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RESEARCH ARTICLE

Monitoring of Vegetation Degradation in various Landscapes of the Moyinkum Desert, Kazakhstan

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Abstract: This study is devoted to assessing the degree of vegetation degradation in various landscapes of the Moyinkum Desert, taking into account the taxonomic diversity of flora, the structure of phytocenoses, and the agrochemical condition of soils. The aim of the work was to identify areas with signs of disturbance and to analyse the factors determining degradation processes. It was established that the flora of the region includes 773 species belonging to 366 genera and 77 families, among which Chenopodiaceae (Amaranthaceae s.l.), Asteraceae and Poaceae dominate. A significant proportion of weed species (up to 85%) in a number of communities reflects the disturbance of the natural cover. Agrochemical analysis showed heterogeneity of soils in terms of humus, nitrogen, phosphorus and potassium content, as well as biological activity. Plots Pm-14-01, Pm-14-02, Pm-15 and Pm-16 showed critically low levels of humus (0.07-0.20%), mobile forms of nutrients and high pH values (up to 10.4), indicating a high degree of degradation. At the same time, plots Rm-06-01 and Rm-10-01 are characterised by better soil conditions, but also by a high level of weed species, which indicates degradation of the vegetation cover. In such communities, half of the species are weeds and have no particular value for agriculture. The results highlight the need for differentiated measures to restore soil fertility and recultivate degraded land using species and technologies adapted to arid conditions.

Keywords: Agrochemical Indicators, Ecosystem Restoration, Moyinkum, Phytocenoses, Soil Fertility, Vegetation Degradation, Weed Species

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Introduction

The degradation of vegetation cover in arid and semi-arid regions is one of the key global environmental issues affecting ecosystem stability and the livelihoods of millions of people. Recent studies indicate that processes of vegetation degradation and desertification encompass more than 40% of the Earth's terrestrial surface, leading to a decline in biological productivity, loss of biodiversity, and deterioration of soil and hydrological conditions. The main drivers of these processes are anthropogenic pressures-such as overgrazing, land compaction due to irrigation, vegetation clearance, and intensive land development-combined with climate change manifested in rising temperatures and decreasing precipitation. The disruption of plant community structures intensifies erosion, reduces the capacity of ecosystems for self-regeneration, and leads to the loss of their regulatory functions. Under these circumstances, an integrated approach is required, incorporating vegetation monitoring, the use of remote sensing methods, climate trend modeling, and the development of sustainable land-use strategies aimed at preventing further degradation and restoring the ecological balance of arid ecosystems.

The Moyinkum Mountains are located in the southern part of the Republic of Kazakhstan, occupying the area between the Shu and Talas rivers. In the south, it borders the Kyrgyz Alatau, in the south-west the Karatau ridge, in the east the Shu-Ili Mountains of the Tien Shan mountain range, and in the north it is bordered by the clayey and rocky Betpakdala desert. The desert stretches from the south-east to the north-west for more than 550 km, from the Shu-Ili mountains to the narrow gorge between Betpakdala and the north-western end of the Karatau ridge. In terms of latitude, the width of the studied territory is 45 km at its narrowest point in the west, while in the east, the expanded part stretches from north to south for more than 160 km. Moyinkum belongs to the Epigercian Turan Plate and is part of the Shu-Sarysu Basin [1, 2].

The Moyinkum sands were formed by alluvial deposits from the ancient Shu and Talas rivers and formed during the Quaternary period. Most of it consists of Middle Neopleistocene-Holocene eolian deposits. Part of the territory in the east, on its northern edge, adjacent to the Shu River, is composed of Middle and Upper Neopleistocene alluvial deposits, which indicates significant meandering of the Shu River channel. In geomorphological terms, the surface of the Moyinkum is classified as an accumulative-denudational plain covered with a sandy substrate. Almost all forms of sandy desert relief are found here, with hummocky fixed sands predominating and cellular-hummocky, cellular-ridge, and hummocky-ridge fixed sands being widespread [1-4].

The degradation of vegetation cover is a serious environmental problem, leading to the loss of biodiversity, reduced ecosystem productivity, and exacerbated desertification processes, especially in arid regions of the planet [5-8]. One such region is the Moyinkum Desert, located in southern Kazakhstan, most of which lies within the Zhambyl Region, with a smaller part located in the north of the Turkestan Region. The uniqueness of this territory lies in its diverse natural landscapes, including barchan sands, fixed and unfixed sand masses, salt marshes and takyrs, each of which is characterised by specific ecological and geographical conditions and types of vegetation [1, 2, 9].

The Moyinkum Desert is a complex ecosystem where vegetation plays a critical role in maintaining landscape stability and preserving biodiversity. The vegetation of this region consists of desert formations adapted to extreme conditions of moisture deficiency, high temperatures, and intense solar radiation. Among the predominant species here are Haloxylon aphyllum, Calligonum spp., Artemisia spp., as well as many ephemeral and ephemeroids plants with a short vegetation cycle and a high degree of adaptation to arid conditions [1, 9-12].

However, despite the high adaptability of plants to unfavourable conditions, anthropogenic impact and climate change significantly intensify the processes of degradation of the vegetation cover of the Moyinkum Desert. The intensification of economic activity in this territory during the first quarter of the 21st century, primarily excessive grazing of domestic animals, as well as the expansion of irrigated land (construction of hydromeliorative structures), an increase in the area under mineral extraction enterprises and infrastructure facilities, is putting significant pressure on the region's natural complexes. This leads to the disruption of soil cover integrity, acceleration of wind and water erosion processes, and, as a result, degradation and desertification of the territory [6, 7]

A significant factor contributing to the degradation of vegetation in Moyinkum is overgrazing caused by an increase in livestock numbers and the lack of an effective system for managing pasture resources. Constant trampling of vegetation by animals leads to its depletion, a reduction in species diversity, and the replacement of valuable forage species with weeds and low-value plants that are unable to perform the ecosystem function of stabilising sandy soils.

Climate change observed in the region in recent years also exacerbates vegetation degradation processes. The increase in average annual temperatures, sharp fluctuations in average annual precipitation and, in some places, a decrease in precipitation are leading to increased aridification of the climate, which negatively affects the productivity of plant communities and their ability to recover after exposure to anthropogenic and natural stressors. Thus, the adaptive mechanisms of plants become less effective, leading to significant losses in biodiversity and the functional state of ecosystems [1, 9, 10, 12].

The issue of vegetation degradation in the Moyinkum Desert requires a comprehensive approach to assessing the current state of ecosystems. An important aspect in this context is the analysis and monitoring of the degree of vegetation degradation in various landscapes of the region using modern methods of remote sensing, geobotanical research, as well as mathematical and spatial modelling. Such approaches make it possible to identify changes in the structure and composition of plant communities in a timely manner, predict the further dynamics of degradation processes, and develop measures to prevent them and minimise negative consequences.

The aim of this work is to comprehensively assess the degree of degradation of the vegetation cover of various landscapes in the Moyinkum Desert, including identifying key factors influencing these processes and developing recommendations for optimising natural resource use and restoring ecosystems in the region. To achieve this goal, the following tasks are to be accomplished: conduct a detailed geobotanical analysis of the vegetation cover of various landscapes of Moyinkum; assess the extent of the impact of anthropogenic and climatic factors on vegetation degradation; apply remote sensing and geoinformation analysis methods to map and assess vegetation cover dynamics; develop practical recommendations for the sustainable management and restoration of degraded landscapes in the Moyinkum Desert.

Material and Methods

Mapping Methods

The objects of study are phytocenoses (communities) and soil cover of the Moyinkum Desert, in particular disturbed and slightly disturbed areas with the participation and dominance of weed species of desert flora. Using QGIS 3.40.2 (https://qgis.org, accessed on 5 July 2025), a map of the points of the studied samples was compiled (Fig. 1). The data for the study points are presented in Table 1.

