude due to its mountainous, geological structure, and climatic characteristics. Mongolia has an arid and cold climate due to its geographical location of inland and mid-latitude highlands. Soils of Mongolia are characterized by severe frost in the upper part of winter with deep freezing up to 3-4.5 m, a long period with seasonal permafrost (6-9 months a year). The coincidence of warm months with rainiest seasons of the year promotes biological activity (Dorjgotov, 2009; Khadbaatar, 2021).

Dry steppe zone with kastanozem soils is widely distributed in the eastern part of Mongolia and extends westwards through the Khangai mountain range to the Great Lakes depression. Mongolian kastanozems are characterized by carbonate accumulation (no gypsum), which is associated with extreme climates and precipitation distribution. Annual precipitation is about 200-250 mm and growing season occurs for 150-170 days. The morphological features of these soils are brownish and dry, with a lot of gravel, unclear granular structure. The predominant textures are loam, light loam, and sand. Some layers of soils are rich in gravels. The thickness of the humus layer varies from 20 up to 50 cm (usually 20-30 cm), and the humus content – from 1.0 up to 4.5 %. The desert steppe (Gobi) brown soil zone includes the Great Lakes depression, the Lakes Valley, the Gobi-Altai Mountains, and the eastern part of the Gobi. Due to low rainfall (100-125 mm per yr and less), high winds, and dry heats in this area, soil formation takes place in dry conditions. The general characteristics of the soil are well-defined layers, loamy, low humus, effervescence in hydrochloric acid from the surface or topsoil, and not solonchak, lack of moisture, no gypsum, covered with gravel. The Gobi brown soil humus content reaches up to 0.3-0.8 % and the lower layer has a more humus content. This is due to the high temperatures of the soil surface, the mineralization of humus, and the spread of plant roots to about 10–30 cm (Dorjgotov, 2009; Doljin, Yembuu, 2021; Khadbaatar, 2021).

