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INNOVATIVE TECHNOLOGY FOR ASSESSING THE DEGRADATION OF THE EARTH BY SAND DESERTIFICATION OF SOILS WITH SPECIALIZED PROCESSING OF SPACE MATERIALS

ABSTRACT

This study provides an assessment of the process of sand landslide degradation of the Abay Region of the Republic of Kazakhstan and space materials (RS-Remote Sensing, GIS-Geographic Information Systems and machine learning data of the soilgrid platform, QGIS Trends). Using the technology of the Earth module and field research, the amount of landslide sand g/kg at a depth of 5 cm was determined and the SDG land degradation target, the land productivity indicator (productivity), the indicator of the impact assessment of the change in the type of surface cover (land cover), the indicator of the change in the carbon stock of soil organic matter (carbon velocity) were calculated in the machine learning module, which uses integrated research to monitor, map and quantify the threat of land degradation. The study was analyzed and obtained between 2015 and 2022 by interpreting data from machine learning images with visual, interactive interpretation. The data of dynamic reverse changes from Sandy and worn areas, in these two stages, were obtained by overlapping the database. The results of the study showed that in the proportion of years obtained, 3009.29 km^2 of newly degraded land was formed, and most of the newly degraded land is the area where sand landslides occur, as is known from the quantitative data of the study, it was found that the share of sand landslide degradation of the surveyed 272 410.4 km^2 area within 7 years is 4.56 % of the total area. By analyzing the results of the study, some constructive measures were proposed aimed at ecological protection of forest clusters in the North-West of Abay Region and planting new forest seedlings.

KEYWORDS: sustainable development goal, sandy degradation, landscape indices, sandy stream, land degradation neutrality

INTRODUCTION

In desert areas, the processes of soil formation occur very slowly, forming a high level of soil degradation and desertification. The degradation of nomadic sandy lands is a type of desertification characterized by soil erosion, mainly caused by excessive human activity in arid and semi-arid regions, including thinning of vegetation layer and forest clumps, etc. [*Mahata* et al., 2021]. This is the main process of land degradation in the Abai Region. The North-Western part of the Abay Region of Kazakhstan, like most of the lands of the southern regions of the arid and semi-arid region, is prone to land degradation problems. The large number of annual windy days in this region, especially in the parts of the Abay Region that were part of the former East Kazakhstan Region, is estimated at about 424.9 thous. ha, including in fields — 199.3 thous. ha [*Issanova* et al., 2020; *Sadenova*, 2022]. The main massifs of wind-eroded soils in the composition

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of agricultural land in the Almaty Region is about 5 mln tons ha, including in the fields — 64.8 thous. ha, in Atyrau — 3.1 mln ha, in the South Kazakhstan Region — 3.1 mln ha, in the Kyzylorda and Zhambyl Regions — about 3 mln ha in each, and in the Abay Region — 1.4 mln ha, including in the field — 445.7 thous. ha or 31 % of it [*Kabysheva* et al., 2020]. One of the main causes of land degradation in the Abay Region is their gradual migration with the formation of sand dunes due to grazing, improper use of vegetation and forest clumps. Land degradation is caused by many reasons, and it occurs at different rates in different climates [*Malinovskaya* et al., 2020]. Sandstorms have a direct negative impact on infrastructure, such as highways, railways, irrigation canals, and agricultural soils, soil erosion, as well as on the environment, at the same time human health [*Abedzhanova*, 2023]. Land degradation has become the main reason for the destruction of vegetation, especially livestock agricultural land of the Abay Region. There is also a major problem with sandblasting of urban areas, which leads to the destruction of forage lands and pastures [*Mirzabaev* et al., 2016]. Unsuccessful experiments to combat sand avalanches and the consequences of repeated fires in Forest clusters in wind gusts and recent drought in the territory have led to further deterioration of the soil and vegetation. According to the summary analysis report on the state and use of land of the Republic of Kazakhstan in 2019, it showed that 5–10 % of the total land of this region is dry and semi-dry zones, and 13.3 % of the land is prone to wind erosion of the soil, especially in the northern part of the Abay Region bordering the Pavlodar Region, where land degradation has become a serious problem.

