SOIL SCIENCE ANNUAL
2025, 76(3), 208822

https://doi.org/10.37501/soilsa/208822

Spatio-temporal analysis of the soil threats in the Kostanay region, northern Kazakhstan, using remote sensing techniques

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Received: 2024-02-28
Accepted: 2025-07-31
Published online: 2025-07-31
Associated editor: Piotr Hulisz

Keywords:

Soil
Degradation
Anthropogenic load
Remote sensing
GIS

Abstract

Currently, a serious environmental issue is soil degradation, primarily caused by pollution, salinization, and the loss of organic matter. A significant part of the Kostanay Region's area, N Kazakhstan, is utilized for human economic activities, often resulting in detrimental consequences for ecosystems. Remote sensing technologies are the most suitable and cost-effective solution for monitoring soil conditions. This work aims to develop a method for evaluating soil cover dynamics under anthropogenic impact using remote sensing data. The technique, developed and tested in the Kostanay Oblast – one of the main mining regions focused on iron ore extraction and crop production – utilises satellite images and field survey results as input materials. As a result of the studies, it was established that the soil cover in the semi-desert zone in the southern part of the region, which exhibits a high degree of degradation, is associated with anthropogenic impacts and natural climatic features that affect soil pollution processes. In contrast, soils with a low degree of degradation are found in the forest-steppe and steppe zones, characterized by high economic development and resilience to anthropogenic impacts. Verifying the obtained results at the remaining 20% of field points allows us to assert that the indicators are reliable at 85% to 91%, confirming the appropriateness of the chosen research methods and techniques. Subsequently, based on the verified map of soil cover degradation, created through space monitoring over a specific period, it is possible to forecast the functioning of soil cover under conditions of anthropogenic impact.

1. Introduction

Soil is one of the most important components of the landscape. As stated by Dokuchaev, the soil is a mirror of the landscape. Multiple studies have established that soil cover generally reflects environmental pollution (Adhikari, 2016; Yaalon, 2000). Due to its ability to accumulate and store substances delivered to the soil surface through dry and wet deposition from the atmosphere, soil cover is an optimal subject for studying and assessing environmental pollution (Dazzi and Lo Papa, 2015; Hamilton, 2015).

Soil occupies a pivotal position among the components of the natural complex. When determining spatial and temporal dynamics, it is essential to recognize that soil is formed through buffering—its ability to "absorb" impacts—and external factors, such as its position in the catena and climatic features that influence soil pollution processes. Various components and flows are closely intertwined within it, where the main biogeochemical processes occur: absorption, decomposition, synthesis, accumulation, and removal of substances, including those of anthropogenic origin. Therefore, soil is a crucial link in the mechanism of geochemical stability of the ecosystem (Dudal, 2005; Mendyk et al., 2016; Waroszewski et al., 2015).

One of the ecosystems where soil degradation is most pronounced is agricultural land. The unstable state of agroecosystems is attributed to their simplified phytocenosis, which does not provide optimal self-regulation, structural constancy, or productivity. In natural ecosystems, biological productivity is ensured by the action of natural laws; however, the output of primary production (yield) in agroecosystems depends entirely on subjective factors such as human intervention, agronomic knowledge, technical equipment, and socio-economic conditions, which leads to instability (Ganasri et al., 2016). The main anthropogenic impacts on soils include erosion (wind and water), pollution, secondary salinization and waterlogging, desertification, and land alienation for industrial and municipal construction (Dabral et al., 2008).

Precise and timely assessments of soil attributes are imperative for informed decision-making regarding land utilization, crop selection, and nutrient management (Taneja et al., 2021). However, soil evaluations have traditionally been conducted through field surveys and laboratory examinations, which can be time-consuming, labour-intensive, and costly (Kirts et al., 2019; Heil et al., 2022). Remote sensing (RS) methods have emerged as a promising solution to these challenges, providing efficient and expansive soil assessment capabilities (Yao et al., 2019; Coble et al., 2018; Abdulraheem et al., 2023).

So far, the use of space monitoring for assessing changes in landscapes has primarily focused on vegetation cover, with less emphasis on soil condition. An example is the land degradation index, which is based on two variants: the NDVI vegetation cover index and the moisture index derived from Tasseled Cap transformation technology and the soil grain size index (Myachina and Malakhov, 2013). The study by Fadhil (2009) focused on monitoring, mapping, and assessing land degradation. Saaty (2008) developed six indices reflecting vulnerability to land degradation. This methodology is primarily aimed at determining the resistance of natural components to degradation. Thus, all the developed methods using remote sensing data characterize land degradation exclusively for agricultural purposes or the resilience of individual components to external impacts, but do not adequately characterize the dynamics of soil cover under anthropogenic influence.

Indexes are commonly employed to enhance the discernment of observed phenomena by isolating spectral bands or reflectance at specific wavelengths. Among these, vegetation indexes constitute a subset that reveals vegetation traits and indicates soil attributes often associated with them. Broadly, we can categorize them into broadband indexes (derived from multispectral data), which encompass a broader spectrum, and narrow-band indexes with meticulously determined wavelengths derived from hyperspectral data (Bednar et al., 2023).

Vegetation indexes are particularly adept at indicating the vitality and health of green flora. They exhibit sensitivity to the cumulative impact of foliage coverage, clustering, and chlorophyll concentration. Notably, they leverage the discrepancy between robust near-infrared reflectance of vegetation and diminished reflectance in the red-light spectrum. Narrow-band indexes, compared to their broadband counterparts, demonstrate heightened sensitivity to subtle variations in vegetation characteristics, particularly in scenarios where vegetation density is influential and narrow-spectral images risk oversaturation (Bednar et al., 2023).

This work aims to develop a method for evaluating soil cover dynamics under anthropogenic impact using remote sensing data. The method was tested in the Kostanay Oblast, N Kazakhstan, one of the main mining regions focused on iron ore extraction and crop production, using satellite images and field survey results as input materials.

2. Materials and methods

2.1. Study area

The study of soil cover dynamics under conditions of anthropogenic impact, exemplified by the Kostanay region, is linked to the continuous growth of human influence on its soils. This region possesses significant reserves of various natural resources—minerals, lands, and forests—whose industrial development is steadily increasing, creating complex environmental challenges. The region has a well-developed manufacturing industry, including machine building, metallurgy, and the production of construction materials. More than 90% of the republic's iron ore products and 100% of iron ore pellets and asbestos are produced here, with these products being exported to various countries. This development results in various soil modifications of different degrees and types.

Based on the stages of economic development, periods for studying soil cover dynamics in the region under anthropogenic impact have been established: 1980, 2000, and 2023. 1980 the economic potential was enhanced by integrating raw materials and fuel-energy resources into the national economy. By 2000, the Kostanay region saw an increase in productivity and the number of industrial enterprises, including the construction of factories for producing metalized products (such as the Sokolov-Sarbai Mining and Processing Production Association and a plant for manufacturing small-section rolled products), as well as mechanical engineering enterprises like "Agromashholding" and food industry enterprises. By 2023, the Kostanay region experienced significant positive changes in key macroeconomic indicators, particularly in the manufacturing sector, where production rates notably increased, especially in mechanical engineering, construction, food processing, and related industries.

The general patterns of natural latitudinal zonality govern the soil cover of the Kostanay region. The gradual change of bioclimatic factors from north to south has led to the formation of two latitudinal soil zones and four subzones across the territory.

To reflect and analyze the spatial distribution of soils in the region, a soil classification based on taxonomic categories developed by the World Reference Base for Soil Resources (WRB) was applied (IUSS Working Group WRB, 2022). This classification began producing at the end of the last century and is now widely used by soil scientists, geographers, and ecologists in many countries. The horizontal zones of typical plains are as follows (Fig. 1).

In addition to zonal soils, intrazonal soils are widely distributed in the region, including Phaeozems, Solonetz, and Arenosols, characterized by Calcisols-type soil formation. These soils do not adhere to the strict regularity of distribution associated with natural zonality and can be found in atypical zones, appearing as spots or isolated massifs.

The Kostanay region is also marked by a high complexity of soil cover, particularly the widespread complexes of zonal Solonetz soils. The parent material is primarily silts; however, the soil texture becomes more sandy as one moves south.

