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IRRIGATION-INDUCED SOIL SALINIZATION AND DESERTIFICATION IN THE AHAL REGION, TURKMENISTAN: REMOTE SENSING ANALYSIS AND PREVENTIVE MEASURES

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ABSTRACT

Land degradation represents one of the most critical environmental challenges in arid and semi-arid regions, particularly in irrigated agricultural systems. This study investigates the processes of land degradation in the Ahal region of Turkmenistan, with a specific focus on soil salinization and vegetation stress associated with long-term irrigation practices. Using remote sensing techniques, Normalized Difference Vegetation Index (NDVI) and drought index data were analyzed to assess spatial patterns of vegetation condition and environmental stress. The results reveal a strong negative correlation between NDVI and drought index values, indicating that areas with reduced vegetation activity are associated with higher levels of environmental stress. Comparative analysis with existing soil salinization maps demonstrates that zones characterized by low NDVI and high drought index values frequently correspond to areas affected by salinity. These findings suggest that irrigation-induced salinization, combined with inadequate drainage, plays a significant role in land degradation within the study area. Based on the findings, the study proposes a set of preventive measures, including improved irrigation management, drainage system enhancement, and targeted monitoring of high-risk zones. These measures are essential for mitigating land degradation and ensuring sustainable agricultural development in the Ahal region.

Keywords: land degradation, soil salinization, NDVI, drought index, remote sensing, Ahal region, Turkmenistan, desertification, irrigation, GIS

PART 1 — IRRIGATION-INDUCED SOIL SALINIZATION STUDIES

1 INTRODUCTION

Soil salinization is one of the most significant forms of land degradation affecting agricultural systems worldwide. It refers to the accumulation of soluble salts in the soil profile to levels that negatively impact plant growth, reduce soil fertility, and limit agricultural productivity (Shokri et al., 2024). This issue is particularly severe in arid and semi-arid regions, where high evaporation rates and limited precipitation promote the accumulation of salts in the upper soil layers (FAO, 2015). As a result, salinization has become a major environmental challenge, threatening sustainable land use and food security (FAO, 2020).

In Central Asia, soil salinization is a widespread and persistent environmental problem. The region's arid climate, combined with intensive land use, has led to significant soil degradation across large agricultural areas (Conrad, 2020). Previous studies indicate that salinity levels have increased over time, affecting vegetation productivity and ecosystem stability (Measho et al., 2022). In Turkmenistan, these challenges are particularly pronounced due to climatic conditions and the dependence of agriculture on managed water systems.

The Ahal region, including Arkadag city, represents an important agricultural zone where environmental conditions favor the development of soil salinity. High evaporation rates, low precipitation, and specific soil characteristics contribute to the accumulation of salts in the root zone (Babaev & Babaev, 2012; Cakir, 2020). These processes lead to vegetation stress and reduced productivity, making the monitoring of soil conditions essential for sustainable land management.

Despite the growing recognition of soil salinization as a critical environmental issue, there remains a lack of detailed, local-scale studies in Turkmenistan. Most existing research focuses on regional assessments, which do not capture spatial variability within individual agricultural areas (Measho et al., 2022). Remote sensing technologies provide an effective tool for monitoring environmental conditions and detecting salinity-affected areas. The Normalized Difference Vegetation Index (NDVI) is widely used to assess vegetation health and can serve as an indirect indicator of soil degradation (Khamraliev, 2023).

This study applies remote sensing and spatial analysis techniques to detect soil salinization in Arkadag city, located in the Ahal region of Turkmenistan. By integrating NDVI and drought index data within a Geographic Information Systems (GIS) framework, the research examines spatial patterns of vegetation health and environmental stress. The aim of this study is to detect soil salinization in Arkadag city using remote sensing indicators and to analyze the spatial relationship between vegetation condition and environmental stress.

2 STUDY AREA

The study was conducted in Arkadag city, located in the Ahal region of Turkmenistan, near the Kopetdag mountain range. The region is characterized by an arid climate, high evaporation rates, low annual precipitation, and marked seasonal temperature variability (FAO, 2015). Such environmental conditions create a favorable setting for the development and persistence of soil salinization, since limited rainfall reduces the natural leaching of soluble salts from the soil profile.

The study area represents an agricultural landscape in which vegetation condition is strongly influenced by environmental stress factors. The terrain is predominantly flat, which facilitates the accumulation of salts in poorly drained areas. In addition, arid climatic conditions increase evapotranspiration, which intensifies the upward movement of salts through the soil profile and contributes to soil degradation over time (Babaev & Babaev, 2012).