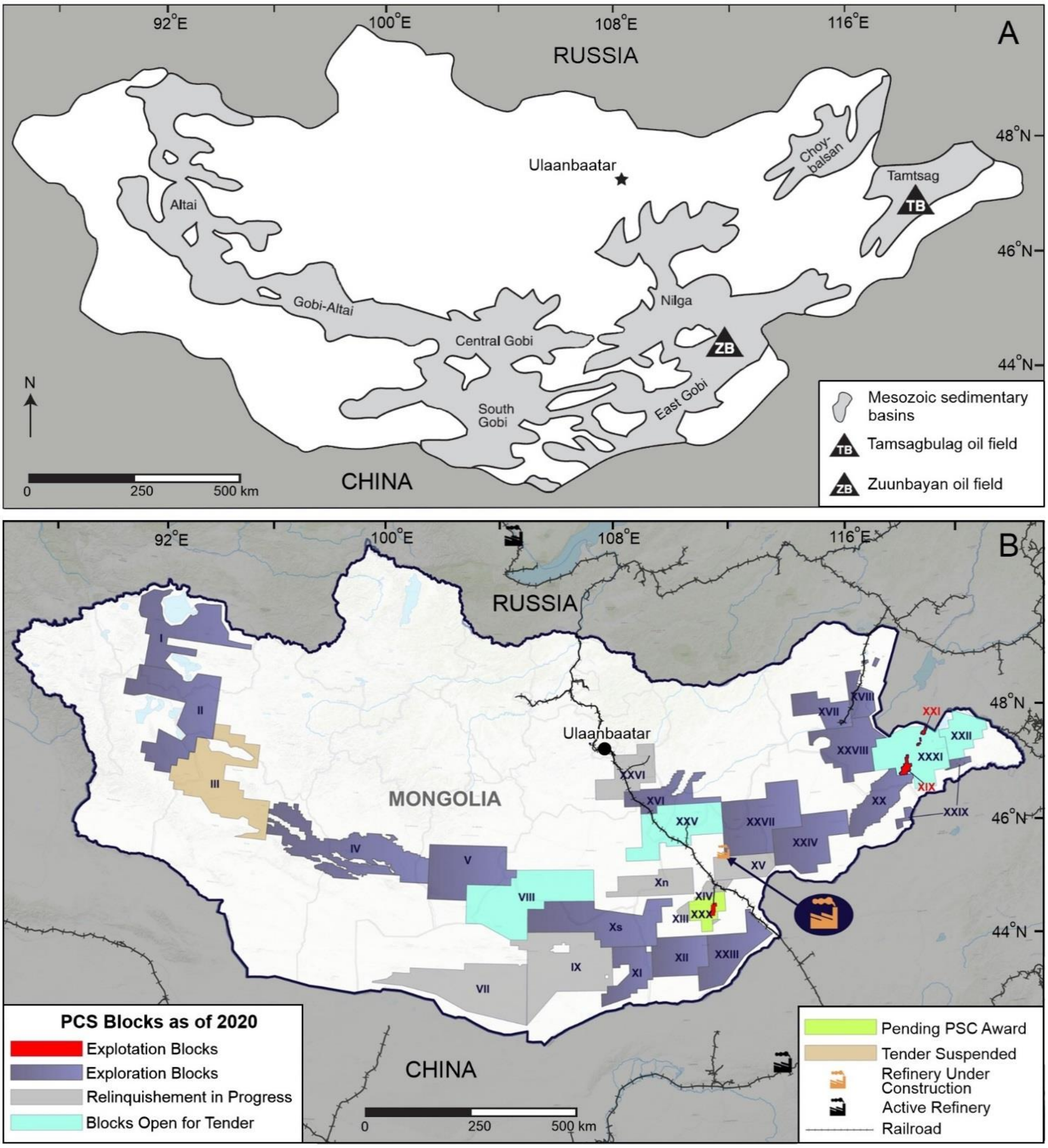

Fig. 1. A. Regional map showing general outlines of Mesozoic sedimentary basins of Mongolia (by Johnson et al., 2003; Penttila, 1994; Steinshouer et al., 1999). **B.** Oilfield blocks in Mongolia (Oil in Mongolia)