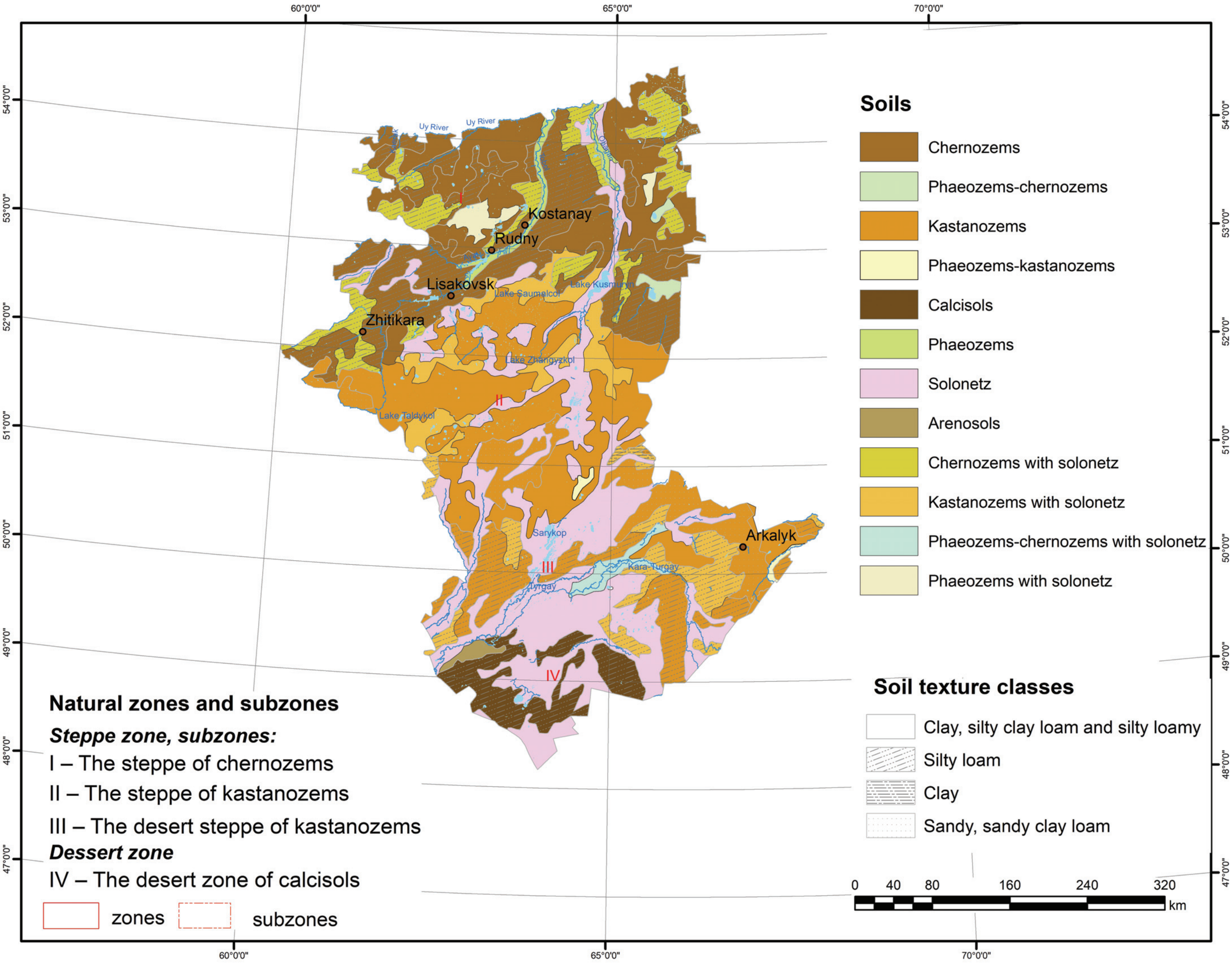


Fig. 1. Soil map of the Kostanay region. Soil units according to WRB classification (IUSS Working Group WRB, 2022)

Exceptions to this trend include areas along former and existing river and lake beds, where clay predominates. Additionally, the Zhylanshykturme upland (located in the southeast of the region), as well as the Turgai and Zauralsk plateaus, feature deposits composed of silts with inclusions of pebbles, rubble, and tresla (Barinova et al., 2002).

2.2. Methods

The proposed method for assessing the dynamics of soil cover under anthropogenic impact utilizes remote sensing data to differentiate and evaluate changes primarily driven by irrational economic activities (Table 1). The stages of assessing land cover degradation resulting from anthropogenic impact are illustrated in Fig. 2.

Stage One: Processing of Satellite Images

The first stage involves processing cloud-free satellite images with high spatial resolution. This includes preliminary steps such as radiometric calibration, atmospheric correction, and geometric correction. The selected indicators for the Kostanay region are assessed for the periods 1980, 2020, and 2023, which correspond to new types of land management practices. Satellite images from Landsat 3, 5, 7, and 8 were utilized for this analysis.

Stage Two: Calculation of Indices

The second stage entails calculating indices based on data from various satellite image channels. The indices with the highest reliability were identified by verifying index values and conducting field studies to map each index. Using 80% of the field points, a range of spectral index values corresponding to indicators of soil degradation in the study region was established. For 75 points, spectral index values were recorded, and the ranges that met the desired parameters for the indicators were determined. For example, waterlogged areas identified during field surveys in the Kostanay region exhibited NDMI index values ranging from 0.8 to 0.9.

Table 1
Indicators for assessing land cover degradation under anthropogenic impacts

Indicators	Indexes	Range values	Time of indicator observations	Sensor
Waterlogging of the soil	NDMI	0.8 – 1.0	April – May, June – July, September	Landsat-3, 5, 7, 8
Soil salinity	NDSI	0.0 – 1.0	April – May, June – July, September	Landsat-3, 5, 7, 8
Solonchakness	Tasseled Cap Transformation (Brightness)	30633 – 50970	April – May, June – July, September	Landsat-3, 5, 7, 8
Soil erosion by water	NDVI GNDVI	0.0 – 0.9 0.0 – 0.9	April – May, June – July, September	Landsat-3, 5, 7, 8
Soil erosion by wind	TGSI Tasseled Cap Transformation (Brightness)	0.2 – 0.8 28868 – 43302	April – May, June – July, September	Landsat-3, 5, 7, 8

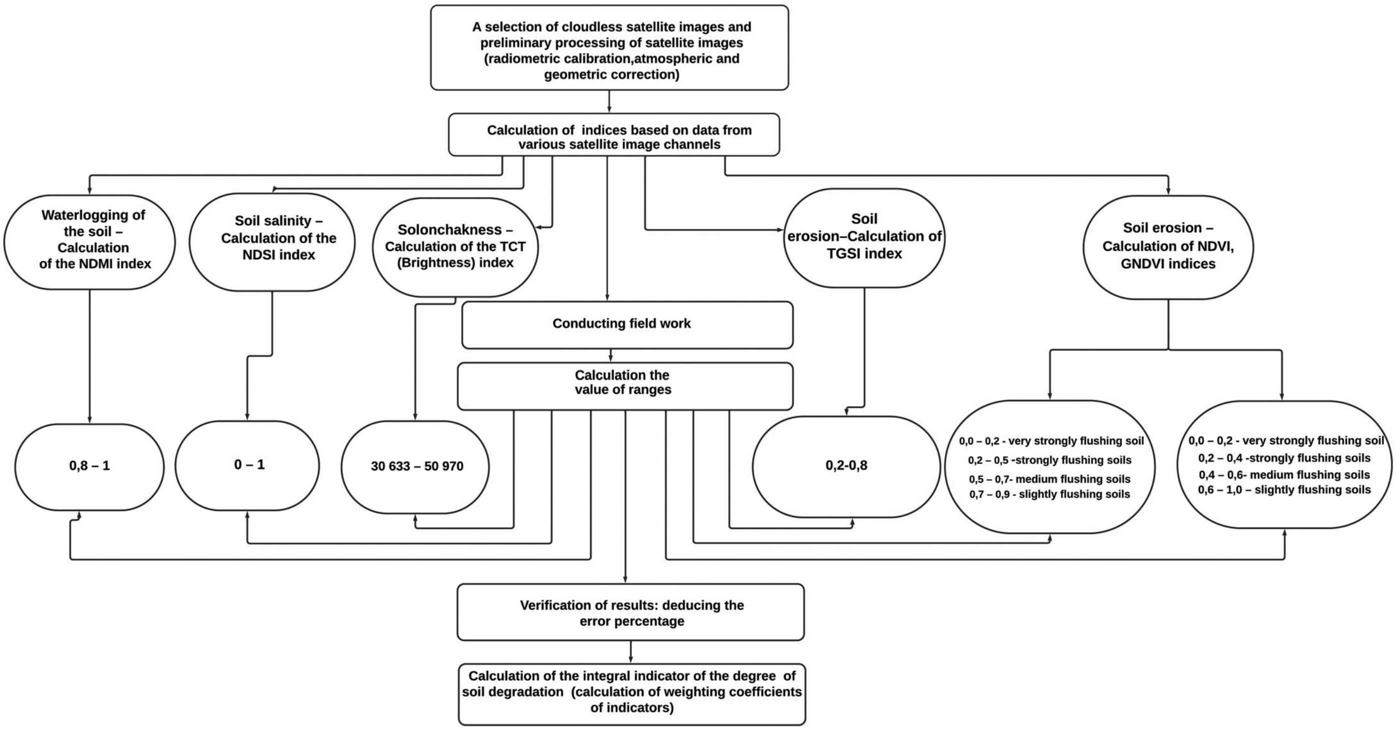


Fig. 2. Stages of land cover degradation assessment under conditions of anthropogenic impact

Waterlogging of the soil. Soil waterlogging is a dynamic natural process characterized by excessive atmospheric or groundwater moisture inflow. As commonly observed, when soils are saturated with water, their structure degrades, aeration decreases, and these conditions adversely affect root development in vegetation, ultimately leading to plant death.

