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Evaluating Land Degradation in East Kazakhstan Using NDVI and Landsat Data

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ABSTRACT

The article discusses the use of the Normalized Difference Vegetation Index (NDVI) to assess land degradation in the East Kazakhstan region. The study aims to evaluate changes in the state of vegetation, utilize the NDVI as a tool for monitoring ecosystems, and provide evidence-based recommendations for the development of sustainable land management strategies. The authors provide a comparison of NDVI values, which reflect the health and density of vegetation, and analyze their correlation with the factors of land degradation. The study analyzed Landsat satellite data from 1993 to 2023, revealing a significant decline in NDVI values across 40% of the southern part of the East Kazakhstan region, indicating severe land degradation. In contrast, 20% of the northern areas showed stable or slightly improved vegetation health, with NDVI values remaining above 0.5, indicating healthier vegetation. As a result of satellite images processing, the authors identify zones with varying degrees of degradation risk, which can be used as a basis for measures to restore and preserve vegetation cover. The study highlights the need to account for various factors, including climate change and anthropogenic impacts, and offers a comprehensive approach to analyzing land degradation. The study concludes that land degradation in the East Kazakhstan region is accelerating, particularly in the southern areas, primarily due to a combination of climate change and unsustainable land use practices. The findings underscore the need for targeted ecological restoration efforts and the implementation of sustainable land management practices. These results can guide policymakers in developing effective environmental policies aimed at preserving the region's ecological integrity and ensuring long-term agricultural productivity.

1. INTRODUCTION

Land degradation in East Kazakhstan has emerged as a critical environmental issue, threatening the region's agricultural productivity and ecological stability [1]. The deterioration of soil quality and fertility in this region is exacerbated by both natural factors, such as erosion and salinization, and anthropogenic factors, including intensive agricultural practices and improper water management. Despite global awareness of land degradation issues, there is a pressing need to understand the specific dynamics in East Kazakhstan, where unique geographic and climatic conditions interact with human activities [2, 3]. The causes of degradation are diverse and include both natural factors, such as erosion and salinization, and anthropogenic factors, including intensive agricultural land use, improper water management, and climate change.

Soil degradation in East Kazakhstan has several negative consequences for its ecosystem, economy, and social sphere. Reduced soil fertility leads to a decrease in crop yields, which threatens food security and worsens the economic situation of farms [4]. Biodiversity loss and landscape changes have long-term effects on natural ecosystems, reducing their resilience to environmental change.

Given these challenges, the relevance of the study of ways to prevent and overcome soil degradation in East Kazakhstan is undeniable. Examination of this topic facilitates not only the improvement of the region's environmental situation, but also the development of sustainable agriculture, the preservation of natural resources, and the improvement of the population's quality of life [5].

The paper examines the use of NDVI to determine land degradation in East Kazakhstan suffering significant impact of anthropogenic and natural factors that lead to soil quality and fertility deterioration. The NDVI is a valuable tool for developing measures for the restoration and rational use of soils [6].

The advantage of the NDVI in the monitoring and analysis of vegetation cover and land degradation is that it provides a quantitative assessment of the state of vegetation while minimizing the subjective factors associated with visual assessment [7].

Earth remote sensing (ERS), used in the determination of the NDVI, is a powerful instrument for monitoring environmental changes, as it enables analysis based on a rich time sequence of data. The use of a series of historical data provides a unique opportunity to track the dynamics of ecosystem processes, including soil degradation [8]. This approach contributes to a more precise understanding of the current conditions and offers a foundation to forecast future trends [9].

The satellite imagery used to calculate the NDVI covers vast areas, allowing analysis on scales ranging from small plots to entire regions and continents. The data is regularly updated and is available to researchers and specialists. This makes the NDVI a highly valuable tool for prompt monitoring and timely decision-making. The accumulated archives of satellite data allow analyzing the dynamics of changes in vegetation and land cover over extended periods of time, which is important in studying land degradation processes and assessing the effectiveness of measures taken.

These advantages make the NDVI a strong instrument for assessing and monitoring vegetation health and land degradation, providing the information needed to effectively manage natural resources and develop conservation and restoration strategies [10].

As part of our literature review on NDVI application for land degradation analysis, we conducted a thorough search of scientific papers and studies. Kazakh researchers tend to focus on the use of remote sensing data to monitor the condition of steppes and agricultural lands, which is an essential part of environmental assessment and land management [11-13].

International studies significantly contribute to the understanding of global land degradation trends and can serve as a useful source for comparative analysis with Kazakhstan. Researchers from around the world use the NDVI to assess changes in land cover caused by various factors, including climate change, human activities, and natural disasters [14, 15].

The papers prepared as part of Kazakh research projects often emphasize the importance of adapting to changing environmental conditions and developing sustainable agricultural methods. This research contributes to the greater effectiveness of agricultural production and plays a key part in the preservation of ecosystems and biodiversity.

Given the urgency of land degradation issues in the East Kazakhstan region, this study seeks to address the following research questions: (1) How have NDVI values changed across different regions of East Kazakhstan from 1993 to 2023? (2) What are the primary drivers of observed land degradation in this region? (3) Can NDVI data be effectively used to identify high-risk areas and guide land management strategies?

