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Assessment of degraded lands in the Ile-Balkhash region, Kazakhstan

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It is estimated that approximately 66% of Kazakhstan's territory is susceptible to desertification. One of the most significantly affected regions in terms of land degradation is the Ile-Balkhash Basin, where environmental pressures have intensified due to factors such as water scarcity, soil erosion and unsustainable land use practices. This study aims to evaluate the dynamics and risk rates of desertification, as well as its severity, in the Ile-Balkhash region. To achieve the set goal of objectives, a variety of methods were employed, including desertification divided index (DDI) for the identification of desertification dynamics, correlation analysis for the detection of relationships between different indicators, and Principal Component Analysis (PCA) for the modelling of the desertification risk rate in the study area. The spatial distribution of desertification degrees (severe, high, medium, low, and non-desertification) was identified using DDI methodologies. The results indicate that the area of severe desertification in the dry region exhibited a decline by 2020, followed by an increase. The area of high desertification and non-desertification regions has increased, while medium and low desertification areas remained relatively unchanged. The northern part of the region is experiencing the most rapid increase in DDI due to human agricultural activities and landscape features. The results of the correlation analysis indicate that precipitation is the primary factor influencing the spatial distribution of desertification. In addition, the results of the PCA model based on spectral indices indicate that the northern part of the region, where land use for pasture is prevalent, is the most vulnerable to desertification. The potential for further land degradation is heightened by the current mismanagement of land and the failure to adequately address shifting climate conditions. Factors such as temperature fluctuations, overgrazing, and specific landscape features serve to exacerbate the process of desertification. This comprehensive examination of land desertification can facilitate the formulation of effective policy strategies for the implementation of land rehabilitation plans in the Ile-Balkhash region and arid areas of southern Kazakhstan.

KEYWORDS

degraded land, desertification, spectral indices, climate change, Ile-Balkhash region, DDI

1 Introduction

Desertification is the degradation of land in arid, semi-arid, and dry sub-humid areas due to climate change and human activities (Oswald and Harris, 2023). Human activity exerts a significant influence on the process of desertification (Varghese and Singh, 2016), and climate change may serve to further exacerbate this process in certain instances (Qi et al., 2024), potentially becoming a more prominent force than the anthropogenic factor (Maity et al., 2024). In arid regions, this could result in an even greater loss of vegetation and land cover (Hailu, 2023). Additionally, it could accelerate the decomposition of soil organic matter, releasing carbon and nitrogen into the atmosphere, which would contribute to the greenhouse effect (Gou et al., 2021; Rutigliano et al., 2023) and further exacerbate global warming.

Desertification directly impacts the wellbeing of over 250 million people and threatens the livelihoods of more than one billion people worldwide. It is estimated that about 12 million hectares per year are currently affected by desertification. Large areas of land at the margins of the world's deserts have been degraded (AbdelRahman, 2023). The phenomenon of desertification has a considerable impact on food productivity, resulting in a reduction in the amount of arable land available for cultivation and a decline in crop yields (Hekstra and Liverman, 1986). The deterioration of topsoil, the process of salinisation and the degradation of pastures collectively impair the conditions that are conducive to the production of foodstuffs and the rearing of livestock (Ashurbekova et al., 2024; Elhini et al., 2024). The increased frequency of droughts and erratic rainfall patterns present significant challenges to crop planning (Bueechi et al., 2023), contributing to food insecurity and higher farming costs (Stringer, 2009; Nkonya et al., 2011). These challenges give rise to further risks to food security, prompting rural-to-urban migration and intensifying socio-economic issues (Mehrabi et al., 2008; Sanzheev et al., 2020).

Central Asia is a significant area affected by global desertification, where more than 75% of the total area is covered by bare lands and pastures (Ma et al., 2021). This dryland ecosystem is sensitive and vulnerable due to difficult climatic conditions and scarce vegetation, which not only causes desertification but also hinders socio-economic development and stability (Jiang et al., 2019b). As a constituent state of the Central Asian region, the arid climatic conditions that prevail across a considerable portion of Kazakhstan serve to heighten the vulnerability of the country's landmass to the processes of desertification. A review of the scientific literature reveals that research on desertification in Kazakhstan has been conducted since the early 1970s (Assanova, 2015). Various studies have been conducted with the objective of furthering the understanding of the processes of desertification and the identification of the principal factors involved (Tokbergenova et al., 2018; Hu et al., 2020). The findings revealed that 13.66% of the study area was classified as being within a critical zone of risk with regard to the potential for desertification (Jiang et al., 2019c). Approximately 76.1 per cent of Kazakhstan's territory is considered a critical desertification risk zone, with medium and high sensitivity. (Salnikov et al., 2015; Hu et al., 2020). Since the 1960s, due to unprecedented agricultural intensification, dust storms and other adverse factors, desertification processes and food crises have been observed. Currently, the total area of abandoned territories in Kazakhstan exceeds 50 million hectares (UNDP, 2019), necessitating the development of a system of measures to combat the desertification process through scientific and practical activities.

The southern part of Kazakhstan, including the Ile-Balkhash region, is also part of Central Asia and is susceptible to land desertification (Laiskhanov et al., 2021). With its intensive agricultural development, this region is one of the main drivers of economic development in Kazakhstan.

Therefore, it is critical to understand desertification processes and their environmental impacts to achieve sustainable development goals (Alimova, 2017).

Various methods have been used to study land degradation, including field observation and assessment, expert judgement (Kapalanga, 2008), and remote sensing and GIS approaches (Hostert et al., 2001; Afrasinei et al., 2017). The mapping and quantification of land degradation status (Liberti et al., 2009; Afrasinei et al., 2017) based on the results of these methods plays an important role in the cost-effective development of land management strategies. Researchers and land managers can use this information to identify the most vulnerable areas and prioritize local intervention (Bewket and Teferi, 2009; Rahman et al., 2009). Evidence of land degradation can be assessed using various methods, such as questionnaires, focus group discussions, direct observation, and expert judgment (Liberti et al., 2009). The application of remote sensing technologies has provided significant opportunities to obtain evidence of degradation over large areas at a relatively low cost and time (Bakr et al., 2012; Wang et al., 2017; Lamqadem et al., 2018).