Waterlogging causes are linked to natural climatic changes and various anthropogenic activities, such as irrigation, hydraulic engineering projects, industrial and municipal water consumption, agrotechnical methods for soil moisture retention, and land management practices.

The most commonly used indices for assessing soil moisture include the Normalized Soil Moisture Index (NSMI), Cropland Soil Moisture Index (CSMI), Surface Water Content Index (SWCI), Universal Drought and Soil Moisture Index (SMADI), Soil Water Index (SWI), and the Normalized Difference Moisture Index (NDMI), among others (Besten et al., 2021; Singh and Pandey, 2014; Al-Maliki et al., 2022; Bukombe et al., 2023). The NDMI was selected for this study due to its demonstrated reliability of 90 to 95% based on our field studies.

The NDMI (Normalized Difference Moisture Index) is an index that characterizes the relative moisture content of soil and plant leaves. According to Wilson and Sader (2002), one of the key attributes of the NDMI is its sensitivity to soil and plant moisture content, making it an effective tool for this analysis (Formula 1).

$$NDMI = \frac{(NIR - SWIR)}{(NIR + SWIR)} \tag{1}$$

Soil salinity. Salinization is a process that leads to an increase in the concentration of soluble salts in the soil, resulting in significant transformations of the landscape. This process alters the index of easily soluble mineral salts in the soil, which can reach levels greater than 0.1% to 0.3% (including sodium carbonate, chlorides, and sulfates). Both natural and secondary soil salinization are factors that exacerbate soil degradation. Secondary salinization typically arises from improper agricultural irrigation practices, particularly through over-irrigation that elevates saline groundwater levels or uses highly saline water for irrigation.

With advancements in remote sensing technology, various methods have emerged for utilizing multispectral imagery to identify and delineate saline areas within the study region. Some commonly used indices for assessing soil salinity include the Salinity Index, Vegetation Soil Salinity Index, and Normalized Difference Salinity Index (NDSI) (Khan et al., 2001; Kedir, 2007). Research has demonstrated that the NDSI provides a high degree of reliability compared to field study results (Formula 2).

$$\mathrm{NDSI} = \frac{(\mathrm{RED} - \mathrm{NIR})}{(\mathrm{RED} + \mathrm{NIR})} \tag{2}$$

The value of the studied index ranges from –1 to +1. Within this spectrum, highly saline areas correspond to index values from 0 to 1 (Khan et al., 2001; Kedir, 2007).

Solonchakness of soils. Solonchaks are characterized by the presence of easily soluble salts in the surface horizons, resulting in salinization throughout the entire horizon. In contrast, solonchak salts are primarily concentrated in the illuvial B horizon. In irrigated and waterlogged areas, secondary solonchak formation can occur when the saline groundwater level rises, leading to an influx of salts into the soil that exceeds their removal through irrigation.

Our study selected the Tasseled Cap Transformation (Brightness) index for analysis, demonstrating the highest reliability when comparing index values with field results.

$$\begin{aligned}\text{Brightness} = {} & 0.3037{*}\text{Blue}+0.2793{*}\text{Green}+0.4743{*}\text{Red}+\\ & +0.5585{*}\text{NIR}+0.5082{*}\text{SWIRI}+0.1863{*}\text{SWIRII}\end{aligned} \tag{3}$$

Soil water erosion: Soil erosion indicates the earth's surface's ability to resist erosive processes. Human activities have a detrimental impact on soil and vegetation cover, exacerbating soil erosion.

Initially, soil erosion is influenced by natural factors, including climate (light, temperature, and precipitation), topography (slope, shape, steepness, and length), soil characteristics (such as water permeability), and the presence of flora and fauna. On the other hand, anthropogenic factors encompass various human activities, such as plowing, soil cultivation, grazing, deforestation, and construction, that disrupt the interactions among climate, soil, and vegetation cover.

The relationship between soil erosion and vegetation productivity is evident in the results of vegetation indices. For instance, the ability of vegetation cover to reflect its growing conditions, which are influenced by soil erosion disturbances, forms the basis for terrestrial phytoindication methods.

The most commonly used spectral indices for assessing soil erosion include the Normalized Difference Vegetation Index (NDVI), Green Normalized Difference Vegetation Index (GNDVI), Short Wave Vegetation Index (SWVI), and Topsoil Grain Size Index (GSI). Based on our research and existing literature (Gusev et al., 2020; Yengoh et al., 2014), NDVI and GDVI are identified as the most effective indicators of water erosion, as demonstrated by the non-parametric Mann-Whitney criterion (Formulas 4 and 5).

$$NDVI = \frac{(NIR - RED)}{(NIR + RED)} \tag{4}$$

$$GNDVI = \frac{(NIR - GREEN)}{(NIR + GREEN)} \tag{5}$$

The statistical analysis was performed using STATISTICA 6.0 software. To assess the significance of differences, the non-parametric Mann-Whitney test was applied. The Mann-Whitney test is used to compare the mean values of two independent samples. The empirical value of the Mann-Whitney test determines the degree of similarity between two independent distributions. The analysis of the intersection of the two samples is based on the sequential ranking of the values.

Soil wind erosion. Anthropogenic factors contributing to wind erosion include:

a) The extensive involvement of land in agricultural practices. There are virtually no uncultivated lands remaining, including low-productive areas such as pastures and hayfields, which have also been subjected to cultivation. This is often done without considering mechanical composition, soil properties, or effective erosion control measures.

b) The widespread use of mechanical tillage, particularly with moldboard plows, has significantly reduced stubble cover by the end of the fallow period. This lack of ground cover increases the soil's susceptibility to wind erosion during summer and winter, mainly due to low snow cover or its complete absence on fallow fields.

According to our studies and existing literature (Xiao et al., 2006; Lamchin et al., 2016; Svetlakov and Tsychueva, 2017; Marchetti et al., 2010), the Topsoil Grain Size Index (TGSI) and the

Tasseled Cap Transformation (Brightness) index are the most effective indices for assessing wind erosion. The TGSI is utilized to identify mobile sands (Formula 3), while the Tasseled Cap Transformation index is employed to characterize consolidated and semi-consolidated sands (Formula 6).

$$TGSI = \frac{(RED - BLUE)}{(RED + BLUE + GREEN)} \tag{6}$$

Stage Three: Confirmation of Results through Field Studies

Field studies were conducted to validate the results obtained from remote sensing data. One of the primary objectives of these studies is to verify the digital map of natural environment degradation developed from remote sensing information. Additionally, ground data are collected for selected key areas, with field studies conducted within timeframes that align with satellite imagery acquisition.

The observation periods for key indicators—such as soil waterlogging, soil salinity, solonchakness, and soil erosion—are scheduled as follows: spring (April 20 to May 20), summer (June 20 to July 20), and autumn (September 1 to October 1).

Sampling points are between 100 and 1,000 meters apart, with a minimum of five points established at each demonstration site (refer to Soils: Methods for Determination of Organic Matter, State Standard 26213-2021). All data collected from field surveys are recorded in a geodatabase in point shapefile format using a GPS receiver. Measurements and data from field forms are documented in attribute tables.

Typical areas in natural settings are selected for full-profile soil transects, considering the influence of anthropogenic factors. Soil samples are collected from distinct genetic horizons.

The soil samples are evenly spread on paper, and any clumps, including larger aggregates, are broken apart. Visibly observable pebbles, insects, debris, and other coarse materials are removed. Prepared soil samples are then crushed using a pestle in a mortar and sieved through a laboratory sieve.