The study aims to outline the key problems associated with soil degradation in East Kazakhstan, analyze the existing methods of combating this problem, and propose effective solutions adapted to local conditions.

This study builds on existing research by applying NDVI analysis to this region, offering insights that are crucial for developing targeted land management strategies.

2. METHODS

The main material in the present study was images obtained through ERS focusing on the East Kazakhstan region. The images selected for analysis covered a 30-year period with a 10-year interval (1993, 2003, 2013, and 2023). According to NDVI analysis recommendations [16], for the most accurate study, the images need to be cloud-free and taken in the period from May to August. Therefore, strict filtering criteria were applied when downloading images to select only those that met the specified parameters. The time range was limited to the period from May 1 to August 31 for the selected years to record the state of vegetation cover during the period of active plant growth [17]. This allowed for a comprehensive analysis of its changes, which is important for agronomic and environmental studies.

The Earth Explorer service belonging to the United States Geological Survey (USGS) [18] allowed us to indicate the boundaries of East Kazakhstan as per the data of the Statistical Committee of the Republic of Kazakhstan. The boundaries of East Kazakhstan are highlighted in Figure 1.

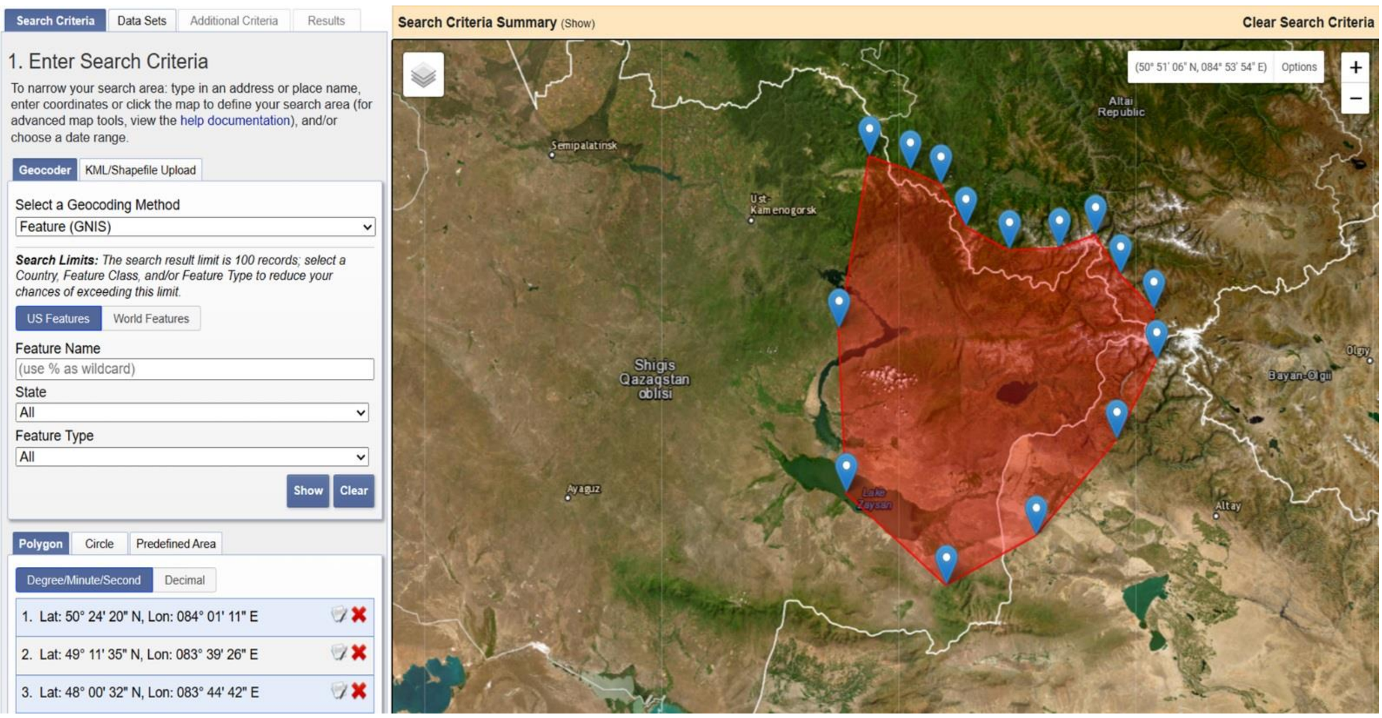

Figure 1. Earth Explorer window with the borders of the East Kazakhstan region marked [18]

The analysis was conducted with the latest methodologies and analysis tools and the most complete and up-to-date information available for the territory under consideration. The research employed geographic information system (GIS) technologies and ERS data processing methods. The developed ERS maps can be used in the design and reconstruction of agricultural facilities considering the national urban planning policy and long-term strategic interests of the country's development in the new conditions [19]. A normative document on construction is recommended to be developed based on these maps [20].

The images used in this study were acquired using the Earth Explorer service (Figure 2) and contained information in the visible red and near-infrared bands, which is crucial for calculating the NDVI.