The geographical location of the study area is the main natural factor contributing to the development of desertification processes in the Ile-Balkhash basin. This location determines the continentality and aridity of the climate, as well as the scarcity and uneven distribution of water resources, resulting in a wide distribution of sands and saline lands. This region's main cause of land desertification is the irrational use of water and land resources. Numerous studies in this basin have primarily focused on water resource utilization, environmental water degradation, and sand desertification. However, only a few studies have been conducted on degraded lands (Tokbergenova et al., 2018; Koroleva et al., 2019; Qi et al., 2019; Kou et al., 2023).

This study aims to evaluate the dynamics of the Ile-Balkhash region and identify the zones most susceptible to desertification risks. This is achieved through the application of Principal Component Analysis and spectral indices. The government can use the results to develop policies to control desertification and to evaluate existing desertification control programmes.

2 Materials and methods

2.1 Study region

The study area is the arid region of Ile-Balkhash Region in southeast Kazakhstan (Figure 1). The area has a total coverage of 413 thousand square kilometers, of which 353 thousand square kilometers are in Kazakhstan. The region is characterized by orographic and climatic heterogeneity and a wide variety of

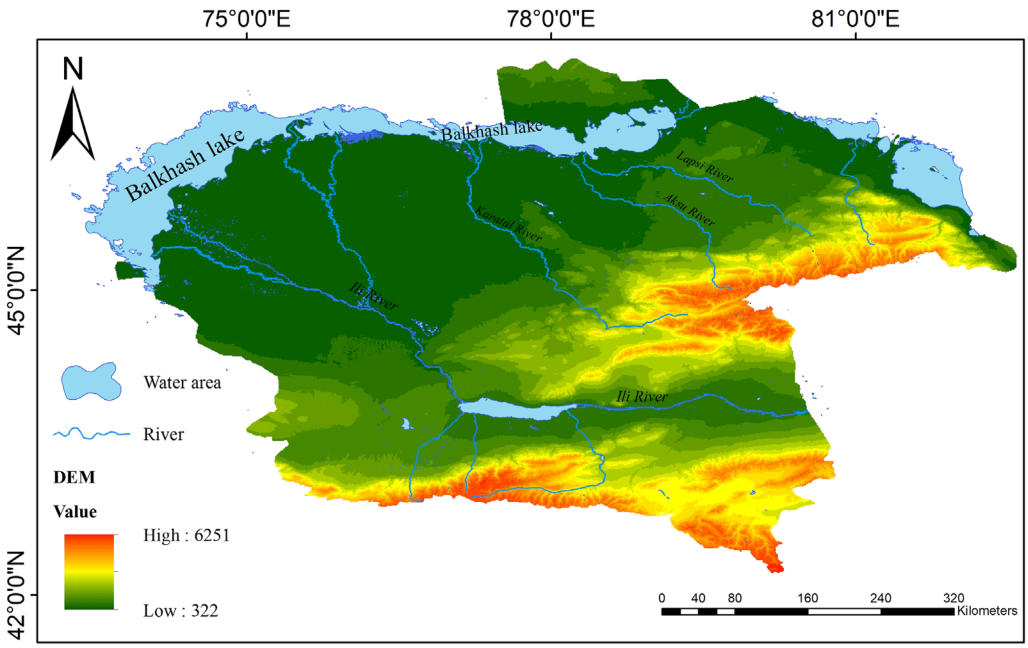

FIGURE 1
Ile-Balkhash Basin (Almaty and Zhetysu region, Kazakhstan).

natural conditions. The narrow strip of arid steppe zone in the north of the basin gives way to the semi-desert of the Northern Balkhash, which in turn becomes the desert stretching from the southern shore of Lake Balkhash to the north of the area (Popov and Simberdeeva, 1970). The climate of the described area is predominantly continental, but highly varied due to its latitudinal extent and mountainous character. The precipitation distribution across the basin area is highly variable. The western slopes of Zhetysu Alatau, at an altitude of 2,500–3,000 m, receive the highest annual precipitation of 2000 mm. In contrast, the coast of Lake Balkhash receives only 150 mm, while the northern and southern Balkhash receive 200–250 mm. In the plain area, the average air temperature during the coldest month of January ranges from −16°C in the north to −5°C in the south. During summer months, the relative humidity in the plain area ranges from 20%–40%, while in winter, it exhibits a notable increase to 75%.

In the basin area of Kazakhstan, there were 3.5 million residents, half of whom lived in rural areas. The region is a typical farming-pastoral area where agriculture and animal husbandry are crucial to the local economy. The increase in population has resulted in irrational land use, including extensive reclamation and overgrazing, exacerbating land degradation and desertification expansion.

2.2 Data

This paper uses NDVI (Normalized Difference Vegetation Index), EVI (Enhanced Vegetation Index), LST (Land Surface Temperature), NPP (Net Primary Production) and monthly values - albedo obtained from the MODIS database with processing level version 6.1 published in 2021 (https://lpdaac.usgs.gov/products/mod09a1v061/). Climatic data in the study area were assessed using annual mean values of temperature and precipitation for the last 22 years obtained from the CRU TS 4.07 (Climatic Research Unit Gridded Time Series) database created by the University of East England (https://crudata.uea.ac.uk/).

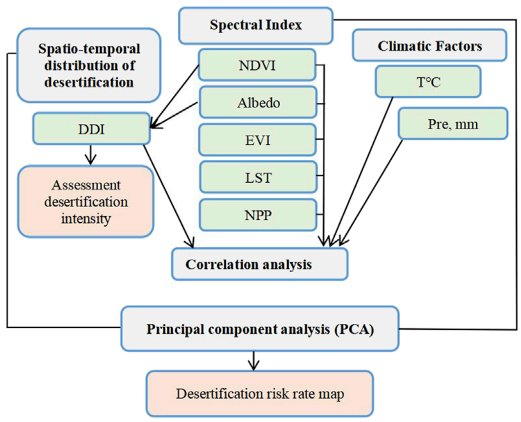

FIGURE 2
The proposed methodology flowchart of the study area.

2.3 Methods

Figure 2 provides a visual representation of the primary procedures employed in the study.