Figure 1. Location of Arkadag City in the Ahal Region, Turkmenistan

Source: OpenStreetMap (2025)

Figure 2. Study Area and Agricultural Field Structure in Arkadag City

Source: OpenStreetMap (2025)

3 METHODOLOGY

3.1 Data Sources and Image Processing

This study applied remote sensing and spatial analysis methods to detect soil salinization in Arkadag city, Ahal region, Turkmenistan. The analysis was based on satellite imagery obtained from NOAA-20 and supported by high-resolution visual data from Google Earth. All image processing, map production, and spatial analysis were performed in QGIS. Remote sensing methods are particularly valuable in arid environments, where field-based monitoring is often limited and where land degradation processes can be effectively observed through spectral indicators (Terekhov et al., 2022).

3.2 NDVI Analysis

To assess vegetation health, this study used the Normalized Difference Vegetation Index (NDVI), one of the most widely applied indicators in remote sensing studies of environmental change and land degradation. NDVI is calculated from the reflectance values of the near-infrared (NIR) and red (RED) bands according to the formula:

$$NDVI = (NIR - RED) / (NIR + RED)$$

NDVI values range from -1 to +1. Higher values generally indicate denser and healthier vegetation, while lower values indicate sparse vegetation, stressed vegetation, or bare soil surfaces (Khamraliev, 2023). In salinity-affected soils, plant growth is limited due to osmotic stress, resulting in reduced vegetation density and lower NDVI values (Terekhov et al., 2022).

3.3 Drought Index Analysis

To complement the NDVI analysis, a drought index was used to evaluate environmental stress related to moisture conditions. The drought index provides additional information about the intensity of stress affecting the soil-vegetation system and helps interpret whether reduced vegetation performance may be associated with broader environmental limitations. In this study, the drought index was mapped across the same study area and spatially compared with the NDVI distribution.

3.4 Spatial Zoning of the Study Area

To strengthen the spatial interpretation of the results, the study area was divided into three representative zones based on visible differences in vegetation condition and land surface characteristics:

Zone	Description
Zone 1	River-influenced area located near the Firuza River
Zone 2	High-salinity zone characterized by reduced vegetation
Zone 3	Reference zone with relatively healthier vegetation conditions

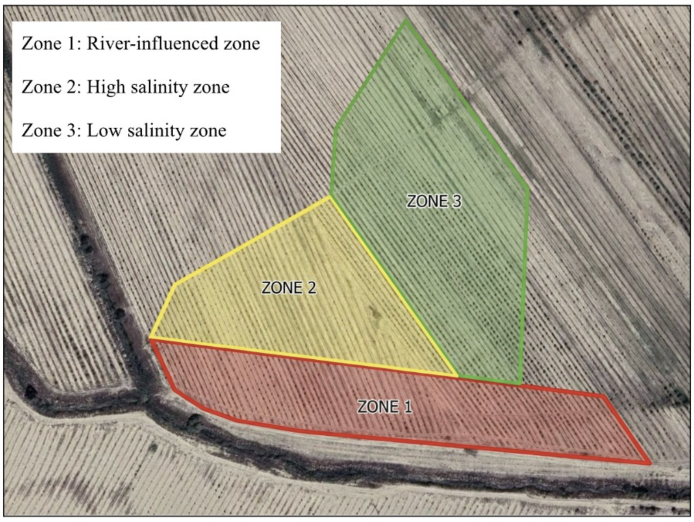

Figure 3. Spatial Zoning of the Study Area (Research Polygons)

Source: Delineation based on NOAA-20 satellite imagery and QGIS analysis, 2026

3.5 Statistical Analysis

To quantify the relationship between vegetation condition and environmental stress, Pearson's correlation coefficient was applied to the NDVI and drought index values. Pearson's correlation is a widely used statistical measure for assessing the strength and direction of a linear relationship between two variables (Mukaka, 2012). The coefficient ranges from -1 to +1. A value close to -1 indicates a strong negative relationship, meaning that as environmental stress increases, vegetation health declines.

4 RESULTS

4.1 Spatial Distribution of NDVI

The NDVI analysis revealed clear spatial variation in vegetation conditions across the study area. Vegetation health is unevenly distributed, with certain parts of the field showing considerably lower NDVI values than others. The central part of the study area is characterized by lower NDVI values, indicating weaker vegetation conditions and possible environmental stress. In contrast, other sections of the field exhibit relatively higher NDVI values, suggesting healthier vegetation cover and more favorable growing conditions.