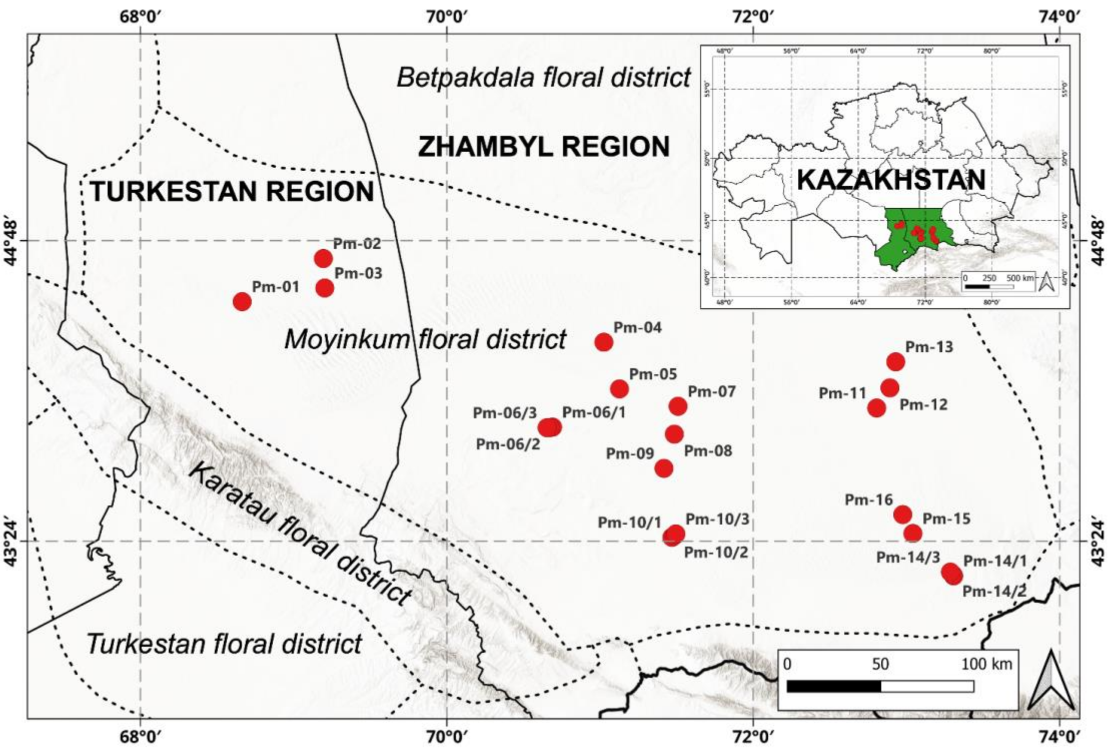

Fig. 1: Map of surveyed points in the Moyinkumsky floristic region

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Botanical Methods

The description of communities and collection of material for soil analysis was carried out during expeditionary research in 2024. Classical botanical methods (route reconnaissance; ecological-systematic; ecological-geographical) were used in the research process. Fundamental summaries were used to identify the collected material. The names of plant species were given in accordance with the International Plant Names Index (IPNI) database. The vegetation was studied using traditional methods of field geobotanical research, and all modern literature on the flora and vegetation of Kazakhstan was also studied [6, 7, 8, 15-18].

Geobotanical Methods

Geobotanical studies are a key tool for analyzing the state and dynamics of vegetation cover, allowing an objective assessment of ecosystem degradation and desertification processes. The applied methods are aimed at investigating the structure, floristic composition, and ecological-cenotic organization of plant communities.

For analytical purposes, permanent sample plots (10×10 m or 20×20 m) are established within the study area, with coordinates recorded using GPS. Landscape conditions - including microrelief, slope exposure, substrate type, and degree of anthropogenic disturbance - are taken into account. On each plot, a detailed inventory of the floristic composition is carried out, along with determination of plant life forms, ecological-cenotic affiliation, projective cover, height, and abundance of dominant species.

The collected data are subjected to statistical processing. To quantitatively assess species diversity, the Shannon diversity index (H') is used, which reflects the degree of species richness and the evenness of species distribution within a plant community. The index is calculated according to the following formula:

$$H^{'} = -\sum_{i=1}^{s} P_i 1np_i$$

Where *pi* is the proportion of the i^{th} species in the total abundance (or total projective cover) of all species, and *S* is the total number of species in the community. The values of the Shannon index characterize the structural complexity and stability of plant communities: High values (H' > 2.5-3.0) indicate stable, weakly disturbed phytocenoses; Low values (H' < 1.5) indicate degradation of vegetation cover, simplification of structure, and dominance of a limited number of species. In addition, indicators such as abundance, frequency, and integral projective cover are calculated, along with indices of synanthropization and ecological stability of the flora [19-21].

The main criteria of vegetation degradation include: a decrease in total projective cover by 20-30% relative to reference (undisturbed) plots; a reduction in the proportion of typical and dominant species, accompanied by an increase in ephemeral and ruderal forms; simplification of the vertical structure and a decrease in total phytomass.

Comprehensive assessment using the Shannon index makes it possible not only to quantify biodiversity levels but also to trace the direction of degradation processes, which is of particular importance for developing scientifically grounded measures for vegetation conservation and restoration under increasing anthropogenic and climatic pressure.

Soil Research Methods

The following instructional and methodological documents were used: Instructions for conducting large-scale soil surveys of the Republic of Kazakhstan; Systematic list and main diagnostic indicators of soils in the flat territory of the Republic of Kazakhstan.

A general route survey of the territory to be studied was conducted with the aim of identifying patterns in the distribution of soils and soil-forming rocks, as well as their connection with vegetation. The route survey of the territory included clarification of the landscape, geomorphological and hydrogeological conditions that determine the impact on soils [22-24].

The reconnaissance survey made it possible to visually determine the initial condition of the soils, the nature of their use, potential factors of degradation, and to identify locations for soil profiles. Observation points were planned based on the results of space image analysis during the preparatory stage.

Soil profiles were systematically established during field studies in 2024, taking into account the meso- and micro-relief, vegetation cover, and the identified types and degrees of degradation. Particular attention was paid to the most characteristic forms of degradation, such as secondary salinisation, erosion, pasture degradation, and soil compaction [25]. Each section was excavated to a depth of at least 100 cm to the parent rock horizon. When describing the horizons, the depth and thickness, colour (according to the Munsell scale), mechanical composition, structure, density, root penetration, pore characteristics, and boundary clarity were recorded. This approach is fully consistent with the FAO [26]. Morphological data were recorded in standard field forms for soil profile description, which ensured the comparability and reproducibility of the information obtained. Based on these diagnostic features, a field genetic classification of soils was carried out in accordance with the WRB reference soil groups [27]. Soil samples were taken from the selected horizons for subsequent physical and chemical analysis.

Soil-ecological studies were carried out to identify changes in the physical, chemical, and physicochemical properties of soils caused by vegetation degradation, anthropogenic impact, and the processes of territorial aridization. This approach allows for a comprehensive assessment of soil fertility dynamics, structural transformations, and their interrelation with the stability of plant communities and overall ecosystem functioning. Soil sampling was conducted at the same permanent plots where geobotanical investigations were performed, ensuring the comparability of soil and floristic datasets. Samples were collected from standard genetic horizons (0-10, 10-30, and 30-50 cm) using soil augers and monolith cores in accordance with international methodological standards [28, 29]. Each sample was placed in labeled polyethylene bags, air-dried, and sieved through a 1-mm mesh. Duplicate samples were taken to increase analytical reliability.

Laboratory analyses included the determination of key parameters characterizing the state and degree of soil degradation. Humus content was determined by the Tyurin method (modified Walkley-Black procedure) in accordance with GOST 26213-91 and ISO 14235:1998. Soil texture (particle-size distribution) was determined by the pipette or hydrometer method [30]. The soil reaction (pH) was measured potentiometrically in water and 1N KCl suspensions [31]. Electrical conductivity (EC) was determined using a conductivity meter to assess soil salinity levels [32]. Bulk density and total porosity were determined by the core (cutting-ring) method, while field moisture capacity and hydraulic conductivity were determined using a double-ring infiltrometer and the Richards pressure plate apparatus [28]. The content of exchangeable cations (Na^+, Ca^{2+}, Mg^{2+}) was determined after extraction with 1N ammonium acetate followed by analysis using atomic absorption spectrometry.

The assessment of soil degradation was performed by comparing the obtained values with those of reference (control) soils unaffected by anthropogenic disturbance. The main degradation criteria included: a reduction in humus content by 25% or more relative to reference soils, indicating organic matter depletion and decreased biological activity; an increase in salinity (EC > 2-4 $dS \cdot m^{-1}$) and alkalinity (pH > 8.0), reflecting the development of secondary salinization and sodicity processes; and an increase in bulk density (> 1.5 $g \cdot cm^{-3}$ for sandy loams and loams), accompanied by reduced infiltration, deterioration of soil structure, and the appearance of erosion features.

The methodological framework of this study complies with current international standards and guidelines as outlined in the FAO Soil Description Manual [28] and the ISO standards [29-32], as well as in the works of [34] and [35]. This ensures the scientific validity, comparability, and reproducibility of the obtained results.

Physicochemical analyses of soils were carried out at the accredited Chemical Analysis Laboratory of the U.U. Uspanov Kazakh Research Institute of Soil Science and Agrochemistry (Almaty, Kazakhstan), which holds an official license for conducting certified soil and environmental research. All laboratory procedures were performed in strict accordance with national (GOST) and international (ISO) standards, ensuring the accuracy, reliability, and reproducibility of the obtained results.

Statistical Methods

For statistical processing, systematization, and visualization of data, the specialized software [36] (OriginLab Corporation, Northampton, MA, USA) was employed. This program represents a modern analytical platform designed for advanced scientific research and provides a comprehensive suite of tools for mathematical and statistical analysis, correlation assessment, and graphical visualization. Its wide range of analytical and visualization capabilities makes it an effective instrument for studies in soil science, ecology, and agrochemistry.