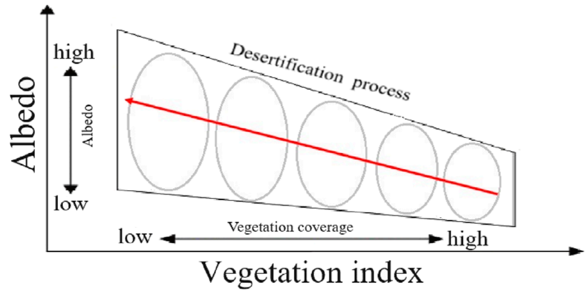

FIGURE 3
Albedo-Vegetation index feature space.

2.3.1 Principles of feature space

This study uses the feature space method to monitor desertification. Long-term research has shown that vegetation cover and surface albedo are indicators for assessing desertification. The normalized vegetation index can reflect the spatial distribution intensity of aboveground plants, which indicates the growth status of plants (Wu et al., 2014). As the amount of above-ground vegetation decreases, the normalized vegetation index decreases, indicating that the degree of desertification is increasing. Albedo is the amount of radiation absorbed by the underlying surface (Calabrò and Magazù, 2016). Changes in surface albedo are influenced by soil moisture, vegetation cover, snow cover and other anomalous land conditions. Many studies have shown that albedo and NDVI are significantly negatively correlated, using the Albedo-NDVI feature space as an example (Zeng et al., 2006; Pan and Qin, 2010; Xie et al., 2022). Figure 3 shows a strong negative correlation between the vegetation index and albedo. As desertification intensifies in the region, the vegetation index decreases and the albedo increases, as indicated by the red arrow.

According to the study by Verstraete and Pinty (Verstraete and Pinty, 1996), if the Albedo NDVI feature space is divided along the vertical direction of the desertification change trend, different desertified areas can be effectively separated. A simple binary linear polynomial expression can be used to fit the position of the vertical direction in Albedo-NDVI feature space well, as follows:

$$DDI = K \times NDVI - Albedo, \tag{1}$$

where "DDI" was the desertification divided index and K was determined by the slope of the straight line fitted in the feature space.

Ma et al. (2011) concluded that DDI values can be classified into five levels of desertification using the natural break (Jenks) method (Ma et al., 2011). These levels are severe, high, medium, low, and non-desertification. The natural break classification method is based on the natural grouping inherent in the data. Its boundary is set to the position where the data values are relatively different (Tung and LeDrew, 1988). The method computes each classification situation and automatically selects the one with the minimum variance values to obtain the optimal classification result. Additionally, it effectively aggregates similar classes and maximizes the differences between them.

2.3.2 Correlation analysis

The correlation coefficients between the two variables were calculated in order to determine their relevance. In this study, the correlation coefficients of spectral indices with precipitation and air temperature were calculated with the aim of determining the response of DDI and other indices to climatic factors.

Pearson's correlation analysis was exploited for the correlation analysis among the different indices:

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}}, \tag{2}$$

where r_{xy} represents the correlation coefficient between the two objects, x_i, y_i represent the corresponding raster values. The value of r_{xy} ranges between −1 and +1. A positive value indicates a positive correlation, while a negative value indicates a negative correlation. A value closer to 1 or −1 indicates a stronger correlation.

2.3.3 The method of principal component

Principal Component Analysis (PCA) (Maćkiewicz and Ratajczak, 1993) is a widely used technique for detecting changes in time series data due to its simplicity and capability of enhancing even subtle changes. PCA is used to derive the component scores for land degradation risk rate.

PCA transforms the original set of variables into a smaller set of linear combinations that account for most of the variations of the original set.

Consider the variables $X_1, X_2, \ldots, Xp$. A principal component analysis of this set of variables can generate p new variables, called principal components ($PC_1, PC_2, \ldots, PCp$) and can be expressed as follows:

$$PC_p = b_{p1}X_1 + \ldots + b_{pp}X_p = Xb_p, \tag{3}$$

where b - the coefficients for PC, each column of b contains the coefficients for one PC. The coefficient for PC_1 is chosen to have the largest variance, and PC_2 is chosen to have the second largest variance subject to the condition that it is uncorrelated with PC_1, and so on.

3 Results

3.1 NDVI, EVI, albedo, LST and NPP

Figure 4 represents the calculation results of the three spectral indices (NDVI, albedo, EVI). The use of NDVI and EVI enables the monitoring of changes in vegetation condition and productivity over time, facilitating the identification of areas at risk of desertification. NDVI is often used to monitor overall vegetation cover, crop health and productivity. In contrast, EVI is capable of detecting subtle changes in vegetation conditions. It is also effective in determining forest vegetation density and assessing changes in grassland productivity.

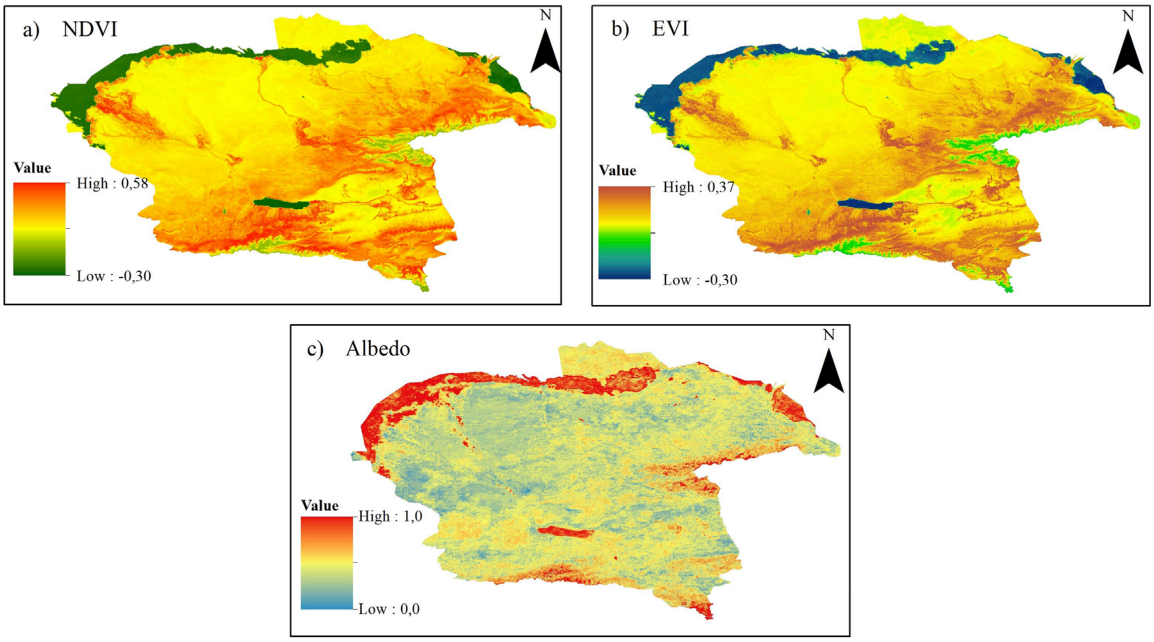

FIGURE 4
(A) NDVI, **(B)** EVI and **(C)** Albedo maps (2022).