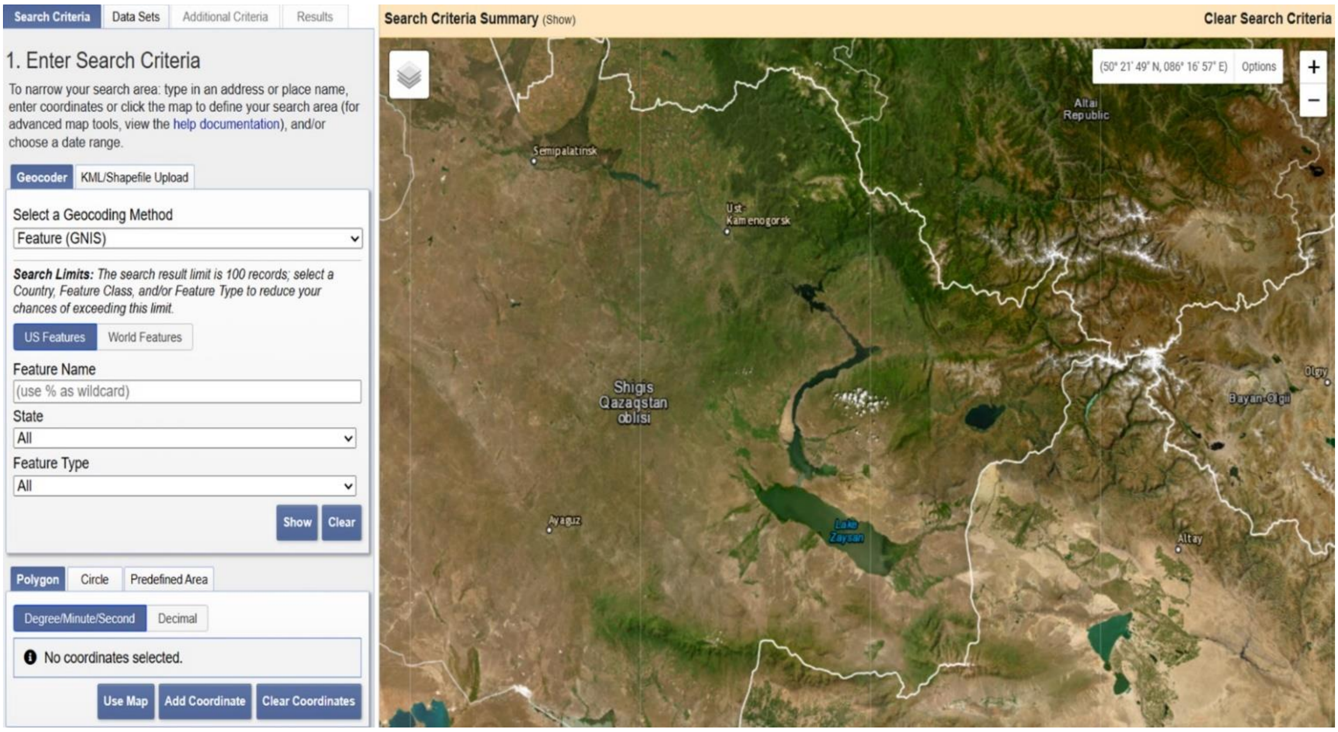

Figure 2. Earth Explorer window [19]

The years 1993, 2003, 2013, and 2023 were selected for this study to provide a consistent 10-year interval, allowing for the analysis of long-term trends in vegetation cover and land degradation.

USGS Earth Explorer provides access to data from various satellite missions, including Landsat satellites, each with its unique characteristics and resolution. Landsat 4-5 satellites for 1993 images, Landsat 7 for 2003 and 2013 images, and Landsat 8-9 for 2023 images reflect the evolution of technology and the improvement of imagery quality [21]. These satellites are equipped with different sensors capable of capturing images in different spectral channels needed for analysis. Before analysis, the Landsat images underwent several preprocessing steps to ensure accuracy and consistency across the dataset. First, the images were subjected to atmospheric corrections using the dark object subtraction (DOS) method to minimize the effects of atmospheric scattering and absorption.

The Landsat satellite series plays a fundamental role in the long-term monitoring of the Earth's surface, providing valuable data for numerous environmental and land use studies. For decades, Landsat satellites have provided consistent data growing in detail and accuracy with each new generation. Improvements in image quality, increased resolution, and a broader spectral range have given researchers the power to analyze Earth processes and changes in greater depth.

Of particular interest in this study were the images acquired by Landsat 7 ETM+ and Landsat 8 OLI/TIRS satellites (Figure 3), which offer images at resolutions up to 15 m for panchromatic and up to 30 m for multispectral channels [22]. These data were chosen due to their ability for high precision thermal imaging and improved spectral characteristics, which allowed for more refined NDVI analysis.