To determine soil waterlogging, the thermostat-weight method (Vadyunina and Korchagina, 1986) is employed. This method allows for the calculation of soil moisture content (W), expressed as a percentage of the dry soil mass, using the following formula (7):

$$W\ (\%\ from\ the\ mass) = \frac{B - V}{V - a} * 100\% \tag{7}$$

where, a – mass of the box, g; B – mass of the box with damp soil, g; V – mass of the box with absolutely dry soil, g; (B – V) – mass of water, g; (V – a) – mass of dry soil, g.

The degree of soil erosion was determined using a morphological description of the key site profile. As a result of field studies, eroded soils were classified into slightly washed out, moderately washed out, strongly washed out, and very strongly washed out (Shcheglov and Gorbunova, 2011). Subsequently, each value of the NDVI and GNDVI indices was assigned to the corresponding classes of eroded soils.

The fourth stage of the work involved calculating value ranges. Both literature sources (Xiao et al., 2006; Chavez and Pat, 1996; Pretorius and Bezuidenhout, 1994; Wu et al., 2008) and the results of our field studies were utilized to determine these ranges. The index ranges were calculated using the "Extract Multi Values to Points" tool in ArcGIS 10.5 software. Point shapefiles from the field studies served as vector data, while the computed indices were represented as raster data. As a result of this approach, spectral index data were assigned to the attribute table of the point shapefile, allowing for determining the maximum and minimum index values and the corresponding search range.

The fifth stage of the work involved verifying the obtained indicators. This verification was conducted by checking the values of the remaining 20% of field points and comparing them with available cartographic materials. At this stage, the percentage of error was also calculated. Verification of selected points for each indicator was based on field survey data. A matrix of indicators was compiled, with columns representing the indicators derived from satellite images and rows representing the verified indicators determined on the ground. The matrix was filled in for all survey points, after which the percentage of accuracy for each indicator was calculated. According to the results of the field verification of the predictive map of soil cover degradation in the Kostanay region, the reliability of the results ranged from 85% to 91%.

The overall error rate is defined as the percentage of ground measurement points that match the classes determined by remote sensing data, relative to the total number of surveyed points. For example, for soil waterlogging, it is calculated as follows:

$$17/20*100 = 85\% \tag{8}$$

where 17 represents the number of field points that matched the class, and 20 is the total number of points. The results and discussion sections describe the interpretation of the errors obtained.

The calculation of the integral indicator of land cover degradation degree constitutes the final stage, where the integral value is computed based on the degradation of each indicator under anthropogenic impact conditions. The digital map of land cover degradation due to anthropogenic impact is generated based on the integral value using the "Overlay Toolset" group in ArcGIS 10.5 software. Weight values must be assigned to each indicator. Weighting coefficients are determined using expert methods, based on the assessment of each indicator's contribution to the degradation of the natural environment under anthropogenic impact. During this stage, soil scientists from the Kazakhstan Research Institute of Soil Science and Agrochemistry, U.U. Uspanova and space monitoring specialists from the national company "Kazakhstan Garysh Sapary" were engaged as experts. The experts were selected and collaborated with them by generally accepted methodological recommendations (Samokhvalov and Naumenko, 2007). A patent for a utility model protects our development in determining the degree of soil degradation (Utility model Patent No. 9282, 2024).

3. Results and discussion

3.1. Waterlogging of the soil

Using the obtained NDMI index data, it is possible to identify areas of the Earth's surface with varying soil moisture levels. The interpretation of NDMI values indicates that this index ranges from –1 to 1. Values above 0 suggest the presence of water, while negative values indicate intense atmospheric and soil drought (Table 2 and Website 1).

According to the characteristics of nature and climate in the study region, soil waterlogging decreases from north to south. It has been established that in 1980, the area of soil waterlogging in the study region was typical for soils of the steppes on chernozems, particularly in the loamy layer plains. Loamy soils possess a greater ability to retain moisture. The depth of groundwater occurrence in waterlogged landscapes ranges from 5 to 6 meters, and along the Turgai River, there are water-retaining strata that reach the ground surface (Durasov and Tazabekov, 1981). The maximum value of waterlogging (0.9) is characteristic of the adjacent area of the Zhelkuar Reservoir. The functioning of the reservoir negatively impacts the soil and vegetation cover, leading to flooding of nearby territories and the formation of swampy areas.

In urban areas, the waterlogging levels vary from 0.5 to 0.8, primarily due to technogenic impacts associated with active infrastructure development, including the construction of reservoirs, canals, pumping stations, water pipelines, and wells. In the cities of Kostanay, Rudnyi, and Zhitikara, there are areas with a high level of waterlogging where the NDMI index reaches 0.8. This level of wetness results from anthropogenic activities related to iron and asbestos ore extraction. It is important to note that anthropogenic waterlogging also leads to chemical soil pollution, negatively affecting the soil and vegetation cover.

In addition to industrial facilities, agricultural activities in the study region also adversely impact the soil cover. For instance, a high NDMI index (0.8) is observed near Fedorovka village, where sown areas are predominantly occupied by wheat and fodder crops, and cattle grazing is practiced. Violations of irrigation technology contribute to the degradation of soil cover in extensive irrigated areas. This degradation manifests as a reduction in the physical and chemical properties of the soil, a rise in the groundwater table, and ultimately results in soil waterlogging (Current Status and Forecast of Socio-Economic Development, 2012).

Notably, specific patterns can be observed during the study of NDMI index changes compared to data from 1980. In 2000, there was widespread soil cover waterlogging in the steppes on chernozems, particularly in the northwestern part of the region. However, by 2022, the values of waterlogging had decreased, remaining only in small areas of the steppe and desert-steppe zones on Kastanozems (0.8–1). There has been an increase in wetted steppes on Chernozems in the northwestern part (0.6–0.8), which can be associated with the growing economic load in this region, especially near large industrial cities such as Kostanay, Rudny, Lisakovsk, and Zhitikara. The expansion of industrial facilities has led to urbanization, an increase in the urban population, and the introduction of transport lines, all of which have contributed to the moistening of the soil cover in the studied region (Fig. 3) (Use of Water Resources by Economic Sectors in Current Conditions and for the Future, 2006).

After field verification of the predictive map of land cover waterlogging in the Kostanay region, the reliability of the results was found to be 85%. This indicates a high level of reliability for the forecast data and its correspondence to the actual conditions on the ground. In this instance, the error can be attributed to remote sensing temperature data. The change in surface temperature of agricultural fields decreases after irrigation and the subsequent water absorption into the soil. Therefore, the difference in surface temperature on different dates can indicate the occurrence of irrigation on a specific date.

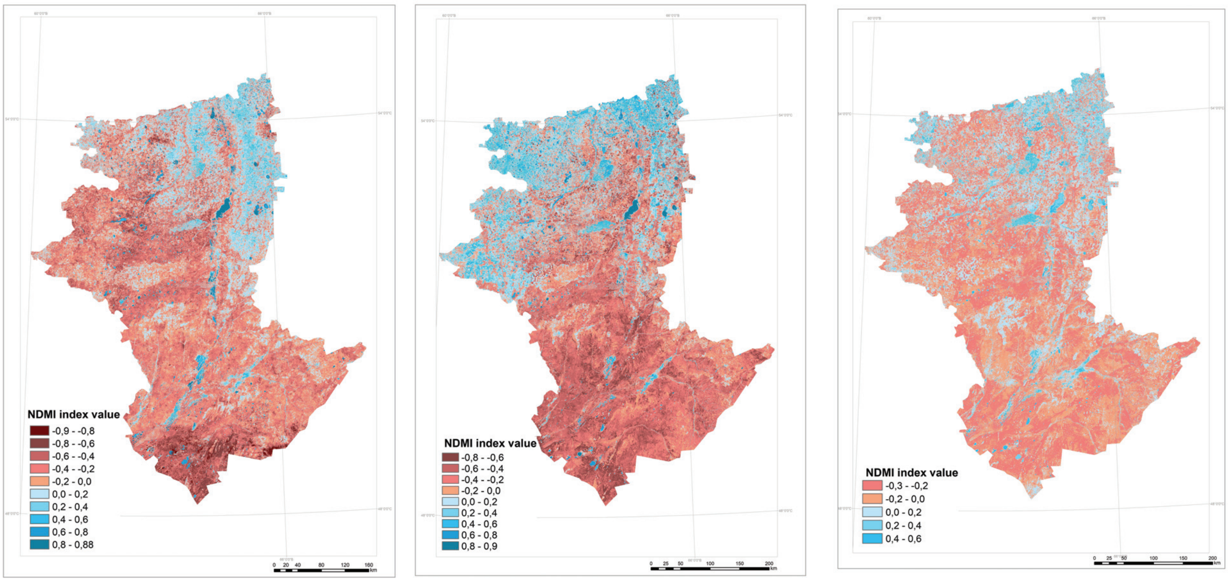
3.2. Soil salinity

The widespread high salinity in the region is primarily related to the geological features of the territory's formation, originating from the Cretaceous period of the Mesozoic era, when the study area was situated between the Caspian Sea and the North-Western lowlands (Efstifeev, 1966).