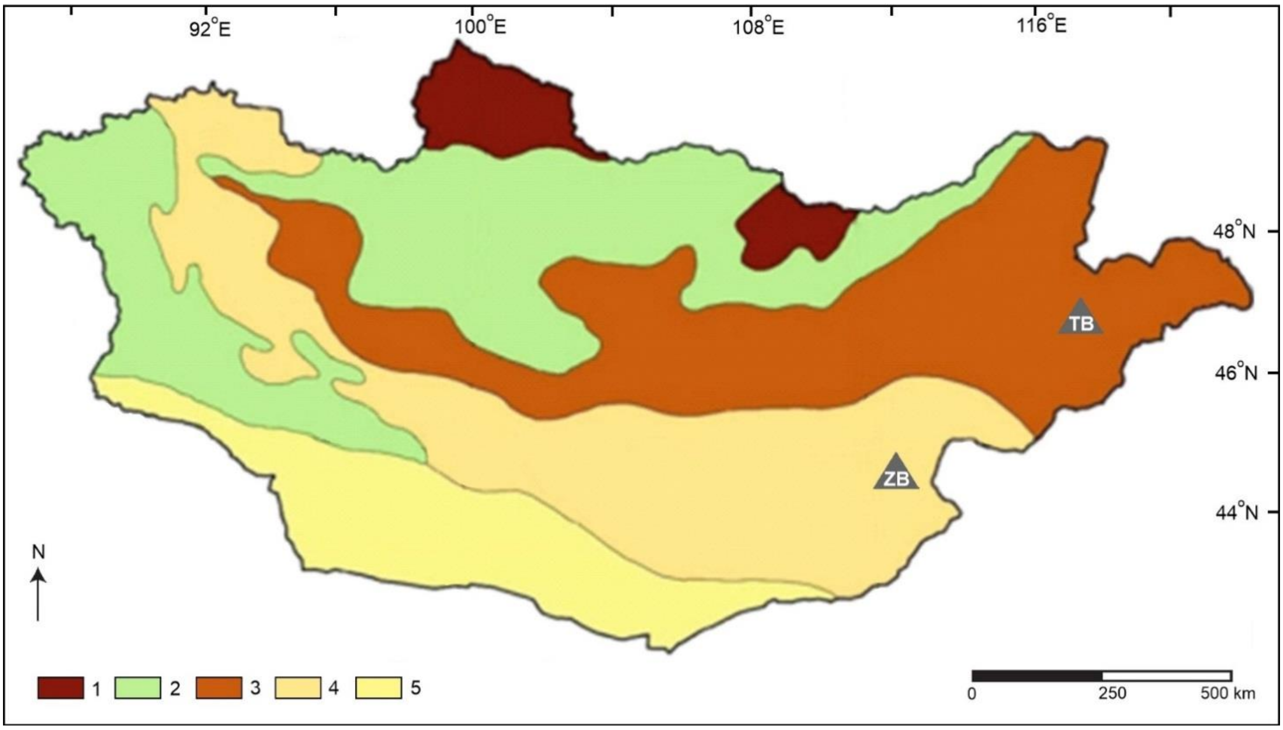

Fig. 2. Soil belt and zones: 1 – mountain taiga belt with cryomorphic-taiga and derno taiga soils, 2 – mountain forest steppe belt with chernozem, dark kastanozem, forest dark colored, and derno taiga soils, 3 – dry steppe zone with kastanozem soils, 4 – semi-desert brown soils zone, 5 – gray-brown desert soils zone (Dorjgotov, 2009; Khadbaatar, 2021).

The aim of this work is to assess the state of the soils and soil cover in the areas of the Tamtsagbulag and Zuunbayan oilfields, their lithological and mineral composition. In this paper, we focus on the Sustainable Development Goals (SDGs), and land restoration (Keesstra et al., 2016, 2018). Aspiration to achieve the SDGs in 2015 adopted by the United Nations is of high importance to avoid further land degradation and to achieve the lofty goals of Land Degradation Neutrality by 2030 is a base of the current and strategic world development framework agendas. The first stage of solving environmental problems in case of soil contamination with heavy oils is the choice of reliable and objective criteria for contamination of soil cover (Gantumur et al., 2021).

2. Objects and methods

Study area and soils

The study was focused on the soils of Tamtsagbulag and Zuunbayan oil fields. They are located in the Matad area of Dornod province (dry steppe zone with kastanozem soils) and the Zuunbayan area Dornogovi province of Mongolia (semi-desert brown soils zone) respectively. Tamtsagbulag soil samples were taken in October 2019 near the well (47°40'49" N and 117°02'59" E) along the perimeter at a distance of 2, 5 and 10 m (in total 12 samples). Zuunbayan soil samples were taken in December 2018 near one (44°27'07" N and 110°05'17" E) of the wells along the perimeter at a distance of 2, 5 and 30 m from the well (in total 5 samples). As control we used "unpolluted" sample sites (10 and 30 m from the wells), because the main soil contamination occurs when oil is taken.

Methods of study

The study was based on granulometric and gross analyses, which were supplemented by electron microscopic studies (SEM analysis) of soils and analysis of soil cover vegetation indices obtained by remote sensing methods. Soil sampling and chemical analysis was carried out in accordance with IS 17.4.3.01-83. Soil samples were taken to the depth of the soil moistening (0-20 cm). The samples (0.5 kg) were selected by the envelope method for physical and chemical analyzes. Than they, dried to the air-dry state, were ground in a porcelain mortar with a pestle with a rubber tip and passed through a 1mm mesh sieve. The granulometric composition of the samples as a whole was determined by the Kaczynski method (Vadjunina, Korchagina, 1973). The gross composition was determined by the X-ray fluorescence method (Pioneer S4, Bruker AXS, Germany) using the silicate analysis technique. The SEM analysis was carried out on a scanning electron microscope VEGA 3 LMH (TESCAN, Czech Republic). For the survey, the samples (preliminary grinded and sieved through a 2-mm sieve) were prepared by the method of pouring, Pt-spraying, magnification – up to 20,000. A backscattered electron detector (BSE detector) was used for the analysis of phases with a high atomic number. When images are acquired using a BSE detector, phases with a high average atomic number are reflected in contrast more vividly than those with a lower atomic number. The X-max 80 energy dispersive spectrometer (Oxford Instruments, Great Britain) was used to analyze the elemental composition of the most representative regions. The capture area of the microanalysis is about 1 μm in diameter. If the analyzed object has smaller, the result of the analysis is distorted due to the influence of the surrounding matrix or the carbon table of the device. The XRF and SEM analyses were carried out in the Analytical Centre at the Institute for Tectonics and Geophysics, Khabarovsk, Far East Branch of the Russian Academy of Sciences. The specific surface was determined using low-temperature adsorption of nitrogen with specific surface analyzer of Sorptometr M series (Shein et al, 2017). Organic carbon was determined by coulometric titration in oxygen flow with AN 7529 express carbon analyzer (Gomel, Belarus) (Milanovskii et al., 2011). Hydrogen test of soil water extract (1:5) was carried out using a combined meter (Seven Multi S-47k, Mettler-Toledo, Switzerland). Determination of the mass fraction of hydrocarbons (HC) in the soils was performed according to the method (END F 16.1:2.2.22–98). The hydrocarbon fraction was isolated by extraction with carbon tetrachloride, purified from accompanying polar compounds on a column with aluminum oxide of the 2nd degree of Brockman activity. The measurements were carried out on the concentration meter (KN-2M, Sibekopribor, Russia).