Using [35], preliminary data processing was carried out, including normalization, distribution testing, outlier detection and removal, approximation, and data smoothing. Subsequently, descriptive statistical analyses were performed to calculate mean values, standard deviations, coefficients of variation, and confidence intervals for key soil parameters such as pH, humus content, electrical conductivity, and bulk density. Correlation analysis was applied to determine relationships among physicochemical soil properties, while regression analysis (linear, polynomial, and exponential) was used to model dependencies between soil degradation indicators and environmental factors. To verify statistically significant differences between samples across horizons and study plots, analysis of variance (ANOVA) was performed. In addition, multivariate statistical techniques, including Principal Component Analysis (PCA) and cluster analysis, were used to classify soil samples based on a combination of measured parameters.

For data visualization, the built-in graphical modules of OriginPro were utilized to construct line and scatter plots, histograms, correlation matrices, three-dimensional surface models, and heatmaps. All figures were formatted according to scientific standards, with labeled axes, measurement units, and statistical coefficients clearly indicated. The application of [35] OriginPro 2024 enabled a comprehensive and methodologically sound analysis of soil-ecological parameters, allowing the identification of spatial and temporal variability patterns and the determination of relationships between soil properties, vegetation cover, and climatic conditions. This approach significantly enhanced the accuracy of data interpretation and the reliability of the scientific conclusions.

Climatic Methods

Climatic data on temperature and precipitation were collected to analyze the long-term dynamics of climatic conditions, identify seasonal variations, and assess their influence on the vegetation cover of the study area. The main sources of information included materials from Kazhydromet, the global databases NASA POWER, NOAA, and WorldClim, as well as data from the nearest meteorological stations. To ensure the reliability of the research, long-term observation series covering the period from 1991 to 2024 were used, allowing the identification of long-term climatic trends and their ecological implications.

At the data preparation stage, all records were verified and standardized. Temperature values were converted to degrees Celsius (°C), and precipitation to millimeters (mm). Missing, duplicated, or anomalous values were removed from the dataset. Based on daily measurements, monthly and annual averages were calculated using the arithmetic mean formula:

$$\bar{T} = \frac{\sum T_i}{n} \; P = \frac{\sum P_i}{n}$$

Where Ti represents daily temperature, Pi is daily precipitation, and n is the number of days in the corresponding month.

Data processing and visualization were carried out using Microsoft Excel, which provides efficient tools for analyzing climatic time series. The tables included monthly temperature and precipitation values for each observation year. Annual averages and totals were calculated using the built-in functions AVERAGE and SUM. Based on the processed data, line charts (for temperature dynamics), bar charts (for precipitation distribution), and combined diagrams (temperature as a line and precipitation as columns) were constructed to visually represent the seasonal relationships between thermal and hydrological regimes. Graph axes were labeled with measurement units, and major climatic seasons-winter, spring, summer, and autumn were indicated. To identify temporal trends in climatic parameters, the “Add Trendline” function in Excel was applied, allowing determination of the direction and magnitude of temperature and precipitation changes over time. The coefficient of determination (R^2) was used to evaluate the reliability of trend approximations and the degree of variability explanation. Additional decade-based graphs were constructed when necessary to compare changes across different time periods. The interpretation of the obtained data was carried out in accordance with the ecological and geographical characteristics of the region. An increase in mean annual temperature combined with a decrease in precipitation was interpreted as an indicator of climate aridization and vegetation degradation. Conversely, an increase in precipitation and a reduction in temperature amplitude were regarded as signs of climatic stabilization. Seasonal differences in precipitation distribution were analyzed to evaluate soil moisture regimes and plant community adaptation strategies. For data systematization and graphical analysis, Microsoft Excel and LibreOffice Calc were employed, while NASA POWER and WorldClim online platforms were used for additional data validation and verification. The results obtained allowed for a quantitative assessment of climatic variability, identification of major trends, and creation of visual models illustrating the spatio-temporal characteristics of temperature and precipitation regimes across the studied area.

The applied methodological approach was based on established principles of climatological and geobotanical research [36-38].

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Results and Discussions

Analysis of the Species Composition of the Moyinkum Floristic Region

Based on the analysis of the presented taxonomic table of the flora of the Moyinkum desert, a generalised scientific assessment of taxonomic diversity can be made, reflecting the characteristics of the arid flora of Central Asia. According to the data presented, the flora of the Moyinkum region includes 773 species of vascular plants belonging to 366 genera and 77 families, which demonstrates a fairly high species and genus richness even in a desert ecosystem. This indicates high ecological plasticity, the adaptability of plants to extreme conditions, and the presence of a wide range of adaptation strategies. [39].

The structure of the flora is dominated by a few families (Fig. 2), which contain the largest number of species and genera (Fig. 3). The Chenopodiaceae family ranks first in terms of species richness, comprising 96 species belonging to 33 genera. This is logical, since representatives of Chenopodiaceae are typical inhabitants of saline, dry, and sandy habitats, possessing xeromorphic characteristics and resistance to drought and salinity. Species of this family are often edifiers of desert communities. Second place is occupied by Asteraceae (composites), represented by 83 species from 40 genera. This is one of the largest families in the world's flora, and its high presence here reflects both the overall floristic richness and its important role in desert and semi-desert phytocenoses. The third most important family is Poaceae (grasses), represented by 73 species from 35 genera, which emphasises the leading role of grasses in the structure of desert vegetation and their wide ecological amplitude [39].

Next come Brassicaceae (72 species, 43 genera), Fabaceae (53 species, 18 genera), Polygonaceae (32 species, 6 genera), Apiaceae (39 species, 15 genera) and Boraginaceae (31 species, 17 genera) (Fig. 2). These families include both ephemeroids and ephemerals, as well as stable perennials capable of quickly completing their life cycle in spring moisture conditions or surviving thanks to their underground organs. The widespread presence of these groups is also due to the high adaptability of their representatives to arid conditions and disturbed habitats [39].

Many other families, such as Caryophyllaceae, Cyperaceae, Scrophulariaceae, Rosaceae, Malvaceae, Solanaceae, and Lamiaceae, are represented by fewer species but also play a significant role in the region's biodiversity. Some of them include species that are highly bioindicative or used for economic purposes (medicinal, fodder, honey plants). The presence of families such as Ranunculaceae, Euphorbiaceae, Tamaricaceae, Limoniaceae, Primulaceae, Orobanchaceae and Convolvulaceae confirms the diversity of ecological niches represented in the Moyinkum Desert - from saline areas and temporary watercourses to psammophytic communities and areas with temporary moisture.

Special attention should be paid to the significant number of monotypic and oligotypic families: in total, about 30 families are represented by only one species. This may indicate the marginal position of the ranges of a number of species, limited ecological and geographical specialisation, as well as the rarity and possible vulnerability of these taxa. Monotypic families such as Ceratophyllaceae, Cannabaceae, Capparidaceae, Iridaceae, Asphodelaceae, Callitrichaceae, Zannichelliaceae, etc. are important in assessing the uniqueness of the flora and the potential need for their protection.

The taxonomic ratio between the numbers of families, genera, and species in the Moyinkum Desert (77:366:773) reflects a high species saturation coefficient (on average about 10 species per family and more than 2 species per genus), which is characteristic of arid zones with high adaptive specialisation and the formation of stable but diverse communities. This ratio indicates both the stability and the sustainable speciation potential of the region's flora.

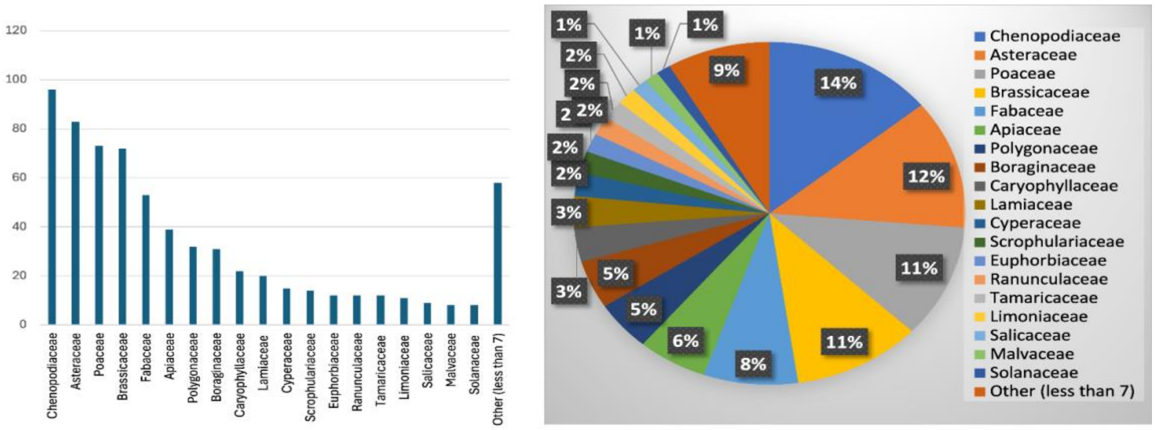

Fig. 2: Quantitative and percentage indicators of the leading families of the Moyinkum Desert