In 1980, landscapes with low NDSI index values, ranging from 0.0 to 0.3, were characteristic of the steppes on chernozems. These landscapes are represented by gently U-shaped valleys covering loamy basement plains. The average value of the salinity index, from 0.3 to 0.5, is also typical for steppes on chernozems. In these areas, hilly and gently sloping basement plains composed of sedimentary and effusive rocks prevail.

Table 2
Interpretation of NDMI values

Interpretation	NDMI index value	Interpretation	NDMI index value
Bare Soil	–1 – –0.8	Average moisture level	0.0 – 0.2
Very low moisture level	–0.8 – –0.6	Medium-high moisture level	0.2 – 0.4
Low moisture level	–0.6 – –0.4	High moisture level	0.4 – 0.6
Medium-low moisture level	–0.4 – –0.2	Very high moisture level	0.6 – 0.8
Intermediate moisture level	–0.2 – 0.0	Waterlogging	0.-8 – 1.0



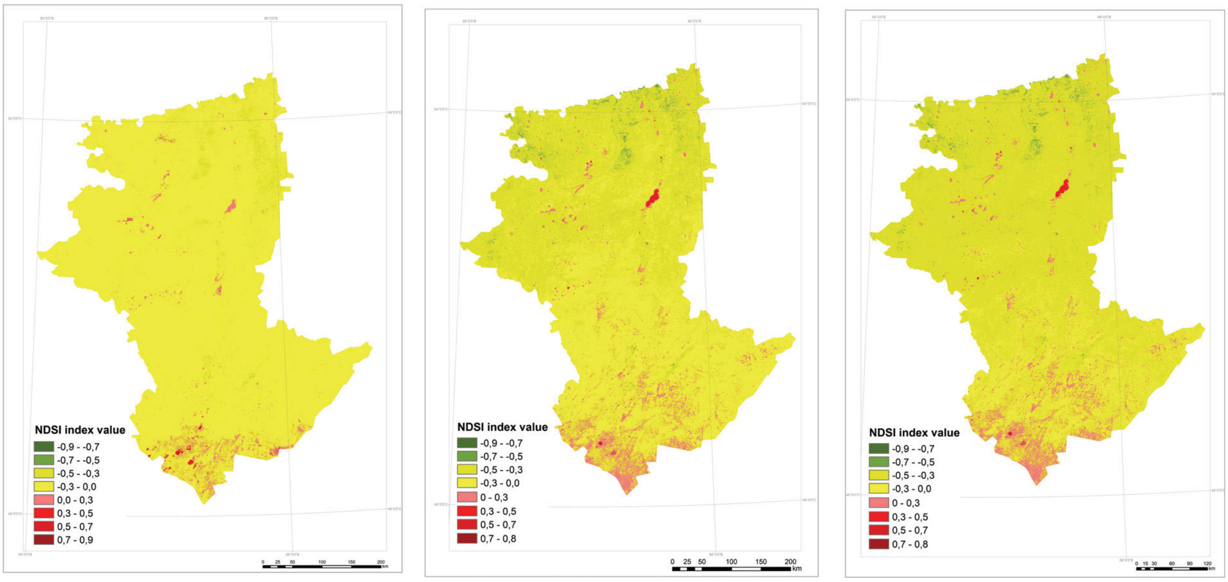
1980 2000 2023

Fig. 3. Normalized Difference Moisture Index

High NDSI index values, ranging from 0.5 to 0.7, are characteristic of soils in the semi-desert zone. These areas are represented by semi-desert sandy eolian plains, characterized by Kastanozems and Calcisols with Solonetz. The maximum land salinity index values, from 0.7 to 0.9, are found in soils of the desert zone. These regions consist of flat-waved sandy loamy plains made up of sandy loam and sand. They are utilized as pastures and arable land, primarily for the cultivation of wheat and millet, with fodder crops accounting for 15–40% of the area (Fig. 4).

In 2000, high salinity levels (0.0–0.3) were observed in the soils of the steppe zone, which are characterized by deluvial-proluvial plain flat plains with *Festuca* and *Stipa lessingiana* vegetation growing on Kastanozems with Solonetz. (Fig. 4). During the 1990s, many agricultural fields used for rainfed and irrigated agriculture were abandoned, leading to secondary salinization.

By 2023, salinization had affected the soils of the steppe zone, characterized by gently sloping loamy plains with mixed-grass and red-grass steppes located on chernozem soils (Fig. 5). Since 1980, these territories have been used for arable land, primarily



1980 2000 2023

Fig. 4. Normalized Difference Salinity Index

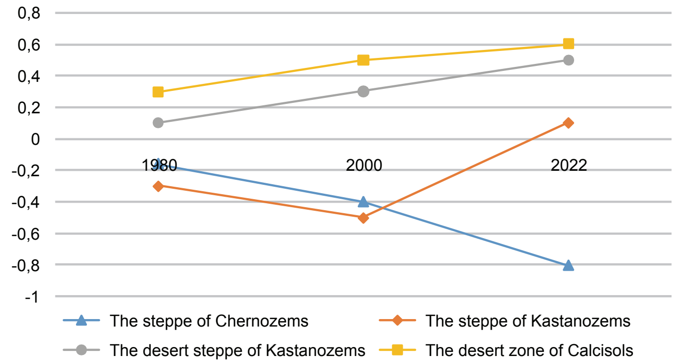


Fig. 5. Chart of Soil Salinity Dynamics (NDSI) in the Subzones of the Kostanay Region

wheat cultivation. One significant reason for the large-scale increase in soil salinity is the violation of irrigation technology, which negatively impacts soil fertility. From 2000 to 2023, the anthropogenic impact of industrial facilities on the region's soil cover has increased. Saline areas are also observed near industrial cities such as Kostanay, Rudny, Lisakovsk, and Zhitikara. Studies indicate that salinity reached a high value of 0.9 in both 1980 and 2000 (Fig. 4). In 2023, the area affected by salinity increased compared to previous periods. This region is bordered by the Ayat and Tobol rivers, whose channels are regulated by reservoirs. One of the main consequences of construction is the increase in groundwater levels, which, in an arid climate, leads to the rise of saline groundwater to the surface, resulting in soil salinization and, in some areas, waterlogging (Prevention and Reduction of the Risk of Harmful Water Impact, 2013).

According to the results of field verification of the predictive map of soil salinity in the Kostanay region, the reliability of the obtained results was 87%.

3.3. Solonchakness

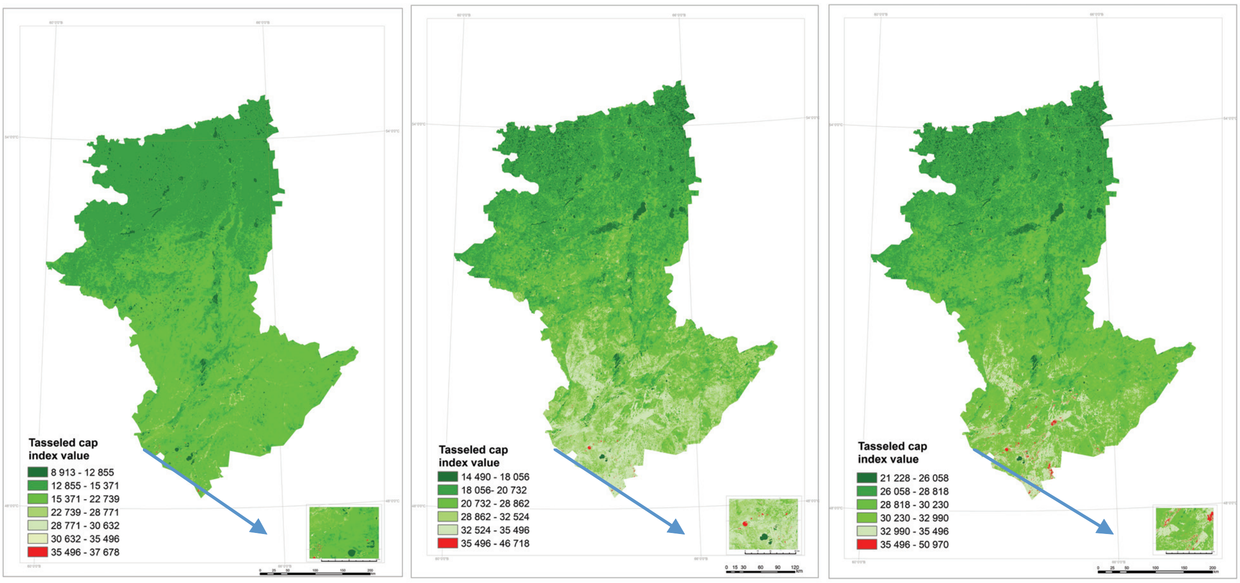
Analyzing the Tasseled Cap index results for 1980, it is evident that solonchaks are characteristic of the area of flat-waved and weakly-waved desert steppe landscapes in the south, where the primary anthropogenic activity is cattle breeding. Tasseled Cap values in this range correspond to 35,497 to 50,970 (2022) (Fig. 6).