The remote sensing methods were used to assess oil pollution of the soil cover of the oilfields – we analyzed the change in vegetation cover using vegetation indices NDVI (Normalized Difference Vegetation Index) and SAVI (Soil Adjusted Vegetation Index). SAVI has an additional correction factor in its formula. This coefficient varies from 0 to 1, and minimizes the effect of soil brightness. SAVI is often used in desert areas where vegetation coverage is negligible. The NDVI and SAVI were determined as follow: $NDVI = (NIR-RED)/(NIR+RED)$ and $SAVI=(NIR-RED)/(NIR+RED+L)*(1+L)$, where NIR – near-infrared reflectance, RED – red band reflectance and L – soil adjusted coefficient. These indices were calculated for test sites (4 km^2) during the period of maximum vegetation growth from 2015 to 2019. For this purpose, Landsat-8 and MODIS Terra satellite images at 30 and 250 m resolution, respectively, were used (Eckert et al., 2015; Sun et al., 2019; Gantumur et al., 2021).

3. Results and discussion

Before characterizing the oil pollution of the studied soils, we introduced data on the gross composition and the particle size distribution of soils, which are their fundamental features and, coupled with the content of humus and carbonates, largely determine not only the physical and chemical properties, but also the ability of soils to absorb and retain oil. According to the obtained data (Table 1), with a close gross composition of oilfield soils Zuunbayan soils compared to Tamtsagbulag soils are somewhat enriched with not only SiO_2, but also Al_2O_3, Na_2O and K_2O. This is due to the presence in their composition of a weighty amount of primary minerals, namely quartz and feldspar (SEM data). Zuunbayan soils are also distinguished by an increased content of physical sand (particle size greater than 0.01 mm) of 90.5 and 85.9 %, respectively. Here and further, we give the average values, since the high content of clastogenic grains of primary minerals (including quartz) in Zuunbayan and Tamtsagbulag soils, in addition to natural spatial variation of soil properties, leads to a the significant difference of the min-max values of the results.

According to the gross composition of soils and the content of physical sand in them, it was possible to expect an increased content of coarser sand fractions in Zuunbayan soils. However, the content of coarse and medium sand (particle size 0.25-1 mm) in Tamtsagbulag soils is significantly higher than in Zuunbayan soils 38.5 and 32.9 %, respectively, and the content of fractions of fine (particle size 0.05-0.25 mm) and medium and coarse sand is close – 39.9 and 38.5 %, respectively. Whereas the fraction of fine sand prevails in Zuunbayan soils (45.3 %).

Table 1. Physical and chemical properties and hydrocarbon content in soils of Tamtsagbulag and Zuunbayan oilfieds