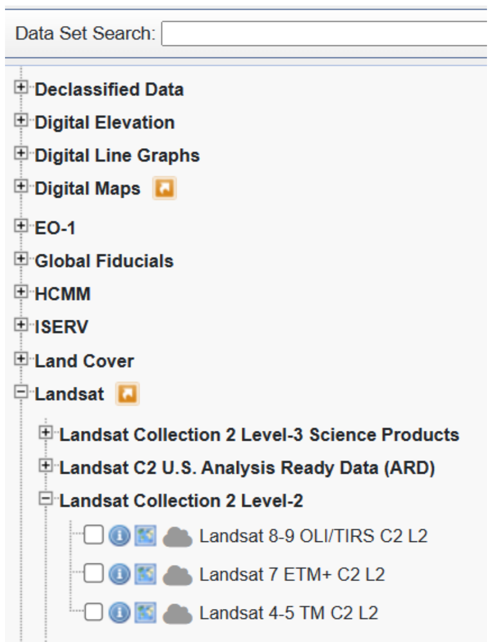

Figure 3. List of data set options on Earth Explorer [18]

In satellite imagery and ERS, a band, or spectral channel, refers to a specific range of wavelengths on the electromagnetic spectrum to which a satellite sensor can respond [23]. Each spectral channel is designed to collect data on specific characteristics of the Earth's surface, such as vegetation, water, soils and their condition, clouds, and other objects or phenomena. Different spectral channels can be used to calculate various indices, including the NDVI, to assess vegetation health, soil moisture, and water availability.

The 1993 images were obtained by creating a mosaic of images from Landsat 4 and 5 satellites using red and near-infrared spectral data. Landsat 4 was launched in 1982 and operated until 1993, while Landsat 5 operated from 1984 to 2013 [24]. Both satellites were equipped with Multispectral Scanners (MSS) and Thematic Mapper (TM) sensors, which allowed collecting data in several spectral bands, including both visible and infrared.

Compared to the images captured on Landsat 4-5, Landsat 7 is equipped with the Enhanced Thematic Mapper Plus (ETM+) instrument, which is an improvement on the previous generation scanner. ETM+ can collect images in seven spectral bands, including the panchromatic band, which provides higher spatial resolution images. The satellite has a special high-resolution data mode (15 meters in the panchromatic band) [25].

Table 1 shows the main spectral channels (bands) for Landsat 7 (ETM+ sensor), Landsat 8 (OLI and TIRS sensors), and Landsat 9 (OLI-2 and TIRS-2 sensors) along with their wavelength ranges and purposes.

Table 1. Channels used in space images [23]

Band No.	Landsat 7 (ETM+)	Landsat 8 & 9 (OLI/TIRS)	Wavelength Range (Microns)	Use
1	Visible (Blue)	Visible (Coastal/Aerosol)	0.45-0.52	Aquatic bodies, aerosol tracking
2	Visible (Green)	Visible (Blue)	0.52-0.60	Vegetation, coastlines
3	Visible (Red)	Visible (Green)	0.63-0.69	Plant health, urban areas
4	Near-Infrared	Near-Infrared (NIR)	0.77-0.90	Biomass, plant condition
5	Shortwave Infrared (SWIR) 1	SWIR 1	1.55-1.75	Soil moisture, cloud detection
6	Thermal Infrared	Thermal Infrared (TIRS) 1	10.40-12.50 (Landsat 7)/10.60-11.19 (Landsat 8 & 9)	Surface temperature
7	Shortwave Infrared (SWIR) 2	SWIR 2	2.08-2.35	Analysis of minerals and vegetation
8	-	Panchromatic	0.50-0.68	Increased spatial detail
9	-	Cirrus	1.36-1.38	Detection of high clouds, atmospheric aerosols
10	-	Thermal Infrared (TIRS) 2	-/10.60-11.19 (Landsat 8)	Detection of high clouds, atmospheric aerosols

At the first stage of the study, specific images from East Kazakhstan relevant to this study were filtered, downloaded, and then processed in detail. The features offered by Earth Explorer enabled us to customize the data collection parameters according to the recommended criteria (zero cloudiness from May to August) (Figure 4). This strict data selection significantly improved the accuracy and depth of our analysis, facilitating significant scientific discoveries in land cover change research [26].

The percentage of cloud cover was limited to a range of 0 to 7%. Images with unknown cloud cover percentages were also included in the sample to avoid missing potentially relevant data due to incomplete metadata. This approach screened out images with undesirable cloud cover, which could have skewed NDVI data and led to incorrect conclusions about vegetation conditions and dynamics.

After setting up filter parameters and choosing the corresponding datasets, space imagery was previewed (Figure 5). This step allowed visualizing images on the map of the terrain to make sure they were suitable for further analysis. Using the geographic coordinates and the borders of the studied object, the examined land plot was precisely identified. Upon satisfying all the criteria, the data for further detailed work were downloaded.

Following this algorithm, images were selected for each of the analyzed years. In total, 12 space images were downloaded for each year, and 48 images for the four years examined.

Next, the obtained maps were analyzed to identify territories showing signs of land degradation, establish zones with different levels of vegetation, and monitor long-term changes. In this process, statistical methods were deployed to analyze NDVI time series, compare different areas, and assess the influence of different factors on vegetation status.