This article explores three main areas:

1) determination of soil degradation data at a depth of 5 cm with SoilGrid-statistical models at a resolution of 250 m;
2) propose a methodology for determining changes in the degradation of sandy lands in the north of Abay Region;
3) classification of territories by combining indicators for determining land degradation at all aggregate levels.

Also, the work presents approaches to a special module for assessing the degradation of sandy land by processing data from remote sensing of the Earth and the course of work on determining changes in the surface [*Apshikur*, 2023; *Toguzova*, 2022]. After a separate vector mapping of the districts of Abay Region, subsequently allocated by the East Kazakhstan Region, a request is made for a machine learning module for this type. Next, the results on the change in the environment with color and digital summary data are presented. The study further presents results on environmental change with color and quantitative aggregate data. In addition, various indicators and quantitative data of the level of degradation of sandy land are obtained, and the results for determining changes are mapped and compared by area [*Kulenova* et al., 2022]. These comparisons provide for the possibility of determining the magnitude of deviations from statistical data in determining changes and monitoring large-scale land degradation in real time. If the indicators obtained by our methods of detecting changes differ from previous studies, then it is necessary to identify changes at the aggregate level by other methods of detecting and consider a common solution in monitoring the degradation of the earth cover by sand avalanches from satellite materials [*Rakhymberdina* et al., 2022]. Finally, it is proposed to use the results of this study to simplify some methodological problems in the science of Earth change [*Rakhymberdina* et al., 2022].

The focus of the study is not on aspects of modeling the degradation of the main sandy lands, but on the development of an empirical methodology for determining changes in the degradation of sandy lands in the studied land [*Sadenova* et al., 2021]. This study did not develop simulation procedures to assess land degradation. The proposed method for determining the decline in land productivity in research is considered to be a universal definition of degradation and should be applied in both global and local contexts. Assessment of the positive and negative amount of vegetation cover and changes in the proportion of move sand migration allows you to measure different amounts of sand degradation. To account for the full range of vegetation cover and changes in the share of displacement of nomadic sand, it is necessary to obtain a standardized amount of changes in annual vegetation and soil indices [*Rakhymberdina* et al., 2021]. This is necessary in order to quantitatively check the normal size of the vegetation cover in the North of the Abay Region and the level of the share of changes in migration sand, so that we can determine significant land degradation over a certain period of time.

The aim of this study is to determine the spatial distribution and size of newly increased degraded land and restored degraded land based on Earth remote sensing data and GIS to monitor and analyze dynamic changes in land degradation from 2015 to 2022. Also, the varieties of degraded land are studied and the causes of dynamic changes in land degradation are analyzed in order to improve the method of inhibition of land degradation and further analysis of sandy land in the future, to obtain useful scientific references and conclusions.

RESEARCH MATERIALS AND METHODS

Abay Region is located in the East of Kazakhstan at 50°24′40″ North latitude, 80°13′39″ East longitude, with a total area of 185.500 km^2. The region was part of the East Kazakhstan Region (about 6.8 % of its total territory [*Oitseva* et al., 2022]) until August 2022 (Fig. 1). To study the determination of the risk of land degradation, the territory of the Abay Region was chosen as the research area.

Fig. 1. Geographical location of the study area

The study used Landsat 8–9 OLI/TIRS C2 L2 satellite images from 2020, 2021 and 2022, downloaded from open access materials that are part of path/row147/025[1]. They have a L2 level

[1] Web resource: https://earthexplorer.usgs.gov (accessed 05.17.2024)

of correction and were georeferenced at Universal Transverse Mercator (UTM), datum WGS 84, zone 44 N. The spatial resolution of the multi-spectral and thermal bands 10–11 after resampling is 30 m.

The Trends.Earth plugin of the QGIS processing platform uses the following Landsat 8–9 OLI/TIRS satellite bands to analyze the state of the Earth and assess degradation:

- Band 2 (Blue, 0.452–0.512 µm);
- Band 3 (Green, 0.533–0.590 µm);
- Band 4 (Red, 0.636–0.673 µm);
- Band 5 (Near Infrared, NIR, 0.851–0.879 µm);
- Band 6 (Shortwave Infrared 1, SWIR 1, 1.566–1.651 µm);
- Band 7 (Shortwave Infrared 2, SWIR 2, 2.107–2.294 µm);
- Band 8 (Panchromatic, 0.503–0.676 µm);
- Band 9 (Cirrus, 1.363–1.384 µm).