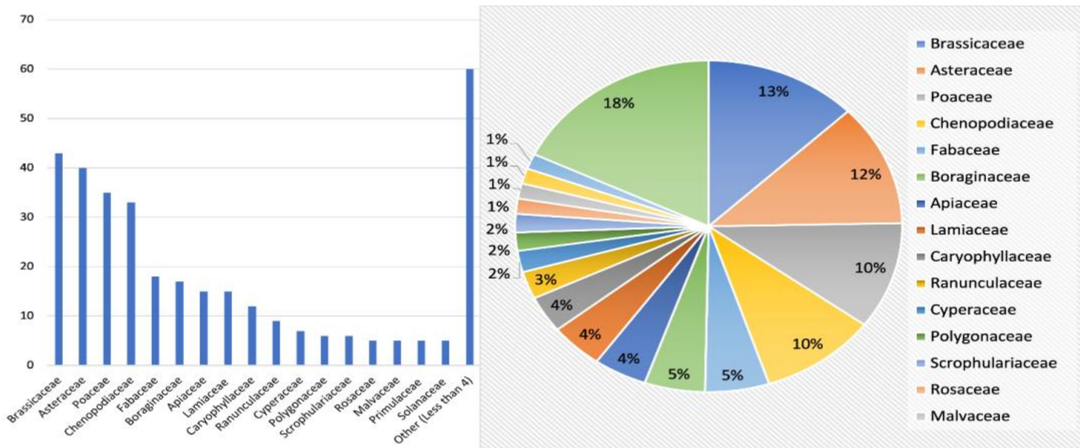

Fig. 3: Quantitative and percentage indicators of births among leading families in the Moyinkum Desert

Thus, the flora of the Moyinkum Desert is characterised by the pronounced dominance of a few arid families, a high representation of ephemeral, ephemeroids and xerophytic forms, as well as the presence of a significant number of unique and limitedly distributed taxa. This diversity reflects the complex historical and floristic path of the region, a combination of elements from various floristic regions (Central Asian, Iranian-Turanian, Siberian) and the high ecological mosaicism of the territory. The data obtained confirm the importance of the flora of the Moyinkum Desert for assessing biodiversity, monitoring natural resources, and developing measures to preserve unique phytocenoses in the face of increasing climatic and anthropogenic pressure.

Average Annual Precipitation in Different Parts of the Moyinkum Desert (Fig. 4)

Average annual precipitation values are an important indicator of climate stability and water balance in natural areas. Analysis of data for a 44-year period (1980-2023) from five climate stations in southern Kazakhstan - Moyinkum, Ojyk, Ulanbel, Tasty and Kulan - reveals spatial and temporal differences in moisture distribution and identifies areas prone to climatic anomalies and possible ecosystem degradation (Fig. 4).

The driest area among all stations is the Ulanbel region, where average annual precipitation ranges from a minimum of 86.5 mm (1995) to 231.2 mm (1993). The long-term average is about 155 mm, reflecting a typical arid climate with a high risk of soil and vegetation degradation. This site is characterised by both significant fluctuations and a lack of steady precipitation growth, especially in recent years. Comparable conditions are observed at the Tasty station, where the average precipitation is slightly higher, at around 144 mm. However, this area shows less stability: more frequent extreme decreases in precipitation are observed, especially during the dry periods of the mid-1990s.

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The opposite picture is observed in Kulan, where the highest average annual values are recorded - over 450 mm, with peaks of up to 643.9 mm in 1987. The average value exceeds 459 mm, which is more than three times higher than in Ulanbel. Such humidity is probably due to the orographic features of the relief and the location in a more favourable climatic zone. Nevertheless, even here in recent years (2021-2023), a decrease in precipitation to levels below 400 mm has been recorded, which may indicate a regional trend towards aridisation.

The intermediate position is occupied by the stations of Moyinkum and Ojyk. In Moyinkum, precipitation varies between 146 and 310 mm, with an average of about 222 mm. The territory is characterised by alternating wet and dry years, with a decline in precipitation levels over the past 10-15 years. In Ojyk, on the contrary, there has been a positive trend, especially since the early 2000s. The average value is about 246 mm, making it one of the most stable among the regions considered. Wet peaks (e.g., in 2003, 2016, 2022) confirm the favourable conditions that have persisted over the past decades.

The year 1995 deserves special attention, as it proved to be critical for all locations. All regions without exception saw a sharp decline in annual precipitation: from 86.5 mm in Ulanbel to 274.9 mm in Kulan. This suggests an extreme drought covering a wide area, which probably had a negative impact on vegetation, soil cover, and water regime.

Thus, a comparative analysis of average annual precipitation reveals clearly defined zonality and spatial heterogeneity of moisture. The most climatically stable areas are Kulan and Ojyk, while Ulanbel and Tasty show signs of chronic aridity. Moyinkum occupies an intermediate position, although signs of moisture reduction have also been recorded in recent years. The general trend towards lower precipitation in the 2010s and 2020s, observed at almost all stations, requires further comprehensive study using climatic and geobotanical data to assess the vulnerability of regional ecosystems and plan measures to adapt to changing climatic conditions.

Assessment of the Temperature of the Study Area (Fig. 5)

Analysis of the average annual temperature in southern and south-eastern Kazakhstan, covering the stations of Ojyk, Ulanbel, Kulan, Tasty and Moyinkum for the period 1980-2023, revealed both general trends of climate warming and territorial differences related to geographical location and microclimatic conditions (Fig. 5). All the stations under consideration show a steady increase in temperatures, which has been particularly pronounced since the 2000s, but the extent and nature of this increase vary depending on the natural conditions of the specific locality.

The highest temperatures throughout the entire period were observed at the Ojyk point. Already in the 1980s, temperatures of 11.0-11.5°C were recorded here, and by 2023 they reached an absolute maximum of 13.8°C. This increase of more than 2.5°C reflects the high sensitivity of this territory to global climate change. Similar dynamics are demonstrated by the Ulanbel station, where temperatures also rose from 9.0-10.0°C in the 1980s to 12.6°C in 2023. The Ojyk and Ulanbel areas probably have similar climate-forming characteristics: low-lying position, flat landscape, and less shade contribute to heat accumulation, making them most vulnerable to warming.

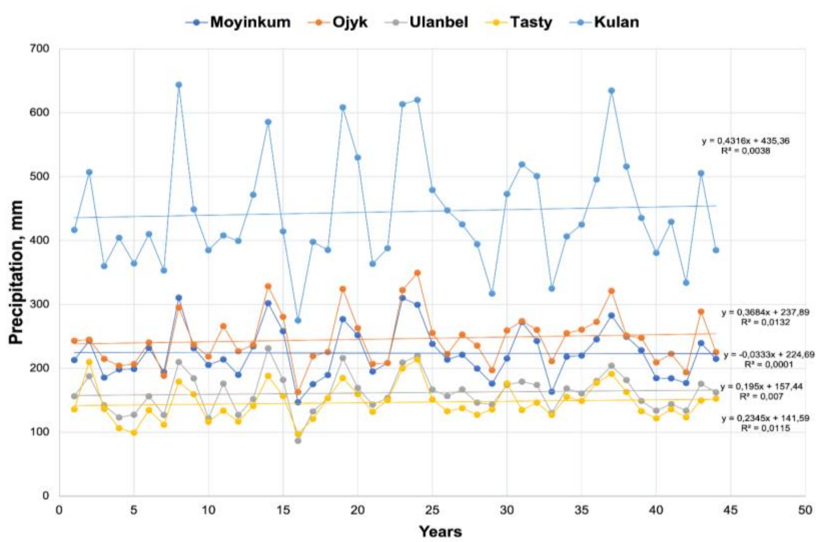

Fig. 4: Precipitation index in the study area

Kulan, on the other hand, has the coolest thermal regime. The average annual temperature here remained significantly lower than at other stations throughout the entire period, dropping to minimum values of 4.9-5.0°C in the 1980s and 1990s. Even in 2023, against the backdrop of general warming, the temperature was only 8.4°C, which is 4-5°C lower than in neighbouring flat areas. This is probably due to the high altitude of the territory, the peculiarities of the relief, or orographic screening, which prevents intensive warming. Despite the continuing temperature deficit, Kulan is also characterised by a positive thermal trend.

The stations of Tasty and Moyinkum occupy an intermediate position in terms of both temperature values and the intensity of their growth. In Tasty, the average temperature at the beginning of observations was about 10.5°C, and in 2023 it reached 13.1°C. In Moyinkum, the situation is similar: from 10.0-10.8°C in the 1980s to 12.9°C in recent years. Such dynamics indicate increased aridisation, especially in sandy and semi-desert landscapes. Here, rising temperatures can have a particularly strong impact on the water regime and seasonal activity of vegetation cover.

Thus, the results of the analysis allow us to conclude that there is a pronounced and accelerated warming of the climate in southern Kazakhstan, accompanied by a clearly expressed territorial differentiation. Flat areas (Ojyk, Ulanbel) show the most intense temperature increase, while elevated and more continental areas (Kulan) remain relatively 'cold zones'. This highlights the need for a regionally differentiated approach to environmental monitoring, climate risk forecasting, and the development of adaptation strategies for natural and agricultural systems.