NDVI values range from −0.3 to 0.58 (Figure 4A). The low values of NDVI correspond to the denuded areas with desert behavior which are generally found on the borders of the delta Ile river. In contrast, the high values reflect soils with high vegetation cover corresponding to the forests in the Ile-Alatau and the Zhetysu Alatau, as well as the irrigated lands along some rivers.

The EVI index values range from −0.29 to 0.35 (Figure 4B). Low values represent water and bare soil, while high values correspond to dense vegetation.

Surface albedo values vary between 0.03 and 0.91 (Figure 4C). The results obtained by this indicator are consistent with the results obtained by the Normalized Vegetation Index (NDVI). Indeed, the low values of the albedo representing a relatively dense vegetation cover are also located at the level of the Ile-Alatau and the Zhetysu Alatau Mountains as well as at the edges of upper part rivers. As for the high values of the albedo, they reflect areas with low vegetation, such as desert and semi-desert areas.

Figure 5A shows the spatial distribution of LST in the region. High temperatures mainly occurred in the western parts of the region, and the temperature increased from east to west. A very high increase in LST values was observed in the middle stream of the Ile River. The main reason for this increase was vegetation degradation because of decreasing surface water in the river.

The spatial distribution of the Ile-Balkhash region NPP dynamic is represented in Figure 5B. There is a general declining gradient in NPP from east to west and south to north, which corresponds to rainfall and soil fertility patterns in the basin. Although absolute NPP values approached 2.52 kg C m^{-2}/year in a few locations, most of the basin is much less productive. Relatively high levels of NPP spatial variability characterized mountain slopes and irrigated croplands in river deltas.

3.2 Temporal and spatial distribution of desertification

Figure 6 depicts the spatial distribution of the degrees of desertification in different periods (Equation 1). The mountainous and foothill areas, as well as the lower reaches of the main rivers that drain into Lake Balkhash have a low degree of desertification. The middle belt of the region, which stretches from southwest to northeast, has a medium degree of desertification. The northern part of the region, where desert landscapes are prevalent, has high and severe desertification. Furthermore, intensive agricultural development in the middle reaches of the Ile River is leading to high and severe desertification. Non-desertification areas are mainly distributed in forested areas in the Ile-Alatau and the Zhetysu Alatau Mountain.

Between 2002 and 2015, land desertification severity in the northwest regions increased rapidly. Subsequently, severe desertification shifted from a scattered to a continuous patchy distribution. In 2002–2022, the low desertification area transformed into medium desertification land. From 2015 to 2022, the degree of desertification decreased in the northern areas.

As shown in Table 1, over the past 20 years, the total area of decertified land in the research area as a proportion of the total land area has been high and shows increasing trend, ranging from 83% to 89%. There is a clear changing trend in the area of different desertification degrees, mainly a decrease in the area of non and low decertified land and an increase in the area of high and decertified land.

From 2002 to 2022, the area of high decertified land increased to 67,317 km^2, an increase rate of 10.5%. The area of severe desertification increased from 22,089 km^2 – 22,964 km^2, an increase

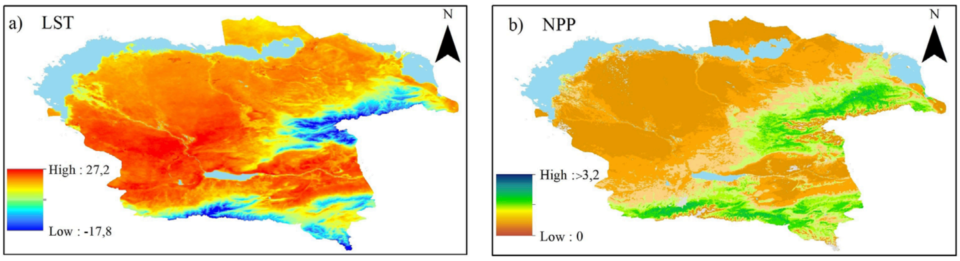

FIGURE 5
(A) LST and **(B)** NPP maps (2022).