And these bands for the study of thermal stress and drought by measuring the temperature of the Earth's surface:

- Band 10 (Thermal Infrared 1, TIRS 1, 10.60–11.19 µm);
- Band 11 (Thermal Infrared 2, TIRS 2, 11.50–12.51 µm).

The combination of bands is automatically generated in the algorithm of the Trends.Earth application to determine the target index.

Before the visual interpretation of the images, in order to obtain a general situation, the data from research were analyzed based on projects already carried out in this area. That is, a map of soil erosion in the region and maps of vegetation type were collected. Fieldwork analysis conducted in parallel with the satellite data processing in the study area includes soil sampling and vegetation cover measurements. The sampling images were selected to create a set of dominant surface objects located using topographic maps of scale 1: 250 000 and GPS. A system of indicators for the interpretation of degraded land and indices for the assessment of degraded land was created as a reference based on previous studies (Table 1).

Table 1. Annual precipitation in Abay region

Month	**Distribution of precipitation per day by month**	**The average amount of precipitation per day, mm**
January	5 %	0.44
February	6 %	0.49
March	6 %	0.50
April	7 %	0.58
May	9 %	0.79
June	12 %	1.02
July	15 %	1.31
August	9 %	0.81
September	7 %	0.61
October	9 %	0.74
November	9 %	0.80
December	7 %	0.60

Due to the fact that the latitude zone of the territory of the East Kazakhstan region is observed quite systematically, the soil cover is diverse. Mainly from North to South, it is zoned with dark brown (dry steppe), light brown (semi-desert) and brown soils [*Plichko* et al., 2020]. Two main natural features of the study area are considered to be the main factor of sand landslides, one of which is the flat relief of the northern part of the region, the mainly unidirectional wind rose and the non-stop blow of the wind force in the dry season, and the other is the reduction of forest clusters, which are natural protection for certain reasons (anthropogenic, fire, drought, etc.), causing sand landslides on the sandy plain in the northern part of the region.

The surface dimensions of the mechanical fraction of vertical flat soils extending north of Semey, according to the results of the study, are coarse sands 1.0–0.5 mm, fine sands 0.25–0.05 mm, medium sands 0.01 sludge ≤ 0.001 mm, while the mineralogical composition is quartz rocks, feldspar, mica, clay minerals [*Kabysheva* et al., 2020; *Petrova* et al., 2022]. The annual rainfall is statistically very low for sandy areas during the months of strong winds (Table 1).

The authors used data such as ARD Landsat U.S. Analysis Ready Data of the US Geological Survey, scientific products with Landsat Level-2 and Level-3 data as research materials, including high-level data that allow better documentation of changes in the Earth's environment. For their processing, the QGIS software package and the Trends.Earth statistical analysis module were used.

Research methods

In this paper, a system of indicators for the interpretation of degraded Earth and indices for assessing the degradation of Earth are presented comparative quantitative data for processing space materials in a special program. In the course of the study, the analysis of climatic changes in the region and natural disasters that occurred in the local environment (fire, drought, wind power, etc.) was first carried out [*Zakonnova* et al., 2021]. In accordance with the objectives of the study in the GIS environment working with Earth remote sensing materials, one of the innovative technologies was used — the method of analyzing Earth degradation by indicators with the Trends.Earth statistical module of the QGIS program.

The operation of this tool is based on the analysis of a large number of satellite data and materials presented in open international sources, which, when using the module algorithm, are converted into information on four indicators for assessing the neutral balance of Earth degradation. Assessment of the neutral balance of land degradation (SDG, Sustainable Development Goals) in the calculation of the indicator of the research area was carried out in two stages. The degree indicator of land degradation, the SDG indicator, is expressed by area share (or calculated by generalizing three independent indicators). Its components (subindicators) were analyzed [*Sims* et al., 2021]:

1) the indicator of land productivity (Productivity);
2) an indicator for assessing the consequences of a change in the type of cover of the Earth's surface (Land cover);
3) an indicator for assessing changes in carbon stocks of soil organic matter (Soil carbon).