Figure 4. Specified filter parameters [18]

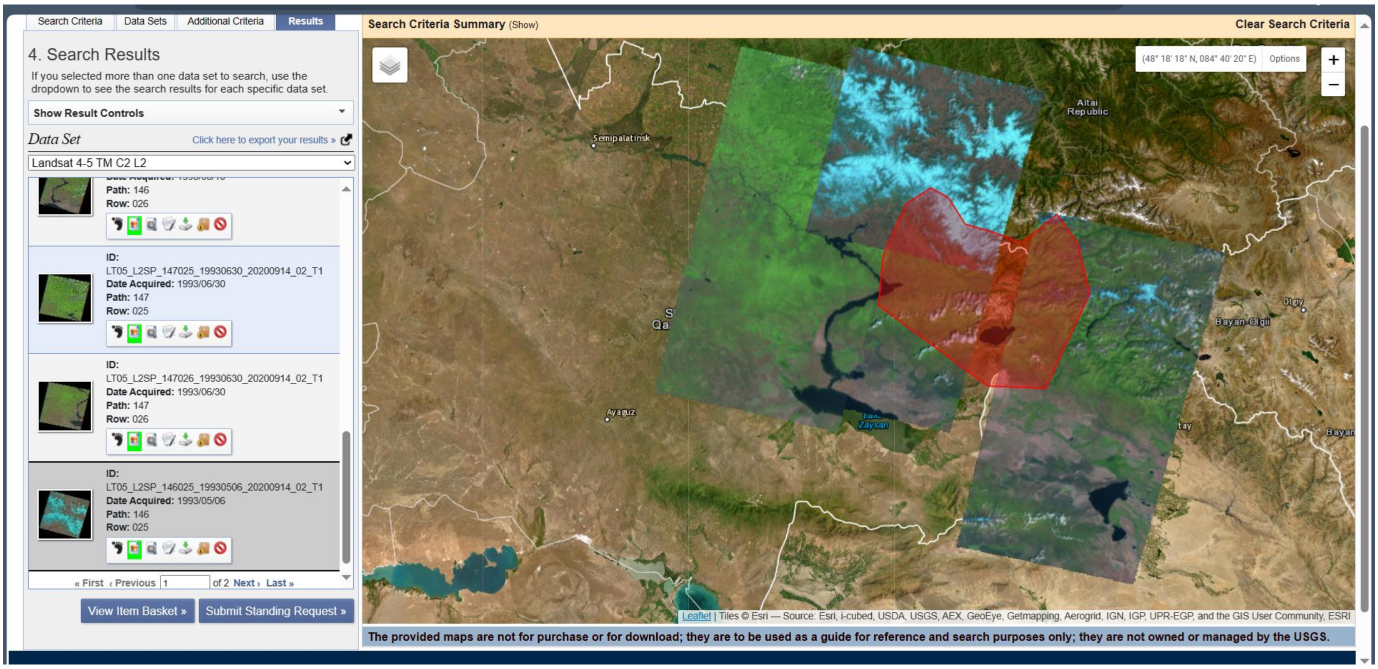

Figure 5. Results of overlaying space images in Earth Explorer [18]

NDVI data were combined with meteorological data, land use maps, and other information sources for a more comprehensive analysis of the causes and consequences of land degradation. Based on this analysis, models were developed to assess future changes in vegetation and land degradation based on current trends and projected scenarios.

The obtained ERS data were processed using the NDVI formula, i.e., by calculating the NDVI for each image pixel using the formula:

$$NDVI=(NIR+R)/(NIR-R) \quad (1)$$

where, NIR and R are reflectivity in the near-infrared and red spectra, respectively.

The calculation of the NDVI and the distribution of territories were conducted in Microsoft Excel, where formulas were applied to calculate land percentages and a chart of the relevant data was drawn up.

NDVI analysis data were obtained and processed using licensed software ArcGIS Pro, which enabled mathematical calculation by year from 1993 to 2023. ArcGIS Pro was selected for data analysis due to its advanced geospatial processing capabilities, which allow for the seamless integration and analysis of large geospatial datasets. The software's robust tools for calculating NDVI and processing time series data made it particularly suitable for this study. Statistical tests were used to compare NDVI values across different years and regions, with t-tests employed to determine the significance of changes in vegetation cover over time. These tests were chosen for their ability to handle the non-parametric nature of NDVI data and to provide reliable comparisons across different time periods.

3. RESULTS

Our results confirmed significant variability in the state of vegetation cover in different areas of the East Kazakhstan region. Using the physical map of the region as a base layer for NDVI data visualization, we showed that certain areas display signs of enhanced land degradation, while others show healthier vegetation.

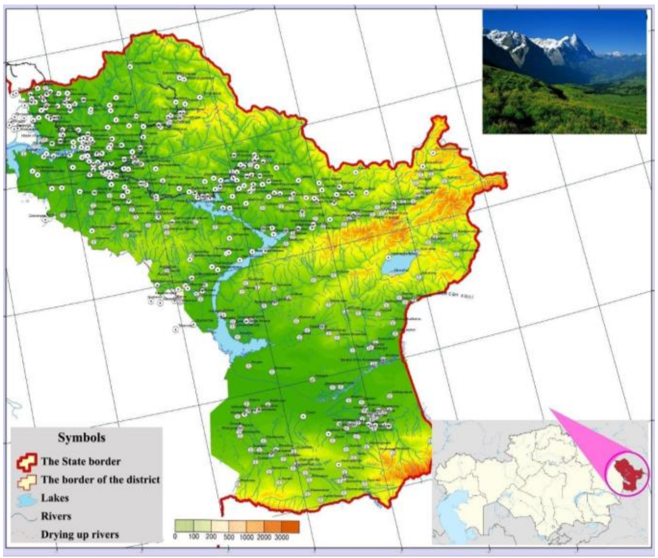

Figure 6. Physical and geographical map of the East Kazakhstan region

Figure 6 presents a physical map of East Kazakhstan compiled using data from open sources and geoinformation technologies and data from the Statistical Committee of the Republic of Kazakhstan [27, 28].