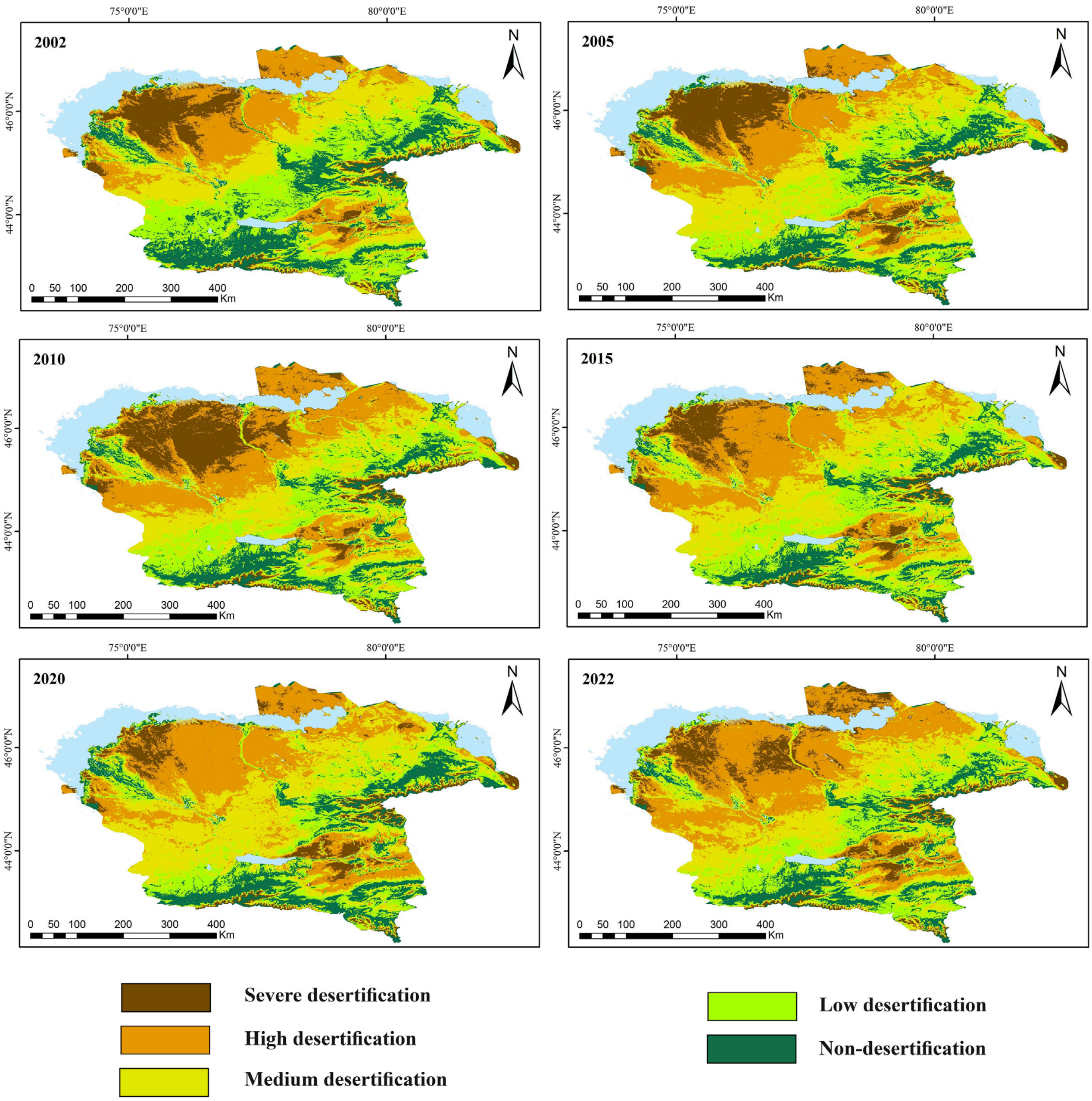

FIGURE 6
Spatial distribution of desertification in the Ile-Balkhash Basin (Kazakhstan) from 2002 to 2022.

TABLE 1 Area showing varying degrees of desertification between 2002 and 2022.

Year	Area/Percent	Severe	High	Medium	Low	Non
2002	thousand km^2	22.1	45.2	51.0	54.5	36.2
	%	10.6	21.6	24.4	26.1	17.3
2005	thousand km^2	28.1	51.2	57.7	44.1	27.6
	%	13.5	24.5	27.6	21.1	13.2
2010	thousand km^2	32.3	58.0	51.5	44.3	23.0
	%	15.4	27.7	24.6	21.2	11.0
2015	thousand km^2	19.0	59.6	62.2	45.0	23.1
	%	9.1	28.5	29.8	21.5	11.1
2020	thousand km^2	15.6	61.0	69.4	34.6	28.7
	%	7.5	29.1	33.2	16.5	13.7
2022	thousand km^2	23.0	67.3	55.0	41.6	22.4
	%	11.0	32.2	26.3	19.9	10.7

TABLE 2 The transition matrix of desertification in 2002–2022.

2002 / 2022	Severe	High	Medium	Low	Non	Total (reduced)
Severe	13,526	7,762	175	24	9	21,496
High	8,061	34,047	2,247	175	26	44,556
Medium	214	23,241	24,680	2,467	95	50,696
Low	25	1,592	26,112	24,353	3,147	55,229
Non	16	18	1,987	15,186	19,323	36,531
Total (increased)	21,843	66,660	55,202	42,204	22,599	

rate of 0.4%. In 2010, severe peaked at 32,297 km^2, accounting for 15%. The area of low and non-desertification decreased significantly, a decrease rate of 6.2% and 6.6%, respectively.

We obtained the transition matrix of desertification in this study from 2002 to 2022, as shown in Table 2. During the research period, the transformation of desertification intensity occurred between different levels of desertification. The conversion area accounted for 44.4% of the total land area. The main desertification transformations were mainly from low to medium, from medium to high, from non to low, from high to severe, and from severe to high, covering land areas of 26,112 km^2, 23,241 km^2, 15,186 km^2, 8,061 km^2 and 7,762 km^2, respectively, accounting for 12.5%, 11.1%, 7.3% 3.9% and 3.7% of the land area.

As shown in the changes in desertification intensity from 2002 to 2022 (Figure 7), the degree of desertification development was divided into five categories (strong deterioration, deterioration, stability, recovery, and significant recovery). The desertification grade stability throughout the area, mainly in the sand lands and mountain area, accounts for 55.9% of the land in the basin. The deterioration areas were primarily spread in the middle part of region, sextending from south-west to north-east. Over the last 20 years, strong deterioration have taken place in the foothill deserts, where intensive pasture grazing has taken place, in the north-eastern part of the region, where grey-brown gravel soils are found, and on the southern slopes of the mountains in the southern part of the region, where intensive erosion processes are taking place.

The recovery and significant recovery lands were sporadically scattered, mainly in the high mountain areas and wetlands of the Ile-Balkhash delta system, accounting for 3.9% of the land in the basin.