An analysis of long-term data on average temperature and precipitation for the period 1980-2023 in southern Kazakhstan (at the stations of Ojyk, Ulanbel, Qulan, Tasty and Moyinkum) revealed stable climate trends that have a significant impact on the state of vegetation, its productivity, composition and structure of phytocenoses. In arid and semi-arid landscapes, even slight fluctuations in temperature or precipitation can determine the direction of degradation or, conversely, the temporary stabilisation of natural ecosystems.

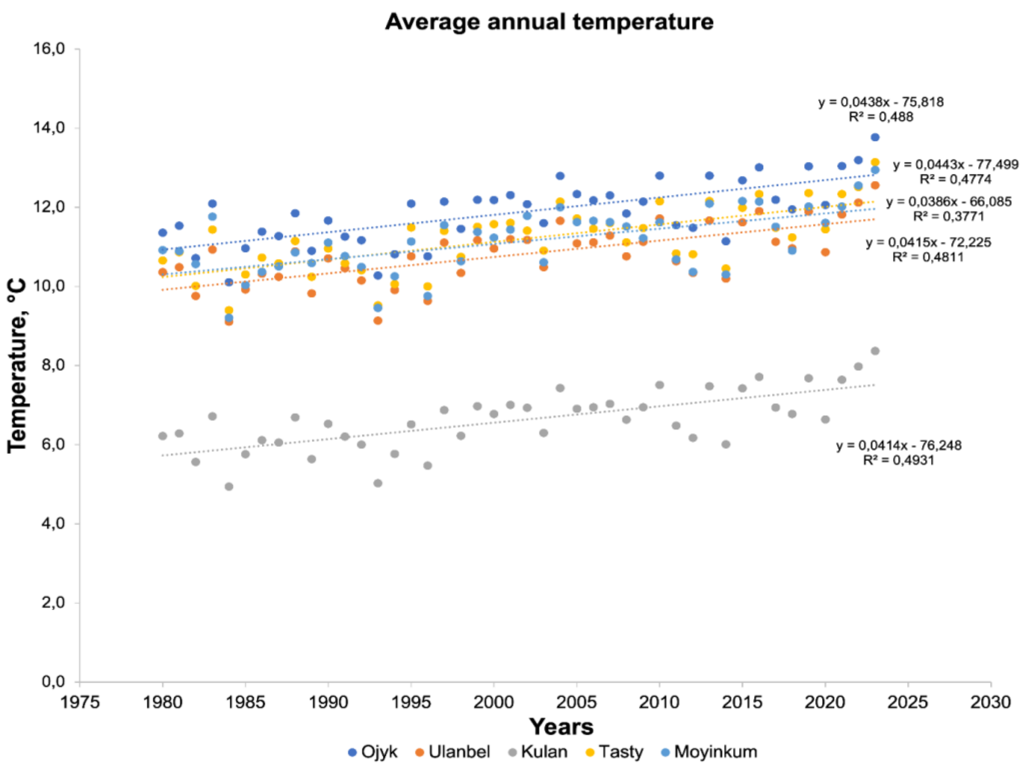

Fig. 5. Average change in temperature conditions in the study area

Overall, during the period in question, the average annual temperature in the study area increased by 2-2.5°C. Particularly intense growth has been observed since the 2000s, and by 2023, average annual values exceeded 12°C at most stations, including 13.8°C in Ojyk and 12.9°C in Moyinkum (Fig. 6). This thermal shift is accompanied by an increase in the length of the growing season, an earlier onset of spring regrowth, and a longer summer photosynthetic season. However, despite the seemingly positive impact on plant growth, this trend has a dual effect.

On the one hand, the increase in temperature contributes to the activation of spring-summer ephemeroid and ephemeral vegetation growth, especially in more humid areas (Kulan, Ulanbel). On the other hand, combined with lower or unstable precipitation, this factor increases aridisation, leads to soil drying in the summer months, accelerates evapotranspiration, and limits the productivity of perennial species, especially in areas with shallow soil profiles and poor moisture accumulation (Moyinkum, Tasty).

Analysis of precipitation showed that, against the backdrop of thermal warming, most locations did not experience a corresponding increase in moisture supply. On the contrary, at a number of sites (Ulanbel, Tasty, Moyinkum), there is a steady trend towards a decrease in average annual precipitation or high interannual variability, including extremely dry years (e.g., 1995, 2012, 2021). Ephemeroid-cereal vegetation and species dependent on spring moisture are particularly sensitive to such conditions.

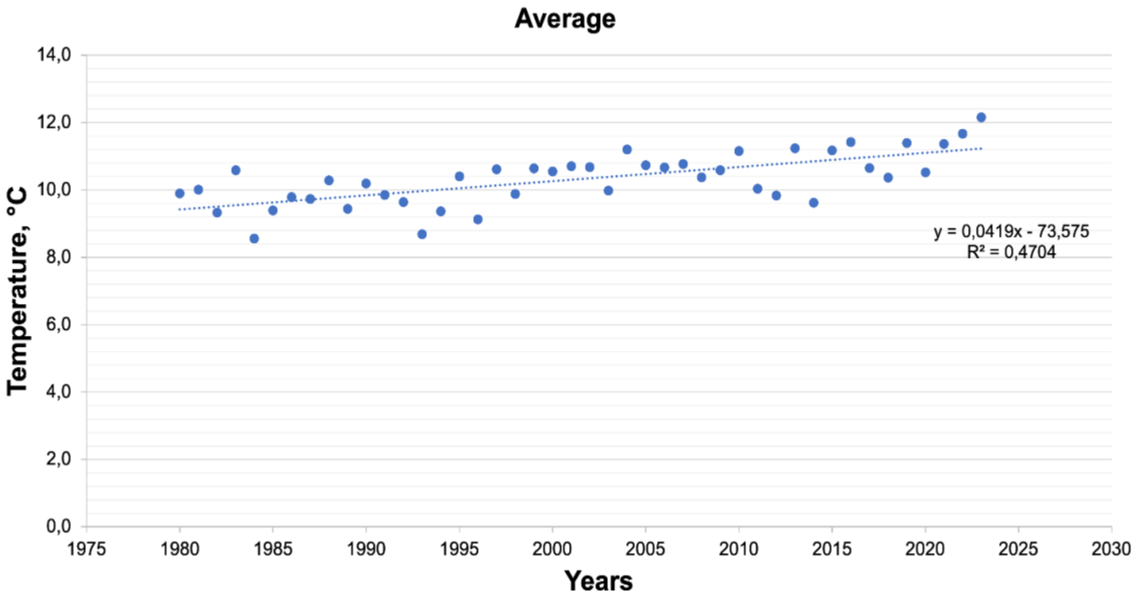

Fig. 6: Average change in temperature conditions in the Moyinkum desert by year

The Impact on Vegetation can be Identified in the Following Aspects

Changes in phenology and biomass. Rising temperatures stimulate early growth and rapid development phases in ephemerals. This leads to a reduction in the active growing season and a decrease in accumulated biomass, especially when there is a lack of precipitation in April-May. Ephemerals bloom earlier but die off more quickly, disrupting the seasonal structure of phytocenoses.

Decrease in the proportion of perennials and xerophytic shrubs. Against the backdrop of warming and lack of moisture, soil moisture reserves are depleted in early summer. This has an adverse effect on the proportion of perennial grasses and semi-shrubs, including representatives of the genera *Artemisia, Stipa*, *Festuca*, and *Astragalus*, which require a longer period of moisture for the formation of shoots and reproductive organs.

Increase in the proportion of thermophilic and desert species. Warming and drying of the environment contribute to the expansion of the ranges of desert and sub-desert species, such as *Anabasis salsa*, *Calligonum* spp., and *Agriophyllum pungens*. This changes the structure of the vegetation cover, increases soil exposure, and contributes to erosion processes.

Increased risk of phytocenosis degradation. Decreased precipitation, especially during high summer temperatures, leads to insufficient recovery of vegetation after spring activity. This results in a decrease in projective cover, an increase in the proportion of degraded areas, and the formation of stable erosion forms. This is particularly pronounced in Tasty and Moyinkum, as sandy and sandy loam soils do not retain moisture well [40-42, 44-47].

Thus, the combination of rising temperatures and unstable or declining precipitation creates conditions for the transformation of natural communities. A warmer climate accelerates plant life cycles, but a lack of moisture makes them less biologically resilient. Areas with light soils, weak humus horizons, and no forest cover are particularly vulnerable. In such conditions, the stability of phytocenoses is determined not only by the climate, but also by anthropogenic pressure (grazing, ploughing, fires), which greatly amplifies the negative effects of climate trends.

Consequently, data on temperature and precipitation, considered in combination, allow us to conclude that the southern regions of Kazakhstan are in a zone of active climate transformation, and without adaptive environmental planning, the destruction of natural ecosystems may accelerate.