Parameter	Tamtsagbulag area (n=12)			Zuunbayan area (n=5)		
	average	min	max	average	min	max
Gross composition, %						
SiO_2	**72.72**	68.17	77.34	**79.92**	75.93	82.17
TiO_2	**0.23**	0.16	0.28	**0.37**	0.32	0.40
Al_2O_3	**7.05**	6.07	7.92	**11.58**	10.90	11.90
Fe_2O_3	**1.79**	1.41	2.13	**2.05**	1.83	2.43
MnO	**0.04**	0.03	0.04	**0.07**	0.06	0.08
CaO	**1.74**	1.05	2.65	**1.02**	0.72	1.75
MgO	**0.64**	0.55	0.76	**0.65**	0.55	0.84
Na_2O	**2.47**	2.14	2.77	**4.00**	3.64	4.27
K_2O	**2.68**	2.54	2.81	**3.80**	3.60	3.93
Particle size (in mm) distribution, %						
>0.01	**85.88**	82.55	90.75	**90.78**	85.59	95.76
0.05–0.25	**39.90**	24.21	48.15	**45.33**	36.04	57.36
0.25–1	**38.47**	28.54	47.93	**32.87**	23.59	42.99
Physical and chemical properties of soils						
pH	**8.4**	7.6	8.8	**8.3**	8.2	8.7
W_{hygr}, %	**0.87**	0.67	1.26	**0.83**	0.61	1.23
ρ, g/cm³	**2.64**	2.49	2.82	**2.63**	2.53	2.75
C_{total}*, %	**0.73/1.07**	0.20/0.88	0.53/1.32	**0.20/0.24**	0.07/0.17	0.13/0.52
C_{org}, %	**0.53/0.76**	0.24/0.38	0.82/1.17	**0.13/0.13**	0.10/0.05	0.15/0.19
$C_{carb.}$, %	**0.20/0.31**	0/0.09	0.36/0.54	**0.07/0.11**	0/0.03	0.23/0.33
S, m²/g	**4.2*****	0.8	5.3	**5.4**	3.3	9.6
HC, mg/kg	**30****	10	670	**12****	9	60

Note. S – nitrogen specific surface area; ρ – density of the solid phase of soils; * – numerator and denominator data for soil fractions smaller than 1 and 0.25 mm, respectively; ** – averaging of data with the exception of abnormally high (300-600 and 50-60 mg/kg for soils of Tamtsagbulag and Zuunbayan oilfields, respectively); *** – averaging of data with the exception of abnormally low values (0.8–1.2 m²/g for soils of Tamtsagbulag oilfield).

The predominance of fine sand in the granulometric composition of Zuunbayan soils explains their higher specific surface area (it largely determines the ability of soils to adsorption) compared to Tamtsagbulag soils – 5.4 and 4.2 m²/g. For Tamtsagbulag soils, the average values are given without taking into account the abnormally low values of oil-contaminated samples, we will return to these data below. The remaining physical and chemical properties of soils (solid phase density, hygroscopic humidity, pH), with the exception of carbon content, are close. Compared with the Zuunbayan soils (semi-desert brown soils), the Tamtsagbulag soils (kastanozem of dry steppe zone) differ in a much higher content of both total carbon and carbon of organic matter. This is especially clear for soil fraction with a particle size of less than 0.25 mm: the values differ by more than 5 times. The latter allows assuming that the absorption of oil should take place with the participation of this particular fraction.

The content of hydrocarbons (HC) in Zuunbayan soils varied from 9 to 60 mg/kg with the maximum content in samples taken at a distance of 2 m from the well (53-60 mg/kg). With distance from the well soil pollution by oil drops sharply and at a distance of 5 and 30 m are 15 and 9 mg/kg respectively. The range of HC content variation in Tamtsagbulag soils is significantly higher. If the minimum values are almost the same (7-9 mg/kg), then the maximum value is an order of magnitude higher and is 670 mg/kg. This concentration and the concentration of 320 mg/kg were detected only in the south direction from the well at a distance of 2 and 5 m, respectively. According to SEM analysis, microclots of oil and microaggregates with its participation up to 150-200 μm in size are diagnosed in these samples (Figure 3). The composition of microaggregates, in addition to oil microclots, includes clay minerals and calcium carbonate. It should be noted that in the Zuunbayan soils, oil microclots and microaggregates occur singly; their size is significantly smaller, up to 30-50 μm. In other directions (including the southern one at a distance of 10 m from the well), the HC content, taking into account the accuracy of the HC determination method, does not exceed 100 mg/kg and averages 30 mg/kg.