The conducted research method is intensively used in assessing desertification of land cover, and is effective in dealing with land degradation. For example, to analyze the consequences of various anthropogenic impacts or to develop a large-scale plan that will help in restoring their fertility.

The accuracy assessment for each image was performed by the authors on the basis of a secondary reading set created by uniform random sampling for each degree of desertification risk. A set of comparative calculations of Landsat images for selected years was developed in one area. The reading sets for each image were compared with the same places on the reference images, which are performed using the accuracy assessment module of the Trend.Earth plugin. If the machine learning set correctly determines the degree of desertification risk, the classification was considered good, otherwise the reading set was assigned to the class corresponding to the reference image. The authors managed to determine the boundaries of the territories by the levels of degradation of the studied territory, as well as to determine the area divided into classes.

Satellite data processing

QGIS Trends.Earth modules are available for processing satellite images for Earth use analysis and environmental protection tools. These modules use machine learning and time series analysis techniques to detect terrestrial landscape changes based on satellite data. The QGIS Trends.Earth modules were linked to Landsat, Sentinel and other relevant satellite data with coordinates of the study area for a given period of time to utilize their functionality in the field of satellite imagery processing. The received data can be accessed automatically. After that, data analysis is performed (based on the results of processing space images) by several machine learning software commands with a secondary polynomial model of Map Products [*Trifonova* et al., 2021].

RESEARCH RESULTS AND DISCUSSION

According to the calculations obtained using the Trends.Earth module, the dynamics of land cover, soil cover of the studied territories in the East Kazakhstan Region is characterized by the predominance of agricultural territories. And in the part of the Abay Region, which was part of this region until 2022, it is noted that the terrain is flat and uniform sandy soil. In addition, carbon stock information was obtained for the top 5 cm soil layer using SoilGrid (a statistical model of the global soil information database) at a resolution of 250 m [*Hengl* et al., 2017]. The used "SoilGrid" is a system for automatic mapping of soils and their properties based on statistical models and machine learning algorithms. Indicators of the study area on a layer of sand avalanches of 0–5 cm were obtained by machine learning of the "SoilGrid" platform for the Abay Region (Fig. 2).

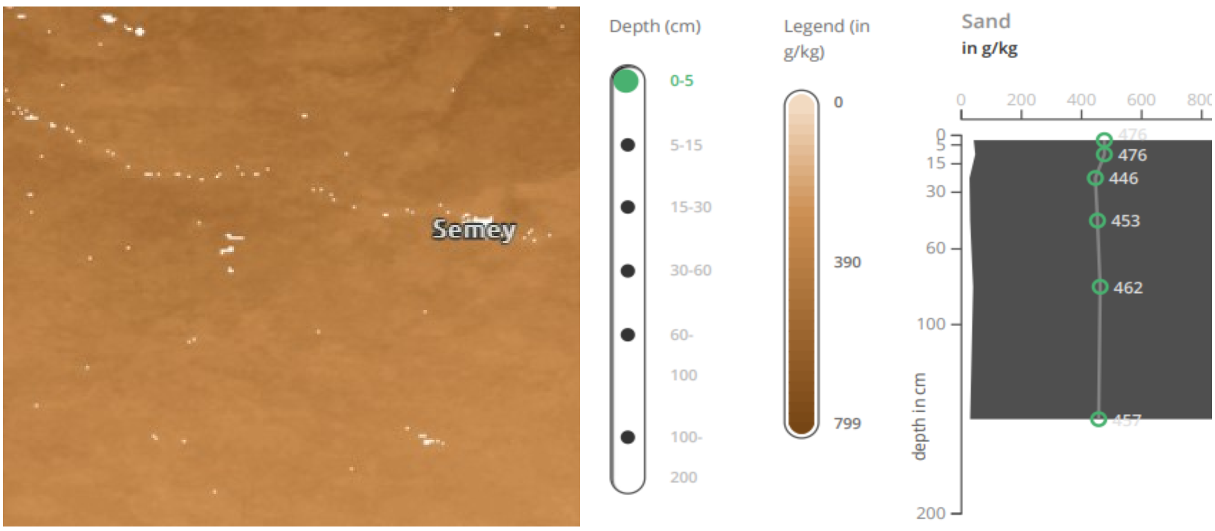

Fig. 2. Depth indicator of the sandy content of the soil of the study area by soilgrid g/kg

Quantitative data from the analysis (Table 2) showed that the green cover reduction index increases with an intensity of −0.13 % in the 7 years taken in the study.