Since 2000, areas with salt marsh distribution have increased from north to south, where livestock production is the main anthropogenic activity. These territories serve as pasture lands where continuous grazing occurs, affecting the reduction of vegetation cover and leading to a saline water regime that attracts salt solutions (Fig. 6).

In 2023, Solonchaks spread to the weakly-wavy plains of the steppe on Kastanozems, likely related to irrigation practices in this area. Grain and leguminous crops, including seed production, are cultivated on these lands (Fig. 6).

Overall, there has been an increase in the area of arable land in the study region. For instance, in 2000, the area of arable land in Kostanay province was 5,605.0 thousand hectares, which increased to 6,293.5 thousand hectares by 2021 (0.266 km¸ on a republican scale). Liman irrigation was primarily developed based on the spring runoff of the Torgai and Tobol rivers. However, constant and excessive irrigation leads to soil saturation, merging with saline groundwater and raising salts through capillaries to the surface, which contributes to the formation of solonchaks (Fig. 5).

Thus, with the increase in agricultural land use, an expansion of solonchak distribution from north to south has been observed (Fig. 6). According to the results of field verification of the predictive map of solonchaks in the Kostanay region, the reliability of these results was 88%. The observed error can be attributed to the sparse herbaceous vegetation on solonchaks, which resulted in a mixed signal from two classes.



1980 2000 2023

Fig. 6. Tasseled Cap Transformation

3.4. Soil water erosion

The results of the field study on soil erosion, along with the values of the NDVI and GNDVI indices, are presented in Table 3.

The Mann-Whitney criterion analysis revealed no significant differences between highly eroded and moderately eroded soils, nor between slightly erodible and non-erodible soils. However, statistically significant differences ($p < 0.01$) were observed when key sites were grouped into three categories: non-erodible soils, highly and moderately erodible soils, and slightly erodible and non-erodible soils.

During the study, it was noted that soil erosion adversely affects the productivity of vegetation cover. Specifically, a higher degree of soil erosion correlates with lower humus and nitrogen content and increased acidity. Greater erosion also results in decreased bioproductivity, which in turn affects the spectral reflective properties of the Earth's surface, as indicated by the NDVI and GNDVI indices (Gusev et al., 2020).

In 1980, slightly eroded soils in the steppe zone, characterized by flat-wave loamy plains, exhibited NDVI index values ranging from 0.7 to 0.9 and GNDVI values from 0.6 to 1.0. Medium-eroded soils in this region, represented by flat sandy historic floodplain terrains, showed NDVI values between 0.5 and 0.7 and GNDVI values from 0.4 to 0.6. Strongly eroded soils, typical of Kastanozems in the desert steppe zone, had NDVI indices ranging from 0.2 to 0.5 and GNDVI values from 0.2 to 0.4. Very highly eroded soils, with NDVI and GNDVI indices from 0.0 to 0.2, were prevalent in significant portions of the steppe and desert steppe zones, including weakly undulating and gently sloping plains composed of clays and sandstones. These areas were particularly prone to erosion and were primarily arable, with mainly fine-textured soils. The leading causes of soil erosion in these regions included improper land use practices, such as continuous plowing of light soils, inadequate agricultural practices, and overgrazing. In 1980, some of these areas were utilized for grazing natural fodder lands and for cultivating fodder crops (hay from natural hayfields and field products), while others were designated as arable land, primarily growing wheat with minimal use of fodder crops (15–30%) and employing fallow and non-tillage practices.

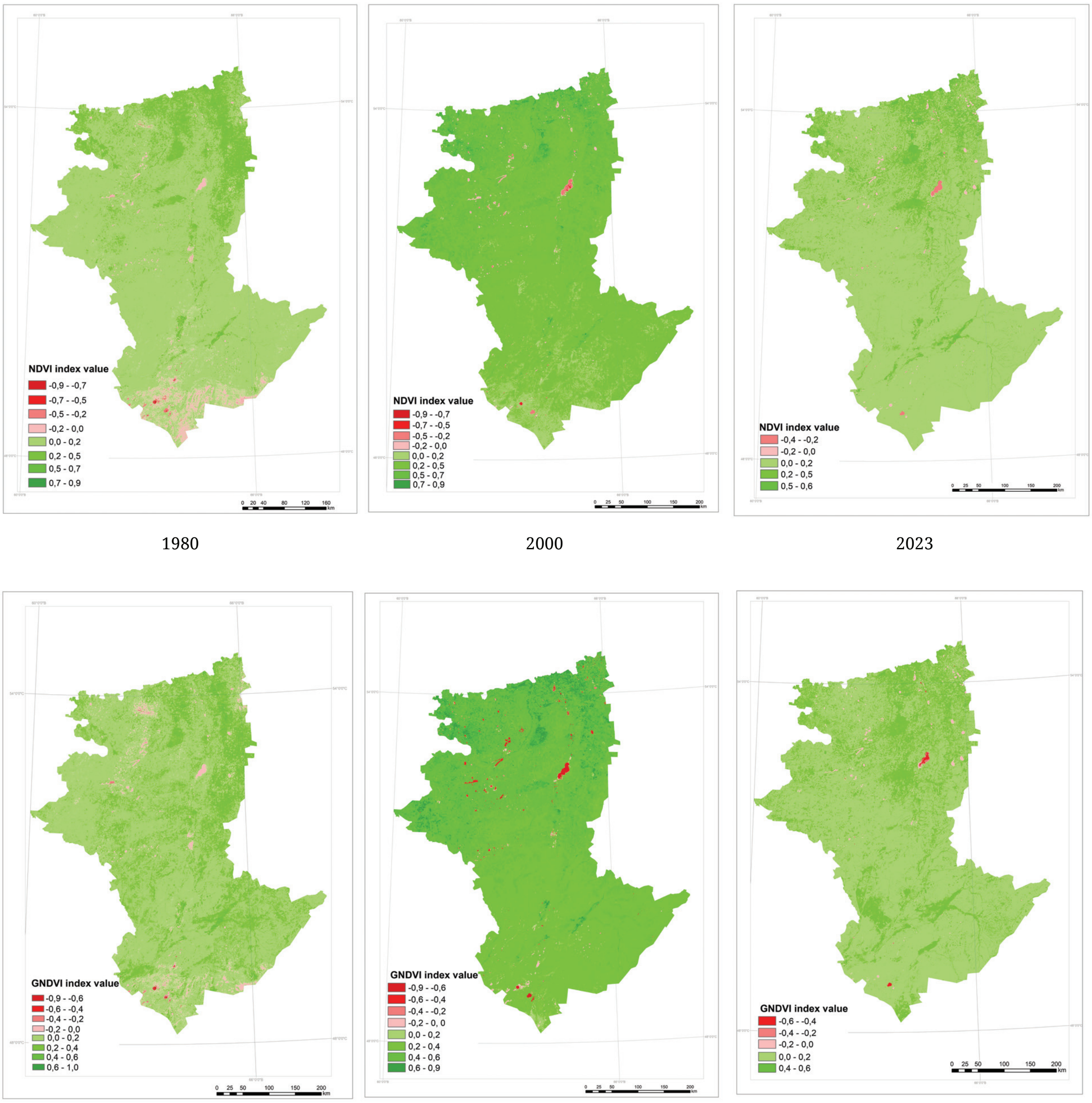
By 2000, steppes on southern chernozems, consisting of clays, sandstones, and their erosion-denudation slopes, were classified as weakly eroded soils with NDVI values from 0.7 to 0.9 and GNDVI values from 0.6 to 1.0. Some semi-desert soils of weakly undulating plains, composed of granites, limestones, and sandstones, transitioned from the medium-washed category to strongly eroded soils with NDVI values from 0.2 to 0.5 and GNDVI values from 0.2 to 0.4. However, intensive plowing, insufficient afforestation and irrigation of arable lands, lack of care for hayfields and pastures, and poor land management practices have led to the loss of the soil's self-regulating properties and the exacerbation of erosion, leaching, and washing away of the fertile layer due to wind and water erosion. This has significantly contributed to the loss of soil fertility and its properties.