Assessment of Phytocenoses

Analysis of phytocenotic data from 22 research sites (Table 1, Fig. 6) in southern and south-eastern Kazakhstan revealed significant differences in vegetation composition, degree of disturbance and the role of weed species in different types of communities. The data presented cover a wide range of phytocenoses - from typical wormwood and cereal communities to pseudo-sapphire and ephemeral-cereal communities, with the proportion of weed species serving as an important parameter for assessing the ecological state of the vegetation cover.

The number of species in communities varies from 7 to 20, reflecting both the natural characteristics of habitats and the degree of anthropogenic impact. At the same time, the number of weed species in some areas reaches 6-8, and their share in the total species composition often exceeds 50%. The average level of weed infestation in the sample is about 35-40%, which already indicates a violation of the stability and succession maturity of a number of plant groups. A particularly high proportion of weed components is recorded in communities represented by the types Hordetum, Pseudosophoretum and Poetum Alhagiosum, where weeds occupy a significant niche in the composition of the layer. For example, at point Pm-06/2, 6 out of 7 species are weeds, which is 85.7%; at point Pm-10/1, weeds make up 50% of the total number, and at Pm-14/3, more than 58%. This indicates an intensive disturbance of the vegetation cover, most likely as a result of prolonged grazing, secondary overgrowth of fallow land, or the impact of water factors in semi-floodplain conditions.

On the other hand, in a number of locations, mainly in areas with a high degree of preservation and a predominance of xerophytic perennials, the number of weed species is significantly lower. Thus, in phytocenoses dominated by species *Stipa capillata*, *Bromopsis inermis*, *Poa bulbosa* и *Krascheninnikovia ceratoides*, such as Pm-10/3, Pm-14/1 and Pm-13, the proportion of weed species varies between 10 and 20%, which indicates the resilience of these communities to exogenous disturbances. The characteristics of the soil and hydrological regime, relief, and exposure of the sites also influence the level of weed infestation: in higher and sandy areas, weed species are less common, while in floodplain and humid areas, on the contrary, their proportion increases. This can be clearly seen at points Pm-09, Pm-10/1 and Pm-14/3, where relatively high humidity is combined with a variety of weed forms and the dominance of aggressive or competitive species such as *Hordeum leporinum, Ceratocarpus arenarius, Pseudosophora alopecuroides* and *Alhagi pseudalhagi*.

Table 1: Described communities in the study area

№	Point number	Community	Coordinates	Total projected coverage, %	Dominant(s)	Number of species	Number of weed species
1	Pm-01	*Atremisietum Calligonosum*	44.518 68.664 h-258 м	10-20%	*Calligonum aphyllum Artemisia terrae-albae*	8	3
2	Pm-02	*Atremisietum*	44.717 69.194 h-252 м	20-30%	*Artemisia terrae-albae*	9	4
3	Pm-03	*Artemisietum*	44.581 69.203 h-281 м	15-25%	*Artemisia terrae-albae*	10	2
4	Pm-04	*Bromopsetum Artemisiosum*	44.330 71.025 h-416 м	15-25%	*Artemisia terrae-albae Bromopsis inermis*	10	3
5	Pm-05	*Hordetum*	44.113 71.127 h-426 м	10-20%	*Hordeum leporinum*	12	1

6	Pm-06/1	*Alhagetum*	43.935 70.690 h-412 м	5-10%	*Alhagi pseudalhagi*	10	5
7	Pm-06/2	*Pseudosophoretum*	43.933 70.674 h-411 м	10-20%	*Pseudosophora alopecuroides*	7	6
8	Pm-06/3	*Artemisietum*	43.932 70.654 h-403 м	30-40%	*Artemisia terrae-albae*	9	3
9	Pm-07	*Artemisietum Bromopsiosum*	44.032 71.509 h-420 м	20-30%	*Bromopsis inermis* *Artemisia terrae-albae*	20	2
10	Pm-08	*Artemisietum Krascheninnikoviosum*	43.902 71.485 h-427 м	50-60%	*Krascheninnikovia ceratoides* *Artemisia annua*	12	4
11	Pm-09	*Hordetum Phragmitosum Pseudosophosum Artemisiosum*	43.742 71.417 h-445 м	70-80%	*Artemisia pauciflora* *Pseudosophora alopecuroides* *Phragmites australis* *Hordeum leporinum*	18	8
12	Pm-10/1	*Poetum Alhagiosum Pseudosophosum*	43.418 71.469 h-494 м	50%	*Poa bulbosa* *Alhagi pseudalhagi* *Pseudosophora alopecuroides*	16	8
13	Pm-10/2	*Artemisietum*	43.426 71.485 h-498 м	80-90%	*Artemisia pauciflora*	10	2
14	Pm-10/3	*Artemisietum Stiposum*	43.434 71.495 h-500 м	90-95%	*Artemisia terrae-albae* *Stipa capillata*	10	2
15	Pm-11	*Poetum Ceratocarposum*	44.024 72.806 h-436 м	75-95%	*Poa bulbosa* *Ceratocarpus arenarius*	9	3
16	Pm-12	*Poetum*	44.118 72.892 h-420 м	80-85%	*Poa bulbosa*	10	3
17	Pm-13	*Artemisia Suaedosum*	44.239 72.930 h-353 м	50%	*Suaeda physophora* *Artemisia terrae-albae*	8	1
18	Pm-14/1	*Aeluropetum*	43.236 73.308 h-610 м	15%	*Aeluropus littoralis*	7	1
19	Pm-14/2	*Pseudosophoretum*	43.242 73.303 h-629 м	30-40%	*Pseudosophora alopecuroides*	9	5
20	Pm-14/3	*Alhagetum*	43.254 73.287 h-632 м	60%	*Alhagi pseudalhagi*	12	7
21	Pm-15	*Hordetum*	43.436 73.042 h-675 м	30-40%	*Hordeum leporinum*	9	2
22	Pm-16	*Hordetum*	43.525 72.976 h-644 м	60-70%	*Hordeum leporinum*	10	2

Pm-n/n - Sampling points are labeled as ‘Pm’ (Project Moyinkum), followed by site and profile number (e.g., Pm-06/1)

The data obtained allow us to conclude that weed species are an important indicator of vegetation condition and reflect both the current disruption of the biocenotic structure and the trajectory of phytocenosis transformation. The increase in weed components is accompanied by a simplification of community structure, a decrease in the participation of perennial grasses and semi-shrubs, and a reduction in overall projective cover. The situation is particularly unfavourable when high weed load is combined with low abundance of dominant xerophytes and poorly developed stratification, which is characteristic of points with low projective cover (up to 10-20%). At the same time, stable phytocenoses with a high degree of closure, species saturation, and the presence of climatic dominants are characterised by a lower level of weediness.

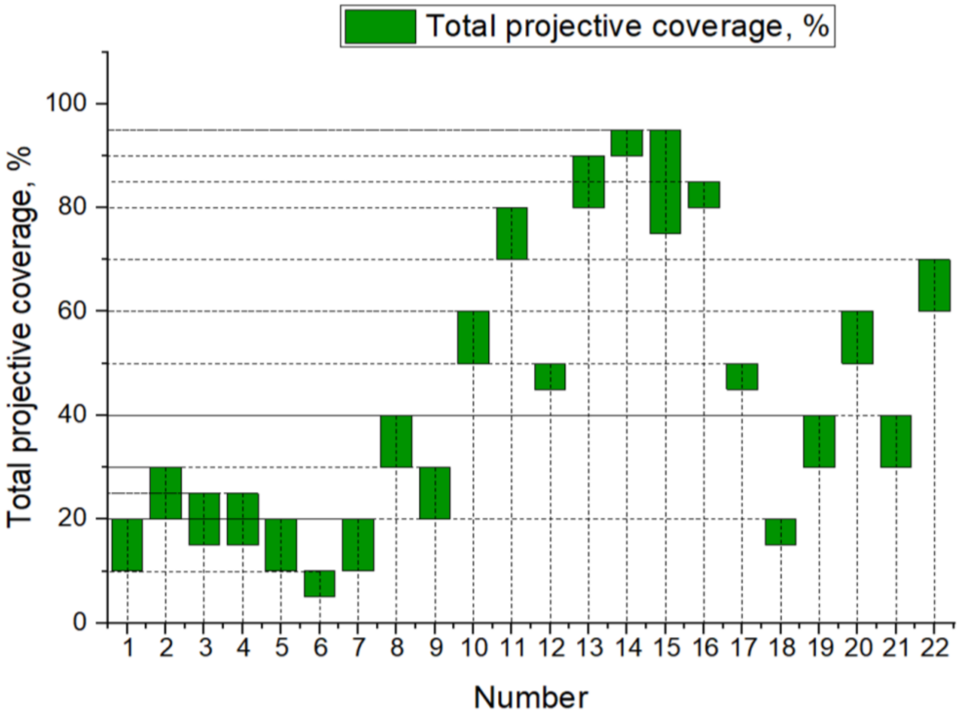

Fig. 7: Total projective coverage

Thus, weed species in the phytocenoses of the region under consideration perform the function of indicators of anthropogenic and climatic stress, reflecting the degree of resistance of plant communities to external influences. Their quantitative analysis and spatial distribution make it possible to judge the trends of degradation, stages of secondary succession, and priority areas of environmental monitoring and restoration of pasture ecosystems in the arid zone of southern Kazakhstan.