Table 2. Land cover change by cover class

Land cover class	Baseline area (km^2)	Target area (km^2)	Change in area (km^2)	Change in area (percent)
Tree-covered areas	26 693.84	27 152.38	458.54	1.72 %
Grasslands	206 387.88	206 128.53	−259.35	−0.13 %
Croplands	32 306.30	34 924.69	2 618.39	8.10 %
Wetlands	916.05	949.01	32.96	3.60 %
Artificial areas	120.78	231.61	110.82	91.75 %
Other lands	6 033.56	3 024.30	−3 009.26	−49.88 %
Water bodies	7 417.83	7 465.73	47.90	0.65 %
Total:	**279 876.24**	**279 876.24**	**0.00**	

Using the Trends.Earth computing module of the QGIS program, as the result of machine learning by the method of estimating the dynamics of Earth degradation (Fig. 3), we can see that there is a significant degradation of the earth by a sand landslide in a flat valley in the western part of the Abay region (purple colors). The fertile territories are mainly agricultural lands with mountainous territories in the east part of the East Kazakhstan Region and irrigated meadow lands (green colors) of the territory of the Kalbatau district administration. In the southern part there are stable soil areas prevailing on field pastures (orange colors), and Rocky Mountains without vegetation cover in the territory of Ridder in the East Kazakhstan Region of the study area on the border with Russia shows a high level of degradation indicator (purple colors). The territory of the Abay region, where the study was conducted, together with the territories which was part of East Kazakhstan, the largest area of eroded soil in comparison with the total land area of the valleys is 424.9 thous. ha, including the land area degraded by sand landslides, accounts for 4.56 % of the total land area (Table 3).