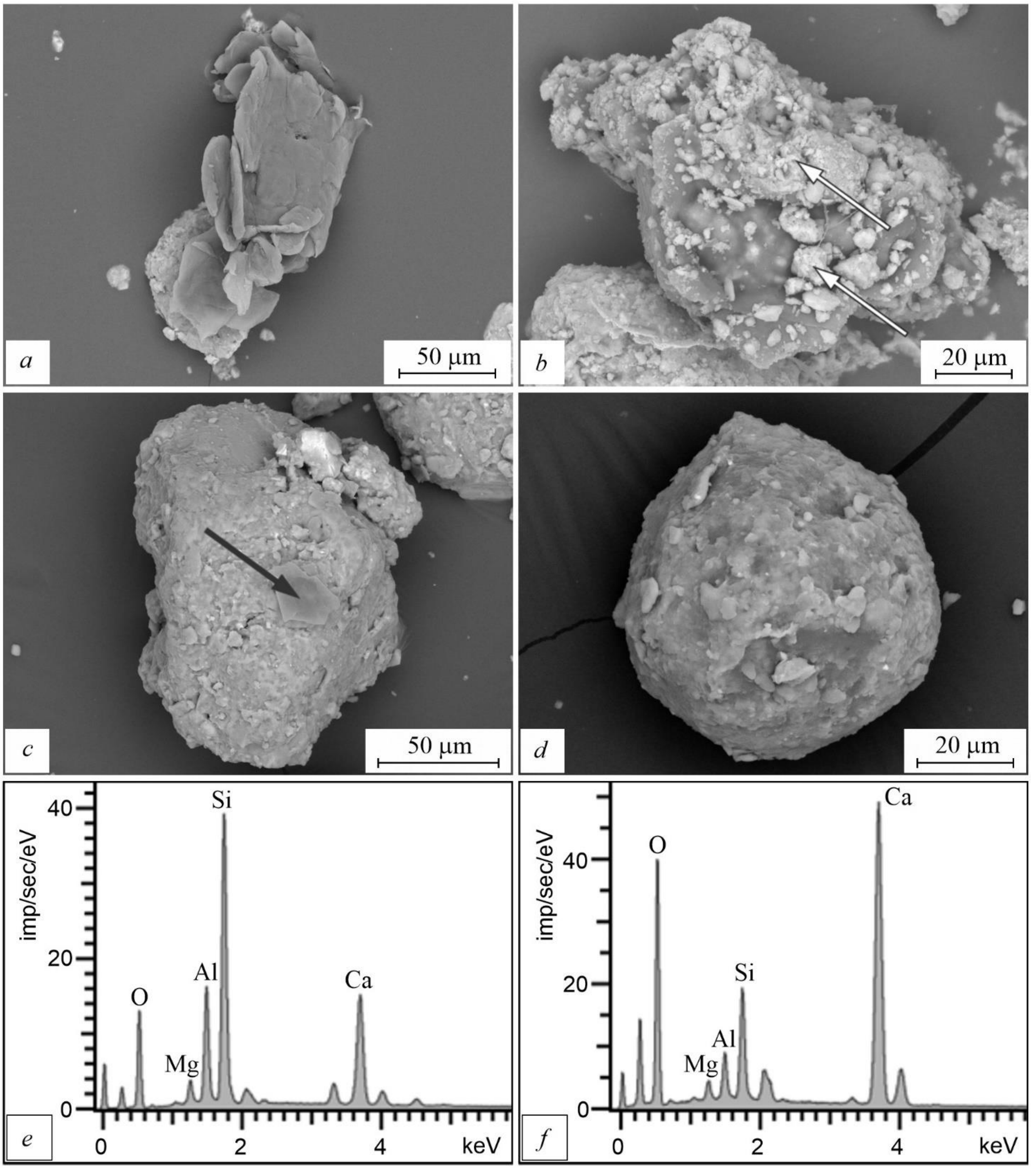

Fig. 3. SEM images of oil microclots (a, c – black arrow) and microaggregates (b, d) from soils of Tamtsagbulag (a, b) and Zuunbayan (c, d) oilfields and EDS-spectrum of points indicated by the white arrows (e and f). For further explanations see text