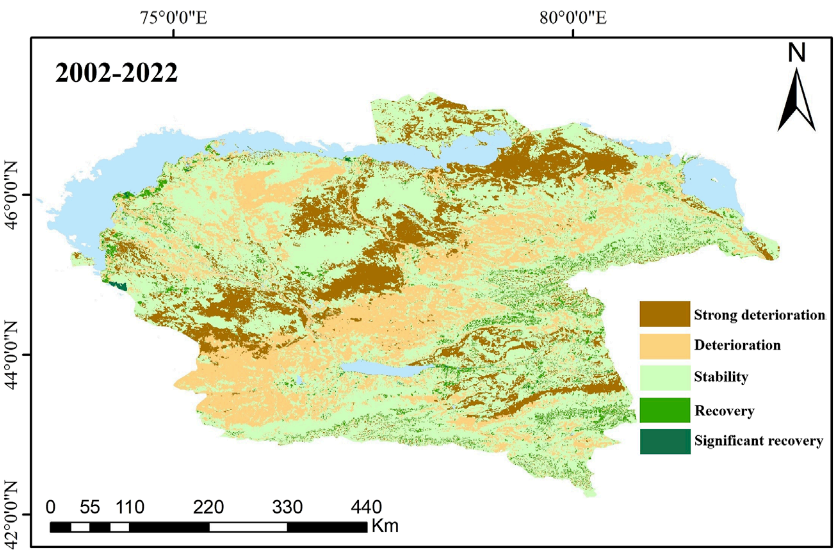

FIGURE 7
Changes in desertification intensity from 2002 to 2022.

3.3 Time-series correlation between spectral indices and climatic factors

The analysis of long-term desertification trends requires attention to the correlation between anthropogenic, abiotic, and climatic factors of desertification (Stringer et al., 2017). Various approaches and types of modelling are widely used to analyze and process long-term climate and remote sensing databases (Huang et al., 2017; Stringer et al., 2017; Aqdam et al., 2023).

To assess desertification rates and risks using spectral indices and modelling, we first conducted Pearson cross-correlation analysis (Equation 2), a widely used method in remote sensing (Figure 8) (Hong et al., 2023).

The cross-correlation matrices' results for each degree of desertification indicate a positive correlation on average, except for the correlation between land surface temperature (LST) and precipitation. The R-values between air temperature, LST, and precipitation have a negative or no correlation in all considered classes. The correlation between temperature and precipitation rate under global warming is predominantly negative, particularly in the temperate latitudes of Central Asia. The mean annual precipitation decreases significantly with increasing temperature (Li et al., 2020). The cross-correlation between climatic factors and vegetation data indicates a strong correlation with the degree of desertification, ranging from strong to weak. According to the legend, the average correlation values for each selected category are 0.62, 0.73, 0.78, 0.78, and 0.59, respectively, although there are differences in correlations between some indicators. The obtained reliability is high enough and can be used for further research.

3.4 Desertification risk rate analysis

Principal component analysis (PCA), also known as empirical orthogonal function (EOF) analysis, helps identify recurring patterns in time series or groups of time series (Khatun, 2009; Mfondoum et al., 2016). The analysis was applied to determine the main trends in the risk rate of desertification in the study area over the last 20 years (Equation 3). Based on the obtained spatial data, a GIS map (Figure 9) was created to show the degree of desertification risks in natural-agricultural systems of the study area.

The obtained final contours of rates and risks of desertification of natural-agricultural systems of the region were finalized using field survey data and area coefficients for each class were calculated.

The desertification risk assessment of the region revealed that 32.29% of the total area represents high desertification risk zones, followed by moderate (20.19%), very high (18.30%) and low (18.18%) risk zones. The calculation did not include water bodies. Areas with a high risk of desertification are located in the study area's southern parts and intermountain plain. The low-risk areas were primarily located in the northern and eastern regions of the study area, in the low mountainous areas. The very low-risk areas were concentrated in the high mountainous regions. This finding aligns with the results of the DDI and other spectral indices.

According to the results of this analysis, the main ecological, biological and socio-economic elements at risk of desertification are concentrated in the northern part of the territory (extensive pastures on sandy and takyr-like soils). In these areas, the adverse effects of desertification due to severe drought and poor land management, can cause significant damage. According to this map of desertification, risk elements and vulnerability have been considered as a risk, which is a basic map for management. This means that changes and aggravation of climatic and technogenic conditions with inappropriate land management and physical development, regardless of the conditions of ecosystem stability (development without complying with land management documents), can lead to serious consequences. Unfortunately, many of these conditions are present in the inland arid ecosystems of the Ile-Balkhash region.

However, in the semi-desert parts of the low and medium mountain ranges, the effects of environmental degradation can