The physical map of East Kazakhstan presents an important tool in understanding the complex geosystem of the region. Geomorphological characteristics, such as orography, edaphic conditions, the hydrographic network, and climatic zones, play a major role in the distribution and dynamics of vegetation and determining the levels of land degradation risk [29]. Multitemporal analysis of these data shows correlations between the physical characteristics of an area and NDVI changes, giving a comprehensive understanding of the spatial and temporal dynamics of ecosystems.

The topographic data included in the physical map allows analyzing the altitudinal zonality of vegetation, showing its dependence on elevation and slope exposure. This approach facilitates a more detailed study of the floristic composition, structural features, and productivity of the vegetation cover [30]. Water bodies depicted on the map carry information about water availability in the region and its hydrological features, which have a direct effect on soil moisture regimes and plants' water stress.

Morphometric analysis based on the physical map of East Kazakhstan makes it possible to assess erosion processes and sediment accumulation potential, which is essential for developing anti-erosion measures and soil fertility conservation programs. The map serves as a basis for modeling environmental niches and determining the vulnerability of biodiversity in the face of anthropogenic and climate changes.

The use of a physical map in combination with the NDVI provides an interdisciplinary approach to the analysis of land resources. It constitutes a fundamental basis for eco-geographical research aimed at solving land degradation and forming a sustainable environmental policy in East Kazakhstan. The use of geoinformation technologies in the study provided us with comprehensive NDVI results based on the formula presented in Figure 7.

Figure 8 presents a map showing the NDVI values for East Kazakhstan in 1993.

Figure 7. NDVI calculation formula for East Kazakhstan region (1993) [31]

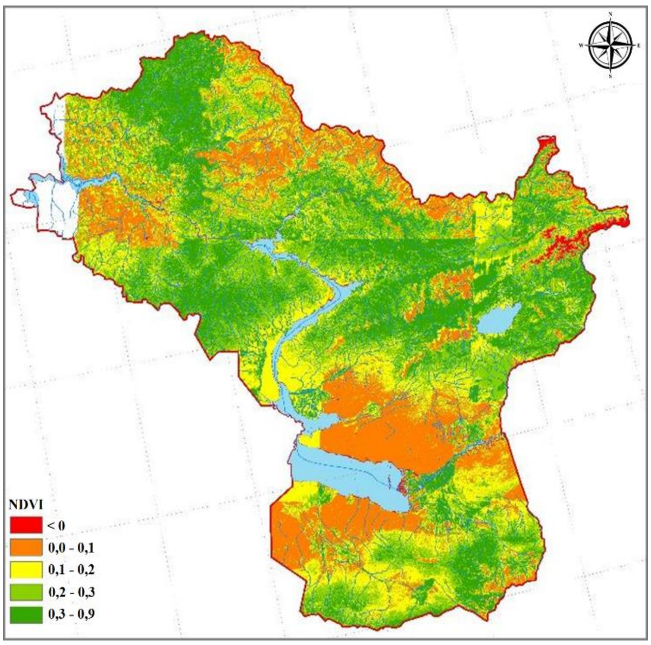

Figure 8. NDVI map of East Kazakhstan region (1993)

The map uses color grading to show the different ranges of the NDVI:

•Red indicates very low NDVI values (below 0) characteristic of bare ground, urban areas, or water bodies [13].

•Orange and yellow stand for low (0-0.1) and moderate (0.1-0.2) NDVI levels, respectively, which may correspond to areas with sparse vegetation or early in the growing season [13].

•Shades of green represent higher NDVI values (0.2-0.3 and 0.3-0.9), indicating healthier and denser vegetation, such as forests, shrubs, or well-developed agricultural crops [13].

The map includes a legend for interpreting the NDVI colors and a compass marking the north. These maps are used for monitoring vegetation health, land management, and assessing and preventing land degradation. As can be seen from Figure 8, the territory of the central and southern parts of East Kazakhstan is prone to land degradation.