Currently, in Mongolia there is no regulatory document that defines the maximum allowable concentration (MAC) of oil. It should be noted that the problem of the hydrocarbon MAC for the soils is practically not solved in the world. Many approaches to the assessment of soil pollution with oil have been proposed and the classification boundaries do not always coincide. Thus, under the classification of V.I. Uvarova (1988), according to the content of petroleum hydrocarbons (mg/kg of dry soil), soils can be divided into: clean – 0-5.5, slightly polluted – 5.5-25.5, moderately polluted – 25.6-55.5, polluted – 55.6-205.5, dirty – 205.6-500, very dirty > 500. According to a latter classification (Pikovsky, 1993), the content of oil products in the soil up to 100 mg/kg corresponds to "background" concentration, 100-500 – "increased background", 500-1000 – "moderate level" of pollution, 1000-2000 – "moderately hazardous", 2000-5000 – "strong" and more than 5000 mg/kg – "dangerous" pollution. If to adhere to this classification, Zuunbayan soils characterized by "background" concentration of HC, Tamtsagbulag soils – from "background" concentration of HC up to "moderate level" of pollution (locally, near the well).

In the work of E.A. Rogozina (2006) it's proposed to assess the degree of pollution of soils by hydrocarbons by the excess of the content of HC over the background value in a specific area and in a specific territory. Therefore, the remote sensing methods were used to assess oil pollution of the soil cover of the oilfields – we analyzed the change in vegetation cover using vegetation indices NDVI and SAVI. These indices allow us to assess the impact of oil pollution on the soil indirectly, namely by the state of vegetation.

Usually, the influence of oil polluting effect on vegetation is quite strong and contributes either to the complete destruction of the cover, or to the development of serious developmental anomalies. Unfortunately, due to the extremely sparse vegetation in the Zuunbayan oilfield area, we were unable to calculate vegetation indices. But for Tamtsagbulag oilfield area, certain results were obtained. Due to the peculiarity of the studied territories, it was necessary to conduct additional research on changes in vegetation cover in the vicinity of the Tamtsagbulag oilfield. For a preliminary assessment and analysis of seasonal changes in the vegetation index, we used the values of weekly NDVI composites obtained using the VEGA-SCIENCE system (MODIS spectroradiometer, 250 m).

The general scheme of processing optical images obtained from the Landsat 8 satellite in the period from May to September 2019 is shown in Figure 4(A). Each spatial-temporal image was a set of 240,000 pixels with a size of 30x30 m. NDVI and SAVI values were calculated for each pixel. Preliminary filtering of outliers and verification of sampling uniformity was carried out. Thus, pixels that fell on roads and various technical objects were removed. Repeated filtration was also carried out on each site measuring 600×900 m, 600 such sites were considered. The total area of the territory was 324 km², with sides equal to 18 km. At the last stage, the average values of vegetation indices for the sites were smoothed by a linear method.

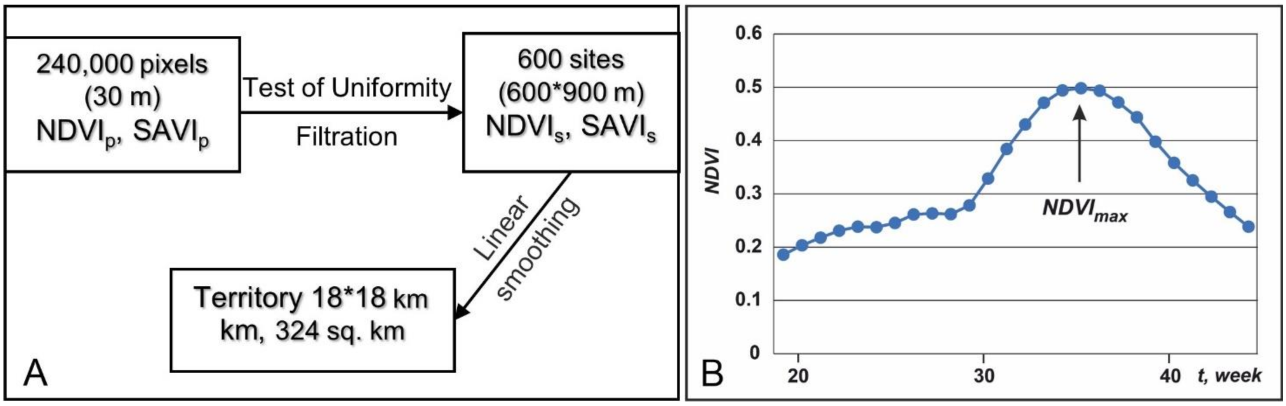

Fig. 4. Scheme of processing optical images obtained from the Landsat 8 satellite (A). Seasonal dynamics of NDVI (MODIS) values in the vicinity of Tamtsagbulag oilfield in 2015–2019 (B).