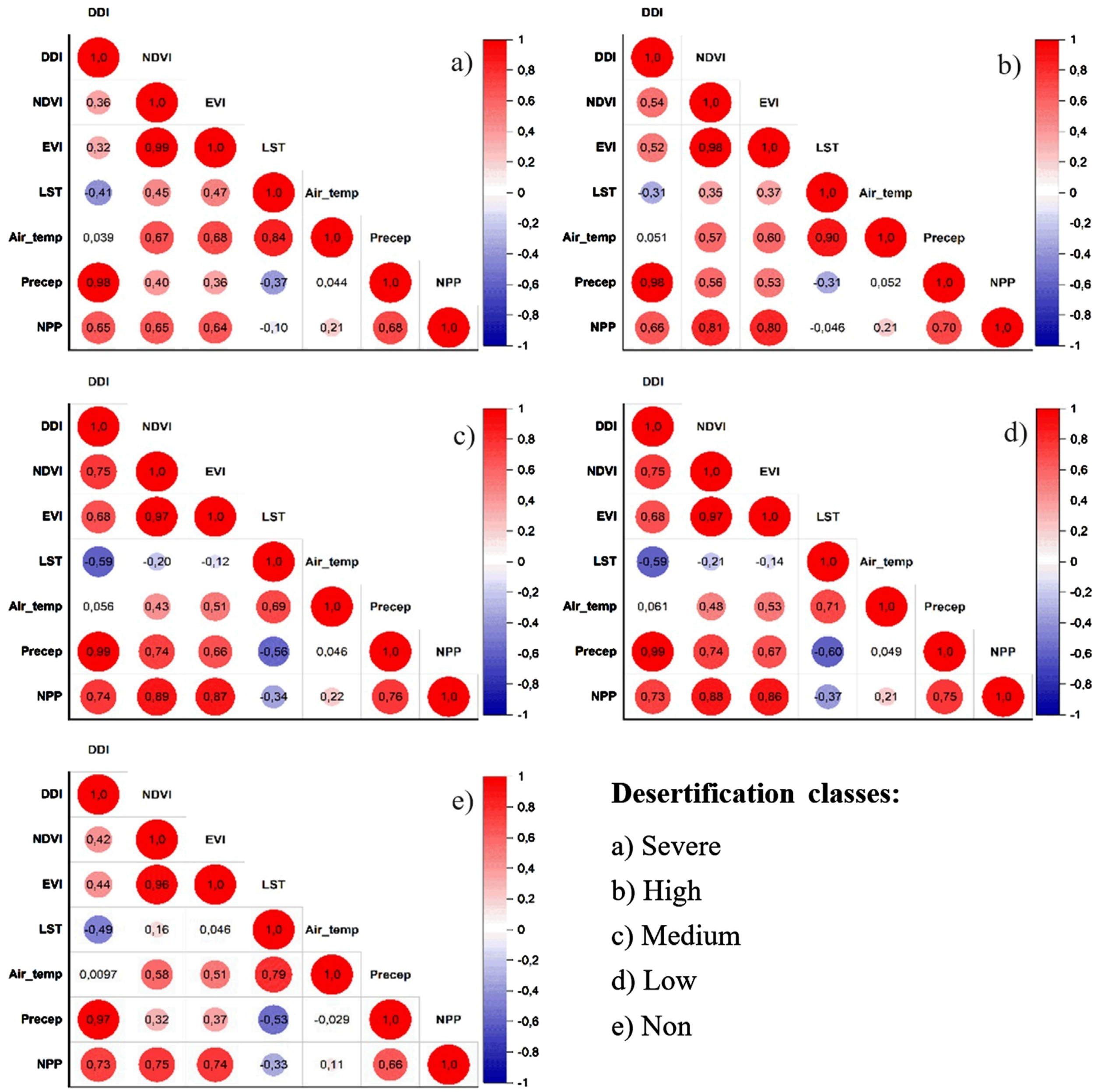

FIGURE 8
Results of cross-correlation analysis of the obtained classes of desertification rates in the study area (**(A)** Severe desertification classes, **(B)** High desertification classes, **(C)** Medium desertification classes, **(D)** Low desertification classes, **(E)** Non desertification classes).

be significantly increased for various reasons, including steep ecological and geomorphological gradients, the presence of agro-cultural zones, population growth and its increasing needs, changes in the climatic situation, increased wind erosion activity, and also abrupt changes in land use. The research results of Kazakhstan and Central Asia by Jiang et al. (2019), Yerkin et al. (2022) and Miao et al. (2015) are consistent with the results of this study (Miao et al., 2015; Jiang et al., 2019a; Yerkin et al., 2022). Figure 8 shows that, except for the mid-altitude forested lands and the high-altitude parts in the south and east, the rest of the lands have a relatively high risk of rate desertification and land degradation.

4 Discussion

The dynamics of desertification are driven by a complex interplay of geomorphic structure (Lavee, 2024) and climatic conditions (Qi et al., 2024), with a significant contribution from human activities and policies (Shi et al., 2023; Chen et al., 2024). The results of our study indicate that changes in climate and land surface are the dominant factors influencing desertification in the region. Comparing the data with maps of geomorphological structure and climatic indicators revealed a strong dependence of desertification dynamics on these factors. Regarding the former, the basin's geomorphological structure is distinctive,

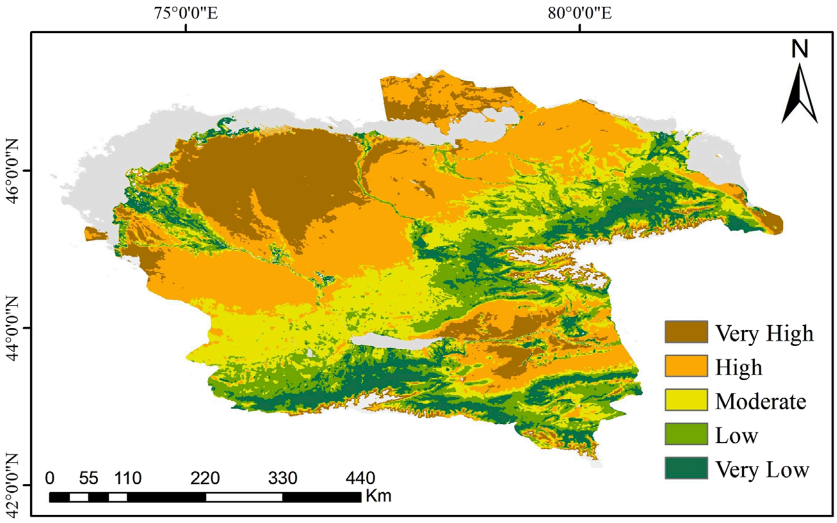

FIGURE 9
Desertification risk rate map.

with the basin bounded in the southeast and southern part by a high mountain range (Visloguzova et al., 1991). This creates conditions conducive to aeolian activity and active erosion processes in the foothill areas (Issanova et al., 2023). In the northern region, the basin contains a significant quantity of Quaternary loose sediments, including aeolian hilly ridge plains, which are susceptible to wind erosion. This provides a source of material for aeolian activity, which in turn causes widespread land desertification (Issanova et al., 2014). In the southern region, the landscape transitions from denudation plain to mountainous terrain.

Among the various natural factors, climate change significantly impacts the development of desertification. The main influencing factors of this process are temperature, precipitation and wind speed. The climate in the south of Kazakhstan, where the study area is located, is characterized by aridity throughout the year, with minimal precipitation. Therefore, precipitation plays an important role in the evolution of desertification. Studies of this region have shown that there is an upward fluctuation of the average annual temperature in the basin (Bayer-Altın et al., 2024), while there is a tendency for a slight increase in annual precipitation (Salnikov et al., 2023). This indicates that the climate has become warmer and wetter over the last 20 years (Akhmetova et al., 2019).

Concurrently, human activity is a contributing factor to the observed changes in DDI values. It is important to note that saxaul plantations are particularly susceptible to desertification. In areas where saxauls are cultivated, trees are felled for human consumption, and the vegetation cover is degraded by cattle grazing (Zhaglovskaya and Aidosova, 2014; Abdimutalip et al., 2023). Furthermore, the arid and semi-arid regions of the region have been extensively utilised for grazing since ancient times (Robinson et al., 2003; Kaldybaev et al., 2022). Since 2003, there has been a significant trend of increasing livestock numbers in Kazakhstan. Furthermore, the consumption associated with livestock production continues to grow, thereby exerting increased pressure on the carrying capacity of pastures. The impact of grazing is particularly evident in the northeastern region. The trampling of scarce vegetation by grazing animals has resulted in soil erosion and the degradation of vegetation cover (Kubenkulov et al., 2019; Gabdykadyr et al., 2020).