Studies indicate that in areas where untouched and uncultivated lands are developed, along with Chernozem and Kastanozems, the prolonged cultivation of monoculture grains has resulted in dehumification and a decline in soil fertility. The Institute of Soil Science of the Ministry of Education and Science of the Republic of Kazakhstan has noted that over the past 50 years, the morphological, physical, and biological properties of chernozem soils have changed significantly (The update of the comprehensive water resource management and protection scheme for the Tobol River basin in the territory of the Republic of Kazakhstan, 2013). This change poses a real threat to the region's erosion and soil degradation. For instance, the humus content in chernozems has decreased by 27% in the 0–20 cm layer, 23% in the 20–50 cm layer, and 16% in the 50–100 cm layer (Fig. 7).

In addition to agriculture, mining activities significantly impact the eroded soil cover in the Kostanay region (Current Status and Forecast of Socio-Economic Development, 2012). Very strongly eroded soils are typically found in flat-wavy plains composed of clays and sandstones. For instance, near the Sarbaiskiy quarry and the "Kazogneupor" LLP production complex (which manufactures aluminosilicate refractories),

Table 3
Interpretation of NDVI/GNDVI index values

Range values		Field method description	Classification according to Sobolev (Shcheglov et al., 2011).
0.7–0.9	0.6–0.9	They include soils in which not more than ˝ of horizon A is eroded. In this case, the lower part of horizon A is plowed.	Slightly eroded soils
0.5–0.7	0.4–0.6	Soils with partially (more than half) or completely eroded A horizon; the AB horizon is plowed. The surface of arable land has a brownish color.	Medium eroded soils
0.2–0.5	0.2–0.4	These are soils where the AB horizon is washed away, the BC horizon is plowed, and the arable layer is underlain by the lower part of the BC horizon transitional to the underlying geological layer. The arable layer has a brown color.	Strongly eroded soils
0.0–0.2	0.0–0.2	Soils with a completely washed away BC horizon and ploughed underlying geological layer C. Brown arable layer is characterized by a clumpy structure.	Very strongly eroded soil



1980 2000 2023

1980 2000 2023

Fig. 7. Normalized Difference Vegetation Index, Green Normalized Difference Vegetation Index

mining activities have resulted in the abandonment of large land plots that are rendered unsuitable for use in the national economy. Additionally, unsuitable areas such as quarries, dumps, tailing ponds, and mine and domestic water accumulators have emerged. Field verification of the forecast map for soil cover erosion in the Kostanay region indicated a reliability rate of 92% for the obtained results.

3.5. Soil wind erosion

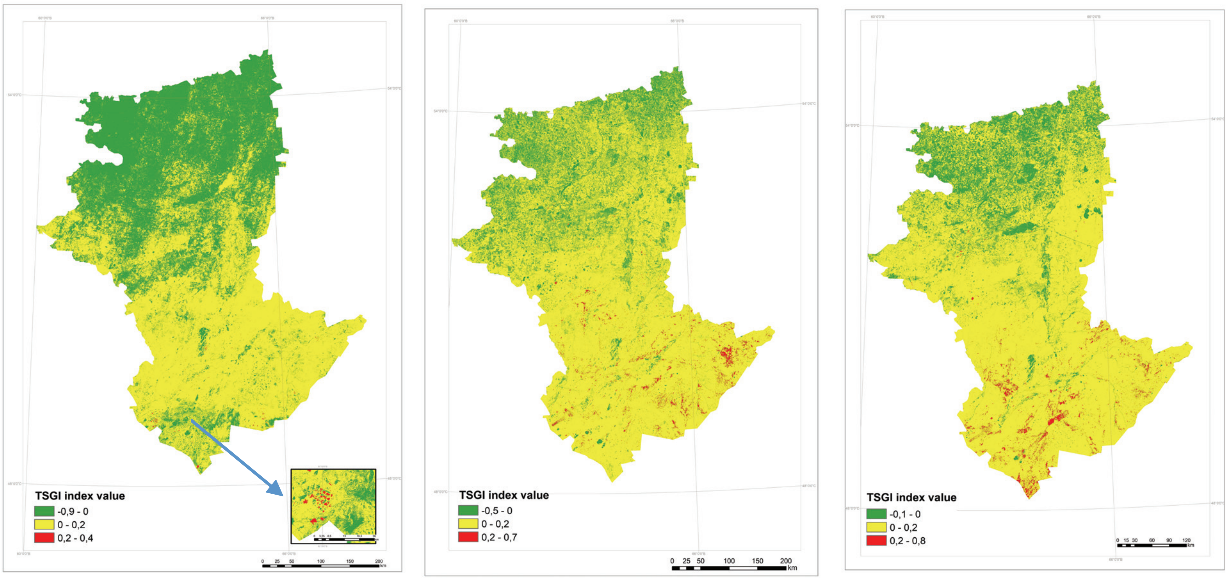
Wind erosion is assessed by interpreting the TGSI and Tasseled Cap Transformation (Brightness) indices, as presented in Table 4.

In the northern part of the steppe subzone of the Kostanay region, wind erosion is minimal due to the limited presence of sandy and sandy loam soils, which lack adequate vegetation cover. In 1980, mobile sands with a TGSI index value ranging from 0.2 to 0.4 were characteristic of a small area of sandy loam soils in the desert zone, represented by flat-wavy plains. This area has historically been used for cattle grazing on natural forage lands, both in 1980 and currently (Fig. 8).

Since 2000, the area of mobile sands with a TGSI value between 0.2 and 0.7 has expanded throughout the desert zone, where cattle breeding is the predominant anthropogenic activity. These territories serve as pasture lands, where continuous grazing has led to a decline in protective vegetation cover. Wind

Table 4
Interpretation of TGSI / Tasseled Cap Transformation (Brightness) index values

Indexes	Description	Range values
TGSI	Movable sands	0.2 – 0.8
Tasseled Cap Transformation (Brightness)	Semi-fixed sands	36085 – 43302
	Fixed sands	28868 – 36085



1980 2000 2023

Fig. 8. Topsoil Grain Size Index

erosion primarily occurs on soils with a light granulometric composition, particularly in areas unprotected from the wind by vegetation. Strong winds, with speeds of 15 $m\cdot s^{-1}$ or higher, are common in this region. Combined with high air temperatures, these conditions quickly dry out the topsoil (General Information about the Basin, 2012). Consequently, soil particles that are prone to erosion become highly malleable and are easily displaced across the surface of the fields.

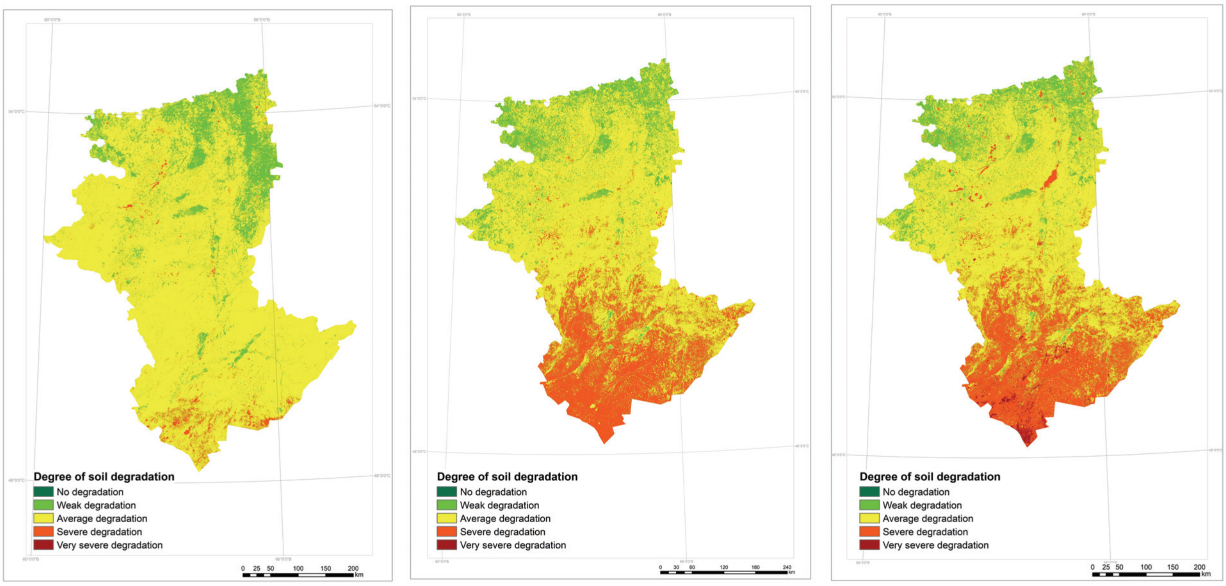
In 2023, shifting sands with TGSI values ranging from 0.2 to 0.8 have spread to the desert's weakly undulating plains on light chestnut soils and the desert-steppe undulating plains on Kastanozems. This phenomenon is likely related to the irrigation practices in the area, where grain and leguminous crops are cultivated. The land is plowed using a moldboard plow with layer turnover, without adequately considering factors such as mechanical composition and soil properties. The widespread use of mechanical tillage, often in pairs, exacerbates the situation. By the end of the fallow period, little to no stubble remains, leaving the soil vulnerable to wind erosion in summer and winter due to low snow cover on fallow fields or its complete absence.