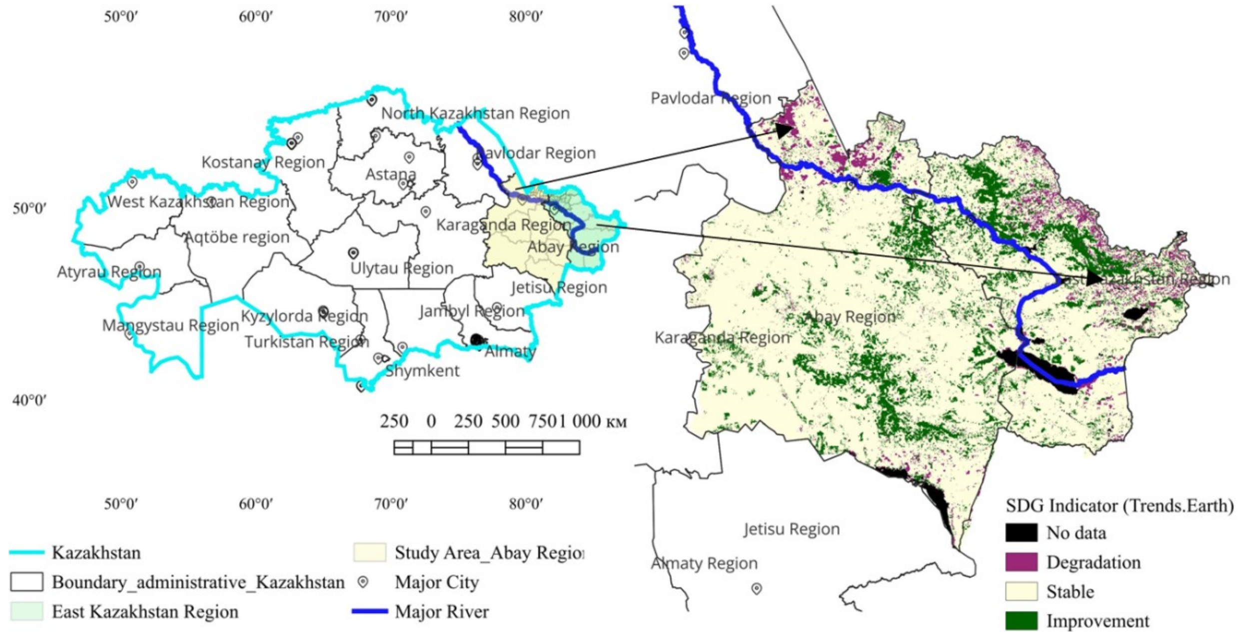

Fig. 3. Assessment of the degradation balance of the land of the research area (SDG, Sustainable Development Goals indicator)

Table 3. Summary of SDG Sustainable Development Goals Indicator

Units of measurement	Area (km^2)	Percent of total land area
Total land area:	272 410.4	100.00 %
Land area, improved:	37 989.1	13.95 %
Land area, stable:	220 702.8	81.02 %
Land area, degraded:	12 434.4	4.56 %
Land area, with no data:	1 284.0	0.47 %

In the analysis of the result, the desertification of the soil cover by wind with a sandy coating is indicated on the map in purple, and the improved areas are indicated in green. The Earth has shown that changes in soil organic carbon reserves occur due to changes in land cover.

The most intense indicator for the studied region is the presence of the wear indicator in one area in the region, that is, the main share of the total wear of 4.56 % corresponds to the sand landslide zone.

"Negative" changes in the ground cover lead to a decrease in organic carbon in the soil and vice versa [*Muter* et al., 2024]. Such a research approach may not provide accurate data for many territories in the south of Kazakhstan, since changes in the carbon content in the soil often occur without changes in the soil cover. This situation is typical of arable lands, where dehumidification occurs by plowing the territory and eroding the upper fertile layer. Positive dynamics can be achieved by the presence of, for example, rational land use and mixed seeding in the composition of one class of lands. For an accurate description of the indicator, the determination of the organic carbon content of the soil should be calculated by taking into account such indicators as relief classes and turnover of arable land. This module indicates that the units of measurement of the imported raster layer are metric tons of organic carbon per hectare [*Aubakirova* et al., 2020]. The result of the analysis with machine learning is that over the years calculated from the initial level of organic carbon reserves of the soil in the study area, the annual percentage change is 0.38 %, and this deviates somewhat from the well-known standard (Table 4).

When assessing land degradation using the Trends.Earth module, along with the SDG indicator of the study area, the following indicators: volume of land with increased productivity by land cover transition types, volume of land with stable productivity, volume of land with decreased productivity, volume of land with moderate decline in productivity, volume of land with decreased productivity in the absence of data on land cover transition types without taking into account the composition of soils, such as land volume indicators, are presented in a color scheme (Fig. 4) and quantitatively (Table 6).

Verification of the accuracy of the data obtained on changes in the ground cover was performed by simultaneously comparing field observations with space images. The data obtained by the machine learning method in the Trends.Earth module correlates with space images in a relatively small volume (at the level of the region and individual areas) and reflects the general nature of the dynamics of the ground cover in the territory of the objects under study. The data obtained by the Trends.Earth module, the dynamics of land productivity and, according to our calculations, a large share of the area of degradation from sand landslides, with changes in vegetation cover, depending on the classes of land cover of the research area, is clearly visible in the northwestern part of the territory of the Abay Region, which was formerly part of the territory of the East Kazakhstan Region from 2015 to 2022.