The study's findings indicate that most arable lands are experiencing a medium to low desertification process. In terms of temporality, the arable lands of foothill areas have transitioned from a low to a medium desertification rate over the 20 year period. In the vicinity of cities such as Almaty and Taldykorgan, the construction of highways and the need for economic development have led to the destruction of vegetation. This results in the conclusion that human activities have a predominantly negative impact on changes in the DDI value.

Since 1997, a series of initiatives have been implemented to combat desertification. Implementing tree planting and reforestation programmes, the restoration of soil fertility, the introduction of effective technologies, sand consolidation, and other similar initiatives can assist in expanding vegetation cover and enhancing ecological diversity (Atakulov et al., 2020). Various activities, including small-scale environmental rehabilitation measures such as reforestation, canal management, land planning, etc., are being implemented in the region (https://www.gov.kz/memleket). The desertification control measures implemented in these places have yielded significant results and improved environmental conditions (Naushabayev et al., 2023).

The human factor represents the most effective means of containing and reversing desertification. In Kazakhstan and the arid regions of Central Asia, desertification in forests and areas with sparse vegetation is highly sensitive to climate change, while human activities primarily drive the desertification of arable lands and grasslands (Hu et al., 2020; Yerkin et al., 2022). Consequently, local governments implement and promote reasonable planning and construction of engineering structures, the vigorous development of water-saving agriculture, and the popularization of optimised irrigation methods.

It is anticipated that, with continued technological advancements and a deeper understanding of climate change and anthropogenic impacts, scientifically grounded requirements and recommendations will play an increasingly pivotal role in combating desertification and mitigating its consequences. Nevertheless, the effectiveness of land management and environmental protection is dependent on the specific region under consideration. Consequently, it is challenging to quantify their role in risk mitigation, particularly on a global scale. Concurrently, this study's findings, which assess the risk of desertification in specific areas, can assist in identifying zones, collating an inventory, and mapping the development of desertification processes in particular natural-economic systems. In future studies, the applicability of this approach in a specific local region should be carefully verified based on comprehensive field data. Moreover, further research is necessary to elucidate these factors' contribution and ascertain the prevailing indicators and criteria for assessing desertification. The research team is currently employing the data obtained to develop a sustainable management system with the objective of preventing desertification.

5 Conclusion

This paper is based on a multi-year series of spectral indices (DDI, NDVI, EVI, LST and NPP) and climate variables for research purposes. The feature space for calculating DDI was constructed using NDVI and Albedo data. This investigates the spatial and temporal variability of desertification in the study region. The paper also analyses the spatial and temporal dynamics of DDI, the influence of climate factors, and human activities on DDI in the study area. We determined the zoning for desertification control in the Ile-Balkhash basin based on the assessment results. The following conclusions can be deduced:

(a) From 2002 to 2022, medium and high desertification land was the most common land type in the Ile-Balkhash Basin. From 2002 to 2015, medium desertification land became the most common land type in the study area, then high desertified land expanded. Severely desertified land area increased from 2002 to 2010, and then land decreased continuously from 2010 to 2020 and accumulated 15.6 thousand km^2.

Relative to its extent in 2002, low and non-desertified land decreased slowly.

Medium desertification land in the Ile-Balkhash Basin occurred primarily in foothill areas or the middle part of the basin, which represents desertification risks to the upland and foothill deserted desert landscapes, especially given neglected protective systems. As precipitation increases, growth of vegetation in foothill areas can promote the transition from medium desertification land to low desertification land.

(b) The intensity of desertification in the study area is mainly concentrated in the north and northwestern parts of the region, which are arranged in takyr soil deserts where overgrazing takes place, intermountain plains where it is actively used for farming.

(c) Precipitation mainly facilitates LST, while temperature plays a suppressing role compared with the correlation between spectral indices and DDI.

(d) The indicators were combined with a Principal Component Analysis (PCA) to develop a Land Degradation Risk area. The desertification risk rate map can be used to identify desertification control zones in the Ile-Balkhash region for which appropriate recommendations can be developed in the future.

The results may prove useful to competent organizations and departments of Kazakhstan in the formulation of comprehensive regional development systems: government agencies; scientific organizations dealing with problems of agriculture, land degradation, etc.

- the establishment of an advance warning system to predict the probability of drought occurrence;
- the dissemination of information to agricultural stakeholders regarding the presence of desertification risk;
- the implementation of a sustainable land management system, comprising land use planning for each specific sub-region;
- the implementation of a strategy for mitigating degradation and responding to areas requiring localized research.

There are still some limitations and uncertainties in this study that require further attention and investigation in the future. Firstly, the results indicate that increased precipitation over drylands can positively affect vegetation and thus prevent the expansion of infertile lands. It is important to note that changes in precipitation, especially extreme precipitation, can also lead to land degradation through soil erosion processes. Further verification is therefore required to confirm this relationship.

Furthermore, the application of the PCA method is not without its disadvantages. The application of PCA and the use of only spectral data resulted in the omission of certain factors that could also affect the analysis of desertification areas, such as soil, terrain, water indicators, land use, etc.

To gain a deeper understanding of the impact of human activity on desertification, it is necessary to conduct further observation-based research. Finally, the long-term dynamics of desertification are driven by climate change and anthropogenic land use and land cover change. Unfortunately, it is still challenging to ascertain the relative contribution of these two factors, given the limitations of the observational data currently available for analysis in this study. Further work based on more detailed modelling is required to address this issue.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: https://modis.gsfc.nasa.gov/data/dataprod/.

Author contributions

SB: Conceptualization, Formal Analysis, Writing–original draft, Writing–review and editing. RS: Conceptualization, Resources, Software, Writing–review and editing. AT: Formal Analysis, Writing–original draft, Writing–review and editing. NZ: Resources, Software, Writing–original draft. JX: Resources, Visualization, Writing–original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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