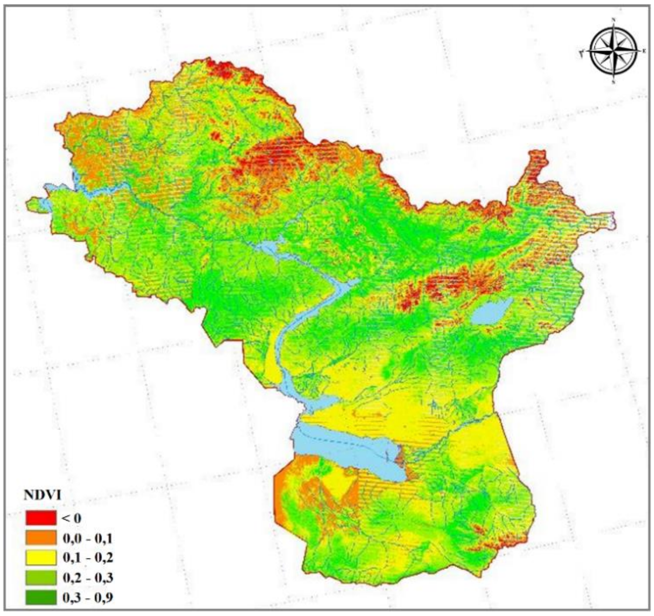

Figure 9. NDVI for 2003 in the East Kazakhstan region

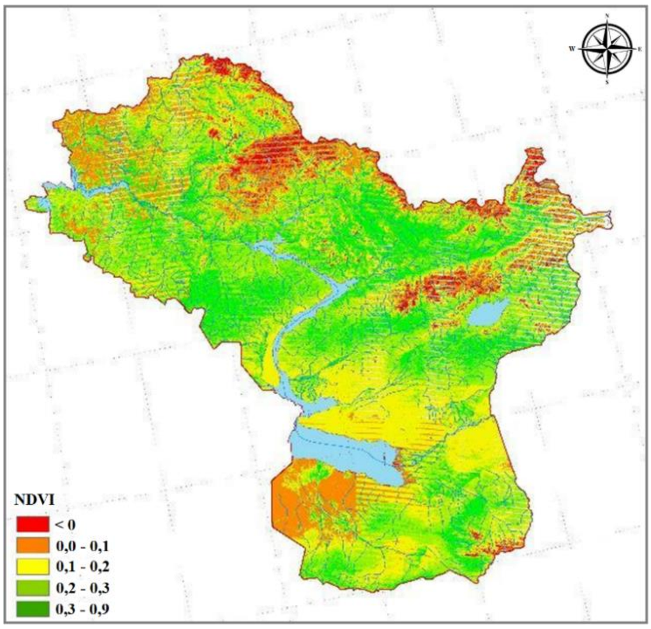

Figure 10. NDVI for 2013 in the East Kazakhstan region

The NDVI data from 2003 and 2013 are presented in Figures 9 and 10.

The NDVI maps of East Kazakhstan for 1993, 2003, and 2013 demonstrate a deterioration of vegetation. To explain this phenomenon, we need to consider several potential causes:

Climate change: changes in the climate, such as higher temperature levels and changes in precipitation and the frequency of droughts, can affect plant growth and the productivity of ecosystems.

Anthropogenic activity: the expansion of agricultural land, especially when accompanied by non-sustainable or intensive farming practices, can lead to land degradation. Activities involving natural resource exploitation, urbanization, and industry can also reduce the area of healthy ecosystems [32, 33].

Forest fires and deforestation: these can significantly reduce forest cover and consequently negatively affect NDVI values.

Examining the images of East Kazakhstan for 2023, we can conclude that the southern part of the region has suffered the most land degradation (Figure 11).

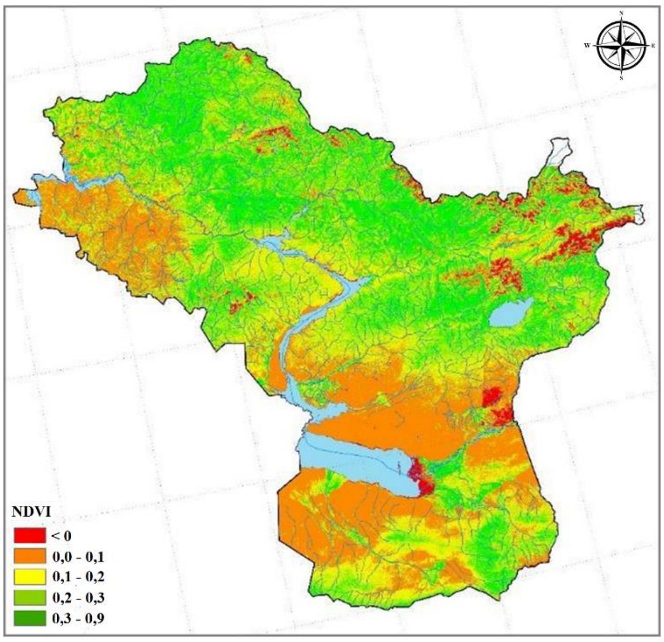

Figure 11. NDVI for 2023 in the East Kazakhstan region

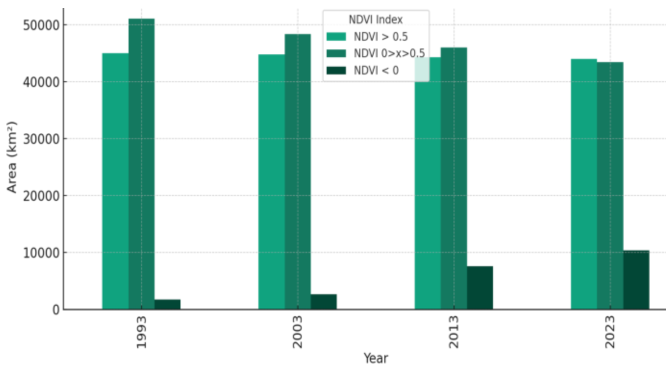

Figure 12. Updated NDVI area distribution over the years

We can note the following reasons behind the deterioration of vegetation on the territory:

Overgrazing and soil erosion: overgrazing can lead to the degradation of soil quality and vegetation loss, which affects NDVI values [34, 35].

Introduction of harmful species: the spread of plant or animal species harmful to the area can upset the ecological balance and affect native vegetation [36].

Water use policies: changes in water allocation, such as dam construction or the reallocation of water for agricultural or industrial uses can change soil moisture and water balance, which directly affects vegetation [37].