Table 4. Changes in soil organic carbon from the initial level over the years of study

Land cover class	Baseline soil organic carbon (tons / ha)	Target soil organic carbon (tons / ha)	Baseline area (km^2)	Target area (km^2)	Baseline soil organic carbon (tons)	Target soil organic carbon (tons)	Change in soil organic carbon (tons)	Change in soil organic carbon (percent)
Tree-covered areas	169.39	169.36	26 654.28	27 134.67	451 502 822.50	459 554 480.15	8 051 657.65	1.78 %
Grasslands	130.04	129.81	206 347.27	206 106.35	2 683 260 933.81	2 675 536 927.30	−7 724 006.51	−0.29 %
Croplands	142.93	143.06	32 299.28	34 916.99	461 645 068.67	499 537 566.37	37 892 497.70	8.21 %
Wetlands	187.85	187.85	908.15	937.60	17 059 642.89	17 612 949.17	553 306.27	3.24 %
Artificial areas	113.14	113.14	120.78	231.40	1 366 521.63	2 618 077.51	1 251 555.88	91.59 %
Other lands	107.95	129.42	6 019.22	3 021.97	64 980 359.45	39 109 620.38	−25 870 739.07	−39.81 %
Total:			**272 348.98**	**272 348.98**	**3 679 815 348.95**	**3 693 969 620.88**	**14 154 271.93**	

Table 5. Area of land with declining productivity by type of land cover transition

Land cover type in baseline year (km^2)	Land cover type in target year 2015 to 2022							
	Tree-covered areas	Grasslands	Croplands	Wetlands	Artificial areas	Other lands	Water bodies	Total:
Tree-covered areas	295.71	4.75	0.16	0.00	0.00	0.32	1.64	**302.58**
Grasslands	4.77	1 179.33	6.85	0.00	0.08	2.32	0.21	**1 193.57**
Croplands	1.34	1.28	107.51	0.00	0.00	0.00	0.17	**110.29**
Wetlands	0.00	0.00	0.00	4.72	0.00	0.00	0.00	**4.72**
Artificial areas	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Other lands	0.04	4.99	0.00	0.00	0.00	209.91	0.00	**214.94**
Water bodies	0.00	1.03	0.00	0.00	0.00	0.29	44.00	**45.31**
Total:	**301.85**	**1 191.38**	**114.52**	**4.72**	**0.08**	**212.84**	**46.02**	**1 871.41**

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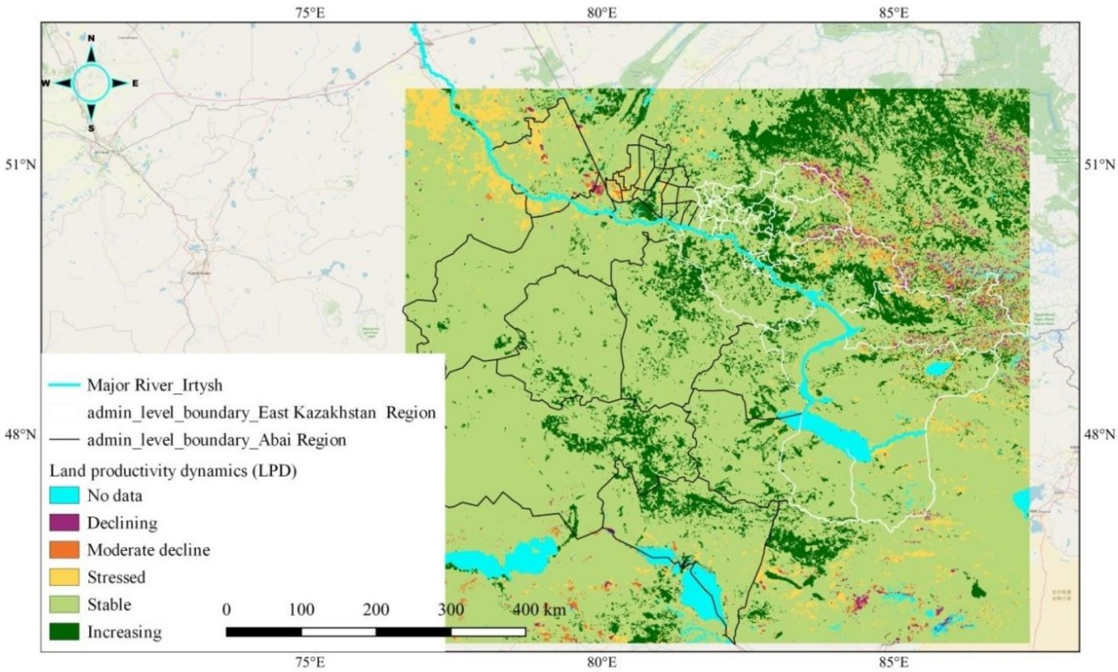