Assessment of Soil Conditions at the Points Under Study

The analysis of agrochemical indicators of soils revealed a pronounced spatial heterogeneity in the studied areas. Points Rm-06-01, Rm-06-02, Rm-06-03, Rm-06-04, Rm-06-05, Rm-06-06, Rm-10-01, Rm-10-02, Rm-10-03, Rm-14-01, Rm-14-02 and Rm-14-03 are located on the outskirts of the Moyynkum sand massif, which are pastures near settlements, the rest of the points are located on the Moyynkum sand massif itself (Figs. 8, 9).

The humus content varied widely, with the highest values recorded mainly in surface soil horizons at points located near settlements in the zone of influence of rivers and irrigation canals. It is in these areas that the accumulation of organic matter was noted, which is probably due to anthropogenic impact and hydrological features of the territory [25]. In the upper layers of some areas (Pm-10-01 and Pm-06-01), the humus content reaches the values of 1.36% and 1.15%, respectively, which indicates an acceptable level of organic matter, which contributes to the improvement of the physical and chemical properties of soils and the increase in their fertility. At the same time, a significant decrease in the concentration of humus in the lower horizons to extremely low values (0.07-0.16%) is observed in most of the studied sections, which is due to limited biological activity and insufficient inflow of organic residues into deep layers in arid climates.

In terms of the content of hydrolyzable (mobile) nitrogen, there is also a pronounced heterogeneity both vertically and horizontally. Maximum nitrogen concentrations (up to 84 mg/kg) were recorded in the surface layers, especially at sites Rm-06-01 and Rm-10-01. This indicates a relatively high biological activity and nitrogen input due to the decomposition of organic matter and the fixation of atmospheric nitrogen by soil microorganisms. In other areas, such as Rm-15 and Rm-14-01, nitrogen levels are much lower (24.5 mg/kg), which limits soil fertility and requires measures to replenish it.

The highest phosphorus concentrations were found at Pzh-07 (Pm-13) (88 mg/kg), Pm-06-01 (64 mg/kg) and Pzh-06 (Pm-12) (52 mg/kg), which provides favourable conditions for plant nutrition and contributes to increased plant productivity. However, in most lower horizons, the mobile phosphorus content drops sharply to critical values (up to 4 mg/kg). This is due to the low mobility of this element and its fixation in inaccessible forms with high alkalinity of soils.

The content of exchangeable potassium shows pronounced differences between the studied areas (Fig. 9). In some areas, an increased potassium content was noted, reaching values of 810-820 mg/kg (Pm-06-01), which indicates its accumulation in soils with a predominance of clay fractions. At the same time, in some areas, such as Pm-15 and Pm-06-03, the potassium content decreases to values of 90-130 mg/kg, which indicates its limited availability for plants and the need for measures to apply potash fertilizers to stabilize the productivity of agroecosystems.

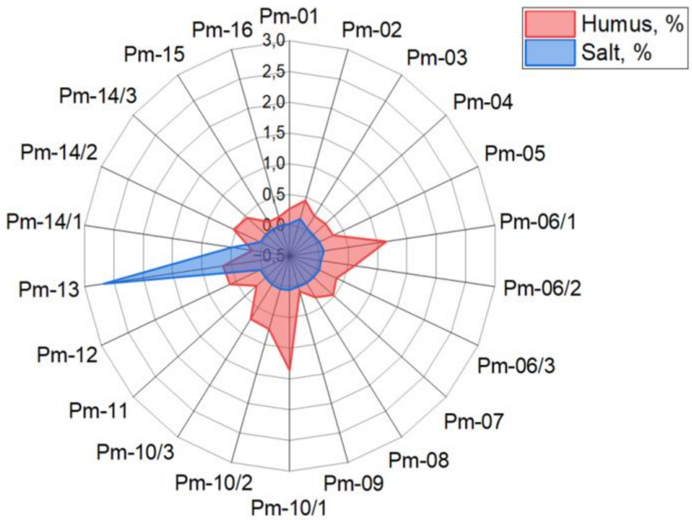

Fig. 8: Comparative percentage of humus and salts in the soil

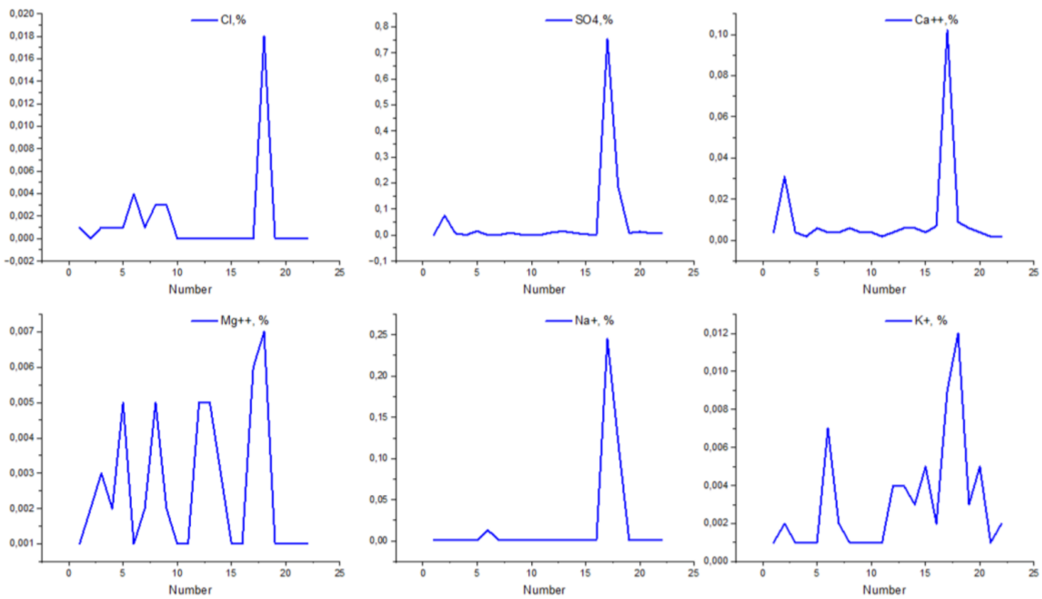

Fig. 9: Percentage of various salts in the soil

The soils of the studied plots are mainly characterized by high alkalinity, which is reflected in pH values exceeding 9.0, and in some cases reaching 10.41 (Pm-14-01). This strongly alkaline reaction limits the availability of many nutrients, including phosphorus and trace minerals, and also negatively affects plant development. Nevertheless, in some soils (for example, Pm-14-02 and Pm-10-01), relatively moderate pH values (about 8.3-8.7) were revealed, which contributes to better availability of nutrients and higher productivity.

Estimates of the biological activity of soils in terms of carbon dioxide (CO_2) emissions also show significant spatial differences. The maximum release of CO_2 (7.93 mg/kg) was recorded at site Pm-06-01, which is associated with a high level of decomposition of organic matter and the activity of soil microorganisms. In contrast, low CO_2 values (down to 0.32-0.49 mg/kg) were found in the Pm-14-02 and Pm-14-03 plots, suggesting limited microbiological activity under conditions of unfavourable humidification or high alkalinity.

Thus, the results obtained indicate a significant heterogeneity of soil fertility, determined by a complex of factors - the content of humus, nitrogen, phosphorus, and potassium, the reaction of the environment, and the biological activity of soil horizons. These data confirm the need for the use of differentiated agrotechnical and reclamation measures aimed at improving soil fertility, optimizing the nutrient regime, and normalizing the acid-base balance to create favorable conditions for the growth and development of plants in the conditions of the studied areas.

Analysis of the obtained data of agrochemical studies allows us to identify areas with signs of degradation of the soil cover. The greatest manifestations of degradation processes are observed in areas with a critically low content of humus, mobile nitrogen and phosphorus, as well as with extremely high pH values of the environment (Fig. 10), which adversely affect soil fertility and biological activity. In particular, the areas subject to pronounced degradation changes include sites Rm-14-01, Rm-14-02, Rm-14-03, Rm-15 and Rm-16. In these areas, the humus content varies at the level of 0.07-0.20%, which is significantly lower than the minimum level necessary for sustainable soil fertility. In addition, there is a low content of available forms of nitrogen (24.5 to 38.5 mg/kg) and phosphorus (4 to 8 mg/kg), which limits the productivity of vegetation cover and its ability to regenerate. High pH values, especially in the Pm-14-01 plot (up to 10.41), lead to a severe deterioration of soil conditions, limiting the availability of nutrients and reducing the biological activity of the soil, as evidenced by low carbon dioxide emissions (0.32-0.49 mg/kg).

An additional sign of degradation is a violation of the granulometric composition and accumulation of salinity in deep horizons, identified by the results of the analysis of water extracts. A high content of soluble salts (for example, Rm-14-01 plots with a total of salts up to 0.486%) leads to salinity and deterioration of soil structure, thereby reducing fertility and contributing to the development of desertification processes (Fig. 9).