Further, according to the data of 2015–2019, a time period was established when the vegetation activity and, accordingly, the values of the vegetation indices are maximum (Figure 4B). This is due to the fact that the maximum is the most stable indicator, and it is advisable to use the values of the extremum for comparative characteristics of vegetation of different sites. It was found that the maximum NDVI occurs in the 35th calendar week, which corresponds to the 20th of August.

To assess changes in vegetation indices depending on the distance from the wells of the Tamtsagbulag oilfield, five sites 2×2 km were selected as test sites: central site where the main operating wells are located (the coordinates of the site center coincide with the coordinates of the studied well – 47°40'49" N and 117°02'59" E) and sites oriented to the cardinal directions and equidistant from the conditional center by 4 km (objects I) and 8 km (objects II). NDVI and SAVI 2019 were calculated for all test sites. The values of vegetation indices in both cases increase reliably with the distance of the test sites from the center of the oilfield. The average range was from 0.53 to 0.61 for NDVI and from 0.36 to 0.41 for SAVI (35th calendar week). It was established that the spatial dynamics of NDVI and SAVI had the same orientation in 2019. At the same time, the calculation of the NDVI index is characterized by greater simplicity. Based on the sum of these circumstances, the spatial-temporal dynamics of the maximum vegetation activity for 2015–2019 was estimated by NDVI.

The average $NDVI_{max}$ values in 2015 were in the range circa 0.5-0.55, in 2016 – 0.30-0.34, in 2017 – 0.34-0.40, in 2018 – 0.46-0.58, and in 2019 – 0.53-0.61. There is a clear trend of increasing NDVI values with distance from the center of the oilfield. Using two-factor analysis of variance, it was found that the $NDVI_{max}$ values significantly differ depending on the year and the distance from the oilfield, the significance level $p<0.01$.

A posteriori analysis using the Tukey criterion showed that the values of the maximum vegetation index reliably increase at a distance of 4 km from the source of oil pollution. For objects I, the significance level was $p < 0.01$, and $p < 0.05$ for objects II. At the same time, there was no reliable difference in the values of indicators for objects I and II.

Thus, despite the locality and "moderate level" of oil pollution of Tamtsagbulag oilfield soils, the study conducted using remote sensing methods showed that pollution has a certain effect on vegetation cover, in particular, the value of the vegetation index decreases at a distance of 4 km from the oilfield. The proposed method using Earth remote sensing data can be used for areas with similar vegetation cover. We hope that the completed works set the vector for further research. After all, in fact, a sufficient number of scientific papers have been published to study the state and contamination of soils in oil production areas. However, there is no single approach that allows using the assessment of the totality of influencing factors to make recommendations on soil remediation. To implement the approach, it is necessary to solve a number of interdisciplinary tasks that are aimed, firstly, at studying the physical and chemical, microbiological and landscape characteristics of soils, and secondly, at studying the dynamics of changes in these indicators based on the information systems and using mathematical methods.

4. Conclusion

The identified physical and chemical features of the studied soils together with specific climatic conditions and peculiarities of the oil composition of the Tamtsagbulag and Zuunbayan oilfields (prevalence of heavy paraffin fractions) characterize their low potential for self-purification from pollution by hydrocarbons. If according to the level of hydrocarbon pollution, Zuunbayan soils can be classified as uncontaminated (HC concentration less than 100 mg/kg is "background"), then Tamtsagbulag soils are characterized by a "moderate level" of pollution (locally, near wells, the content of hydrocarbons reaches 670 mg/kg). Study conducted using remote sensing methods showed some negative impact of oil pollution on vegetation cover Tamtsagbulag oilfield area within a radius of 4 km; in particular, vegetation index values are statistically reliably reduced. Sustainable solutions for planning the oil production, transportation, and pollution prevention will help to implement Land Degradation Neutrality and refine the currently not effective strategic world development principles.

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