Fig. 4. Productivity dynamics of the soil of the research area

Table 6. Summary of change in productivity

Units of measure	Area (km²)	Percent of total land area
Total land area:	272 410.4	100.00 %
Land area with improved productivity:	33 749.1	12.39 %
Land area with stable productivity:	226 855.0	83.28 %
Land area with degraded productivity:	10 735.9	3.94 %
Land area with no data for productivity:	1 070.4	0.39 %

In the process of comparing Trends.Earth's cartographic data, a number of patterns were identified, combined with space images, resources, and literary data. Thus, in almost all regions there is a fairly high decrease in productivity, especially in areas with sand avalanches, where erosion processes are actively developing, on the border of the Pavlodar Region with the Beskaragay district and the western outskirts of the city of Semey in the Abay Region (Fig. 4).

As can be seen from the results obtained from machine learning to select the performance of the ground cover by classes, the performance is distributed by complex parameters for these areas. With the unevenness of the territories by these parameters in comparison with the total area of the studied lands and the total area of the Abay Region taken for the study, intensive degradation of the territory can be observed (Table 5).

When analyzing the volumes of lands with a decrease in productivity by the type of transition of soil and vegetation cover, it was found that the structure of green lands on the plains of steppe pastures is less susceptible to the influence of anthropogenic factors. There is an increase in the area of steppe lands, wetlands and water sources, as well as a large area of lands of another class, which are the main cause of sand slides; it is 214.94 km^2.

The considered QGIS module, based on the volumetric land index determined with less time than the traditional determination of neutral equilibrium indicators of land degradation, allows the analysis of land reclamation potential (ratio of improved and degraded territories) to allocate the studied areas differently. As a result of the study, it is possible to propose to make engineering decisions with a detailed study of degraded areas into separate contours, to stop the reverse process in them by planting forests, long-term preservation of spring moisture in the ground, the creation of bulk land structures that form snowdrifts in the winter period, resulting in its compaction, etc.

CONCLUSIONS

The share of degraded lands from the total area of the territory in the studied regions of East Kazakhstan and Abay Regions is 272410.4 km^2; the share of lands with potentially dangerous sand avalanches is 12434.4 km^2.

A research on the example of the East Kazakhstan Region use a module Trends.Earth that can provide sufficient information spatial and quantitative data on the state of the Earth at the regional level to assess the neutral balance of land degradation proposed by the United Nations Convention to Combat Desertification (UNCCD). With the help of it, from the data of remote sensing of the Earth, the dynamics of the main global indicators were shown and the values of the indicator of the share of degraded lands were calculated. Trends defined by the method of using the Trends.Earth module should only be considered as an additional source of information and should not be considered to be used to describe current processes as "absolute" data. In the indicators for assessing the neutral balance of land degradation, a number of obvious processes of land degradation are not fully covered. For example, the increase in gorges or the lack of use of degraded land, the effect of wind power on sand landslides, the lack of clarification of meadow and shrubland areas, etc. It considers the degradation of the Earth's cover along with sand landslides, as well as the impact of other natural or anthropogenic factors. The main reasons for the increase in the area and volume of sand landslides in one area are the destruction of forests in recent years for various reasons, and a decrease in the amount of precipitation during windy seasons. It was found that differentiation of these processes without involving high-resolution images and additional ground data does not provide complete information. Based on the calculated indicator of the share of degraded land from the total area of the region, the possibility of determining the indicators of individual sand landslide territories under study, if necessary, was determined. The considered territories require measures to protect the soil and prevent sand landslide erosion. It is proposed to regularly monitor the degree of soil degradation with the help of remote sensing space images and carry out verification of the obtained data at each stage of restoration work. In general, the proposed approach makes it possible to identify the root cause of the degradation of the Earth, although large-scale detailed research requires the development of complex algorithms using space images and high-resolution data. For a more accurate calculation, it is necessary to further improve the method of using the module used by the authors and adapt it for use in other regions of Kazakhstan, including on the basis of data on the spatial distribution and dynamics of soil organic carbon reserves.

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