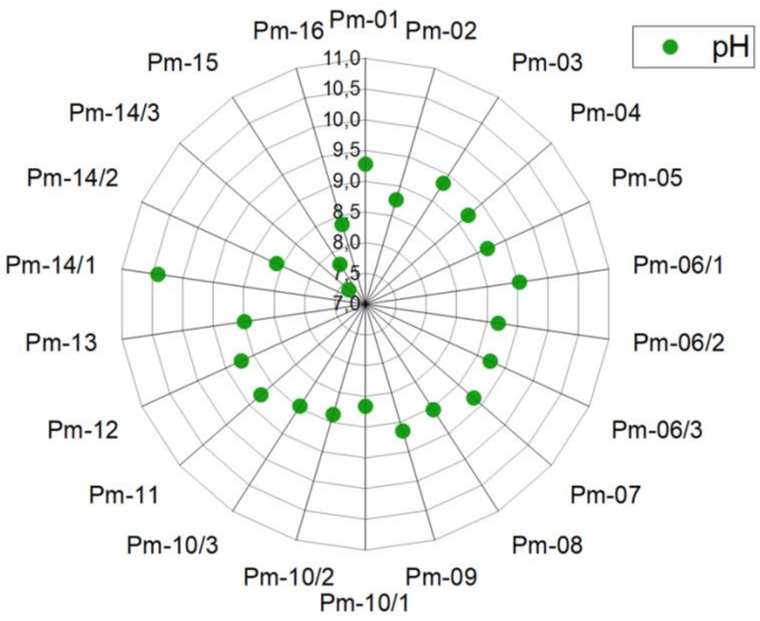

Fig. 10: Soil pH data

Thus, these areas require special attention and urgent measures for the reclamation and restoration of fertility using integrated approaches, including the application of organic and mineral fertilizers, regulation of the acid-base regime, measures to reduce salinity, as well as agronomic practices aimed at improving the structure of the soil and increasing its resistance to further degradation.

The results of a comprehensive analysis of vegetation, phytocenotic structure, and agrochemical characteristics of soils in the Moiynkum desert indicate the presence of a pronounced spatial heterogeneity of environmental conditions that determine the degree of degradation of the vegetation cover. On the basis of floristic studies, it was established that the flora of the Moiynkum desert is distinguished by high taxonomic diversity, including 773 species belonging to 366 genera and 77 families. The dominant families are Chenopodiaceae, Asteraceae, Poaceae, Brassicaceae and Fabaceae, whose representatives have high ecological plasticity and resistance to arid conditions. However, the identified quantitative and qualitative differences in the structure of phytocenoses, including the degree of participation of weed species, indicate a different degree of disturbance of the vegetation cover in some areas.

Of particular scientific importance is the analysis of the share of weed species in communities, which in some cases exceeds 50% of the total number of species. The highest litter load was recorded in communities with the participation of *Hordeum leporinum*, *Pseudosophora alopecuroides* and *Ceratocarpus arenarius*; this indicates degraded or secondarily formed phytocenoses associated with pasture transformation, erosion and succession processes on disturbed lands. At the same time, in stable communities with the dominance of cereals (*Stipa capillata*, *Bromopsis inermis*, *Poa bulbosa*) и subshrubs (*Artemisia terrae-albae*, *Krascheninnikovia ceratoides*), the proportion of weed species is much lower, which allows us to talk about the relative stability and preservation of these ecosystems.

The obtained agrochemical data complete the picture of degradation, demonstrating a significant heterogeneity of the soil cover and its fertility. At a number of sites, critically low values of humus content in the lower horizons (0.07-0.16%), extremely limited content of mobile nitrogen (up to 24.5 mg/kg) and phosphorus (4-8 mg/kg), as well as extremely high pH values exceeding 10.0, were noted, which indicates a pronounced alkaline reaction and salinity of soils. These parameters are key indicators of degradation, as they directly limit the availability of nutrients for plants, reduce the biological activity of soil microorganisms, and slow down the processes of humus formation. In particular, at sites Rm-14-01, Rm-14-02, Rm-14-03, Rm-15 and Rm-16, extremely low levels of organic matter, low emission of carbon dioxide (less than 0.5 mg/kg) and accumulation of salts were recorded, which indicates a high degree of desertification and destruction of the soil structure.

The opposite picture is observed at sites Pm-06-01 and Pm-10-01, where the concentrations of humus (up to 1.36%), nitrogen (84 mg/kg), mobile phosphorus (64 mg/kg) and exchangeable potassium (up to 820 mg/kg) indicate more favorable conditions for vegetation growth. The high biological activity of the soil, confirmed by the intensive release of CO_2 (up to 7.93 mg/kg), indicates the presence of active microflora and effective decomposition of organic residues. This helps to maintain the stability of the vegetation cover. But even in these communities, there is a high level of weed species, which indicates degradation of the vegetation cover. In such communities, half of the species are weedy and do not have much value for agriculture, mainly due to anthropogenic impact on vegetation, indirectly or directly, which is often recorded near villages.

Based on the results of a comprehensive analysis of the phytocenotic structure, agrochemical characteristics of soils, and floristic composition of the ecosystems of the Moiynkum desert, a differentiated assessment of the degree of degradation of the vegetation cover was carried out. It has been established that degradation has a mosaic (spatially heterogeneous) nature and is due to both natural arid conditions and anthropogenic impacts.

Sites with a high degree of degradation are characterized by a significant transformation of phytocenoses, accompanied by the predominance of weed species, the share of which exceeds 50% of the total species composition; formation of vegetation with the participation of *Hordeum leporinum*, *Pseudosophora alopecuroides* и *Ceratocarpus arenarius*, which indicates secondarily altered or degraded communities.

The average degree of degradation is characterized by a partial violation of the structure of vegetation while preserving individual stable elements. The characteristics of this category are: the share of weed species in the range of 30-50%; participation of both degraded and relatively resistant species; moderate decrease in the content of humus and nutrients.

Low degree of degradation (relatively stable communities): this category includes phytocenoses that have retained their natural structure and biogeochemical stability. Main features: predominance of xerophytic cereals (*Stipa capillata*, *Bromopsis inermis*, *Poa bulbosa*) and subshrubs (*Artemisia terrae-albae*, *Krascheninnikovia ceratoides*), also a low proportion of weed species (<25%).

In communities with low overall projective cover (5-20%), such as Alhagetum (Pm-06/1) and Pseudosophoretum (Pm-06/2), there is limited species diversity (7-10 species) and a high proportion of weeds (up to 60-70% of the total composition), indicating low Shannon indices (H' ≈ 1.0-1.3). Such phytocenoses are characterised by a disturbed structure, an unstable ratio of dominants, and reduced ecological stability.

In the central and northern parts of the arid gradient, where the projective cover reaches 50-70% (Hordetum Phragmitosum Pseudosophosum Artemisiosum, Poetum Alhagiosum Pseudosophosum), species richness increases (16-18 species), and the proportion of weed forms varies between 40-45%. These communities are characterised by average H' values (1.6-1.9), indicating a moderately stable state and transitional stages of vegetation recovery.

The maximum Shannon index values are expected in phytocenoses with the most balanced species composition and high vegetation cover density - Poetum Ceratocarposum, Poetum, Artemisietum Stiposum, where the total coverage exceeds 80-90%, the number of species reaches 10-12, and the proportion of weeds does not exceed 20-30%. Such communities are characterised by H' values of around 2.0-2.3, which indicates a high degree of structural organisation, ecological stability, and a complete stage of succession.

Overall, the sample shows a positive correlation between the number of species and the Shannon index (r ≈ 0.75), as well as an inverse relationship between H' and the proportion of weeds. The greatest differences between communities are observed along the moisture and anthropogenic pressure gradients: from degraded and unstable (Alhagetum, Pseudosophoretum) to relatively stable (Poetum, Hordetum).

Conclusion

Thus, the degree of degradation of vegetation cover in the Moiynkum Desert is determined by a whole range of factors, including both the structure of vegetation and weed load, as well as the physicochemical properties of soils. The most degraded areas are characterized by poor species composition, a high proportion of weeds, a low content of humus and basic nutrients, a pronounced alkaline reaction, and weak microbiological activity. Reclamation measures. Such measures include the application of organic and mineral fertilizers, measures to reduce salinity, normalization of the acid-base balance, and restoration of natural communities by phytomelioration using xerophytic and sand-loving species. These approaches should be differentiated, taking into account local heterogeneity of natural conditions, and are focused on ensuring sustainable restoration of vegetation cover and stabilization of soil fertility in conditions of increasing climatic stress and anthropogenic load.

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Author’s Contributions

Omirzhan Taukebayev and Bektemir Osmonali: Project management, development of the research methodology, overall coordination of the work, editing of the final version of the article.
Salavat Duisenbayev, Zhassulan Smanov, Kanat Zulpykharov and Zhanarys Turymtayev: Development of the research methodology, overall coordination of the work.

Daulet Abdildanov and Serikbay Ussen: Literature review, article design, bibliography, proofreading and preparation of the text for publication.

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