An integral indicator has been developed to assess the degree of degradation of the soil cover. Based on research that utilized indicators reflecting the state of soil cover under anthropogenic influence, the territory of the Kostanay region has been zoned according to the degree of degradation. The resulting integral indicator identified the following gradations: absence, weak, medium, strong, and very strong (Fig. 9).

According to the assessment and zoning of the Kostanay region, weak anthropogenic degradation of soil cover is common in the steppes on chernozem soils composed of loams in the northern part of the study area. Hilly-wavy plains with temporary watercourse beds predominantly characterize these territories. Despite being home to significant settlements such as Kostanay and Rudnyi, the region demonstrates relatively high resistance to anthropogenic impacts, which have long experienced high anthropogenic pressure. All types of anthropogenic activities are represented here, and the land use structure is classified as intensive-extensive, with a predominant focus on the mining industry. However, natural factors contribute to the region's high resistance to these impacts.

The results indicate that the maximum values of the vegetation index (NDVI, GNDVI), which are widely used to quantify vegetation health and density, range from 0.6 to 0.9 for NDVI and from 0.6 to 0.9 for GNDVI in this region.

Most of the soil cover in the study area exhibits a medium degree of degradation, accounting for over 30% of the total area of the Kostanay region. These territories are primarily represented by moderately arid steppes on Chernozems and dry steppes on Kastanozems, including low-humus Kastanozems.



1980 2000 2023

Fig. 9. Zoning of the territory of Kostanay region by the degree of soil cover degradation under anthropogenic impacts

The land use structure in these areas is characterized as extensive-intensive, with a focus on agriculture and mining. The assessment results indicate average erosion values (NDVI) ranging from 0.5 to 0.7 and GNDVI values from 0.4 to 0.6, with waterlogging values (NDMI) ranging from 0.0 to 0.2.

Territories classified as severely degraded are mainly steppe landscapes featuring flat and rocky loamy stratified plains in the desert-steppe zone on Kastanozems. The primary economic activities in these areas include animal husbandry and transport. The evaluation results show high values for solonchakness (Tasseled Cap), ranging from 30,633 to 50,970, and erosion (NDVI) values from 0.2 to 0.5.

The category of very severe degradation is attributed to the desert zone, particularly in areas with settled deserts on Calcisols, represented by flat-wavy loamy stratified plains. These territories experience higher temperatures and lower precipitation levels. Although these areas are sparsely populated and experience minimal anthropogenic load, they are unstable to human influences due to the natural factors that shaped them. The assessment results indicate that the maximum values for solonchakness (Tasseled Cap) range from 30,633 to 50,970, while erodibility (NDVI) values fall between 0.0 and 0.2.

From 1993 to 2022, the Kostanay branch of the Republican State Enterprise “Scientific and Production Center for Land Cadastre” established a network of 134 permanent observation points, including both stationary and semi-stationary ecological sites. Observations on soil indicators revealed a widespread decrease in humus content across the region, with 2-3% reductions over 3–5 years. The analysis of soil indicator dynamics showed a decline in soil fertility, evidenced by the decrease in humus levels. This decline is attributed to irrational land use practices, insufficient application of organic and mineral fertilizers, and the progression of erosion processes. Additionally, all soil subzones exhibited decreases in total nitrogen and phosphorus reserves, further contributing to declining soil fertility (Report of the Kostanay Branch of the Republican State Enterprise “Scientific and Production Center for Land Cadastre”).

The high vulnerability of the soil cover in these territories is primarily due to the presence of highly dissected relief forms, such as plateau-like and hilly plateaus composed of effusive rock with weathering crust, as well as undulating and hilly upland plains. A significant factor that intensifies limiting and destructive processes is the high degree of disintegration of the region’s rocks, contributing to deflation and washout.

As illustrated in Fig. 8, the degradation of soil cover under anthropogenic impact increases from north to south, correlating with heightened economic development activities in the Kostanay region. The steppes on chernozem soils in the northern part of the study area exhibit high resistance to anthropogenic impacts influenced by physiographic conditions. However, increasing anthropogenic activity inevitably degrades soil cover in these densely populated and industrially developed territories.

Soil stability should be understood as the ability of soil to maintain its state (composition, structure, spatial position) over time, despite relatively minor changes or fluctuations in soil formation factors, as well as its ability to restore its primary qualitative characteristics after disturbances. Our analysis of studies conducted over various years on soil stability in the Kostanay region (Baisholanov 2017; Evstifeev 1966; Tyuluova, Golubeva 2018) indicates that chernozems exhibit the highest degree of functional stability. Indicators such as horizon thickness, pH, cation absorption capacity, humus content, and mechanical composition are considered in assessing soil stability. Increasing soil pollution reduces the soil’s ability to self-clean and self-regulate. Therefore, protecting soil and ensuring its rational use are among the most critical tasks in natural resource management.

4. Conclusions

The proposed method for assessing the dynamics of soil cover under anthropogenic impact allows for the differentiation and evaluation of individual soil indicators primarily affected by unsustainable human activities. To map each indicator—namely, soil waterlogging, soil salinity, solonchakness, and soil erosion—indices with the highest reliability were determined, supported by verification against field survey data.

Verification of the obtained indices using data from the remaining 20% of field points confirmed the results with a reliability range of 85% to 91%. This finding validates the appropriateness of the selected methods and techniques, particularly the choice of field methods and using vegetation and non-vegetation indices for assessing the selected indicators.

The study of soil cover degradation in the Kostanay region under anthropogenic influence revealed territories with varying degrees of degradation, ranging from weak to very strong. It was found that soil exhibiting high degrees of degradation is primarily located in the desert zone on Calcisols in the southern part of the region. In addition to anthropogenic impacts, the degradation of these soils is influenced by natural climatic conditions that affect soil cover pollution processes. Conversely, soils with a low degree of degradation are associated with the steppe zone, characterized by a high level of economic development and greater resistance to anthropogenic impacts.

In the northern part of the Kostanay region, steppes on Chernozems demonstrate high resistance to anthropogenic impacts, influenced by physiographic conditions. However, increasing anthropogenic activity is still leading to the degradation of soil cover in these areas.

The intensity of degradation processes, including waterlogging, salinity, solonchakness, and erosion, was assessed. It was established that the long-term conversion of soils to arable land has resulted in widespread development of degradation processes, as evidenced by the increasing areas of eroded, overwatered, saline, and solonchak soils.

Moving forward, the verified map of soil cover degradation, developed through satellite monitoring and field study results, will facilitate the forecasting of soil cover functioning under ongoing anthropogenic impacts.

Acknowledgments

This study was conducted within the framework of grant funding for young scientists on scientific and (or) scientific and technical projects for 2022-2024 by the Ministry of Science and Higher Education of the Republic of Kazakhstan (IRN №AP13067925).

Conflict of interest

The authors declare no conflict of interest. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. This research did not involve human or animal subjects.

Author Contributions

Zhanar Ozgeldinova – Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing). **Zhandos Mukayev** – Conceptualization, Data curation, Investigation, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing. **Luiza Mukaeva** – Investigation, Supervision, Validation, Writing – original draft, Writing – review & editing. **Altyn Zhanguzhina** – Supervision, Validation, Writing – original draft, Writing – review & editing. **Meruyert Ulykpanova** – Writing – original draft, Writing – review & editing.

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