In Figure 12, we provide bar charts showing the distribution of territories by their NDVI.

The chart shows:

•The area with NDVI > 0.5, representing highly densely vegetated areas.

•The area with NDVI between 0 and 0.5, representing areas of medium vegetation density.

•The area with NDVI < 0, indicating water bodies or territories showing land degradation [12].

Figure 13 visualizes the data from the conducted NDVI analysis in the period from 1993 to 2023.

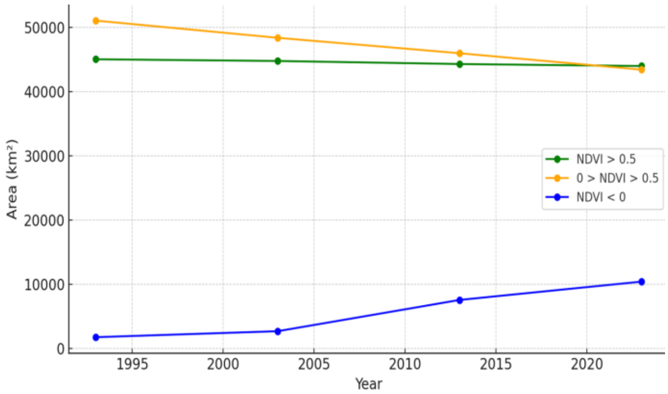

Figure 13. Updated NDVI analysis over the years

Based on the NDVI maps of East Kazakhstan from 1993 to 2023, the vegetation cover of the region has changed over the 30 years. Spectral analysis and NDVI data time series indicate environmental changes stemming from various anthropogenic and natural factors. Phenological patterns, which reflect the seasonal cycles of vegetation growth and wilting, also show changes, which can be connected with changing climatic conditions, such as fluctuations in temperature and precipitation.

The evaluation and comparison of the maps allows us to observe dynamics and potential vegetation trends. Spatial and temporal analysis of NDVI data reveals changes in plant biomass and photosynthetic activity, which has direct implications for the carbon balance of the region and the dynamics of biogeochemical cycles.

These findings are consistent with other research conducted in similar arid and semi-arid regions. For instance, in a study conducted by Pal et al. [38] in India, a similar pattern of declining NDVI values was observed. The study attributed these declines to a combination of increasing temperatures, erratic rainfall patterns, and overgrazing, leading to reduced vegetation cover and accelerated desertification.

Comparing the maps, we found that certain land plots, especially in the south and east of the region, show changes in color gradation, which can signal a decline or improvement in vegetation health. Changes in spectral signatures, particularly an increase in areas colored in green shades, can correlate with an increase in leaf area and photosynthetic activity, while the predominance of orange and red hues can represent a decrease in chlorophyll and biomass characteristic of degradation processes.

In addressing these challenges, it is essential to consider the recommendations of studies such as those by Wang et al. [39] and Fassnacht et al. [40], which emphasize the importance of integrating remote sensing data with ground-based observations to improve the accuracy of land degradation assessments. Such an integrated approach could enhance the effectiveness of monitoring programs in East Kazakhstan, allowing for more precise identification of degradation hotspots and more informed decision-making.

The use of NDVI as a tool for monitoring vegetation health and land degradation has proven to be effective in this study, providing valuable insights into the spatial and temporal dynamics of the region's ecosystems. However, it is important to acknowledge the limitations of relying solely on NDVI data. While NDVI is a robust indicator of vegetation health, it may not capture all aspects of ecosystem dynamics, particularly in areas with sparse vegetation or in regions where other environmental factors, such as soil moisture or land use changes, play a significant role.

4. CONCLUSIONS

The integration of NDVI data in studies on land degradation in the East Kazakhstan region shows substantial variability and dynamics in the region's ecosystems. NDVI data collected using the Landsat satellite system allows qualifying fluctuations in vegetation health and density, providing key biophysical parameters for assessing the condition of land and its resilience to environmental stresses. These results underscore the urgent need for targeted interventions to mitigate land degradation and promote sustainable land management practices in the region.

Consecutive NDVI data from 1993 to 2023 confirm changes in vegetation structure that can be attributed to anthropogenic impacts, such as land use change, deforestation, and agricultural intensification, and to natural processes including climatic anomalies and environmental disturbances. The decline in areas of high vegetation density in several locations can be indicative of accelerated degradation, which necessitates intensified ecological restoration and adaptive resource management measures.

Distance monitoring with the NDVI offers a quick and objective means for continuous observation of the ecological state of territories, supporting informed decision-making and the development of measures to conserve biodiversity and prevent environmental degradation. An integral part of sustainable monitoring is a multidisciplinary approach that combines satellite observations with ground survey data, ecosystem modeling, and socio-economic pattern analysis.

One area that warrants further investigation is the integration of NDVI data with other remote sensing indices, such as the Soil Adjusted Vegetation Index (SAVI) or the Enhanced Vegetation Index (EVI), which could provide a more nuanced understanding of vegetation dynamics in regions with sparse vegetation cover.

The final assessment demonstrates the significance of the NDVI as a comprehensive indicator for assessing land degradation. Continued use of the NDVI as part of long-term environmental planning and resource management sets the path for the sustainable development of the region and the preservation of its natural potential.

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