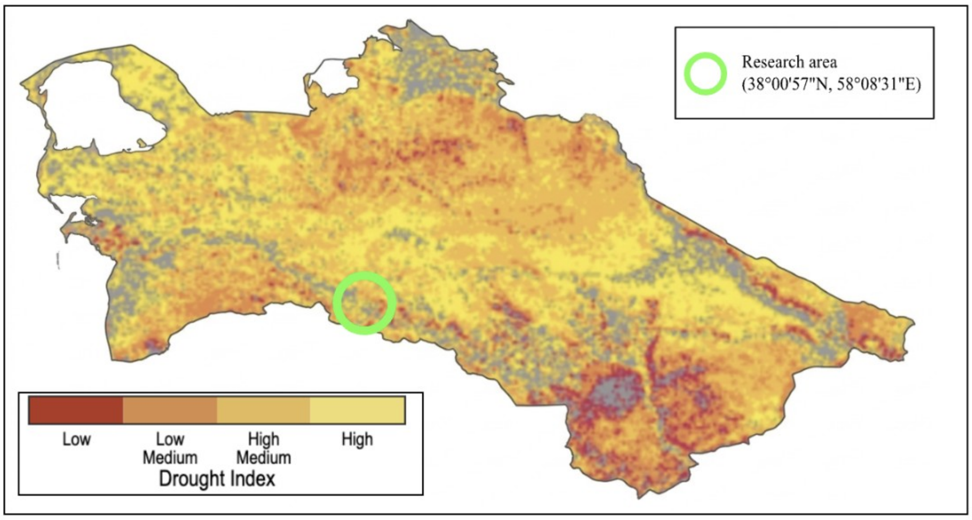

Figure 4. NDVI Map Showing Vegetation Health Distribution in the Study Area

Source: Based on Google Earth satellite imagery; NDVI analysis and visualization performed in QGIS, 2026

4.2 Spatial Distribution of the Drought Index

The drought index map also demonstrates strong spatial differentiation within the study area. Areas of increased environmental stress are concentrated in particular parts of the field rather than being evenly distributed. Importantly, these areas correspond closely to the zones where NDVI values are lowest. This overlap between high drought index values and low NDVI values indicates that vegetation stress is spatially associated with broader environmental stress conditions.

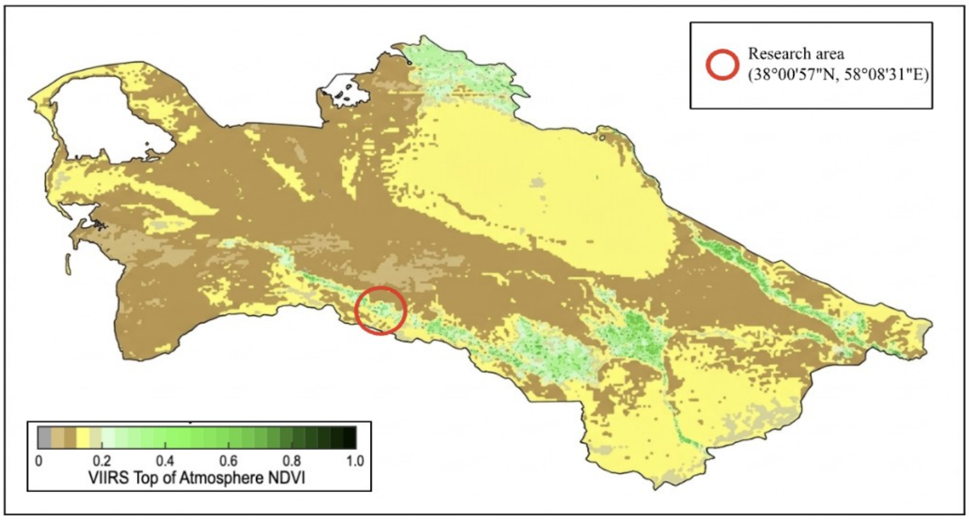

Figure 5. Drought Index Map Indicating Environmental Stress Conditions

Source: Based on Google Earth satellite imagery; drought index analysis and visualization performed in QGIS, 2026

4.3 Zonal Comparison

The zonal analysis provided a more detailed interpretation of spatial variability within the study area. **Zone 2** was identified as the most degraded part of the study area, exhibiting the lowest NDVI values and the highest drought index values. **Zone 3** showed relatively higher NDVI values and lower drought index values, serving as the reference area. **Zone 1** displayed intermediate characteristics, suggesting a transitional environmental condition.

4.4 Correlation Between NDVI and Drought Index

The statistical analysis confirmed the visual patterns observed in the thematic maps. Pearson's correlation coefficient between NDVI and drought index values was calculated as **$r = -0.97$**, indicating a very strong negative relationship between vegetation condition and environmental stress. As environmental stress increases, vegetation health declines. This provides a solid basis for interpreting vegetation decline in the study area as closely associated with environmental stress conditions that may reflect salinity-related degradation.

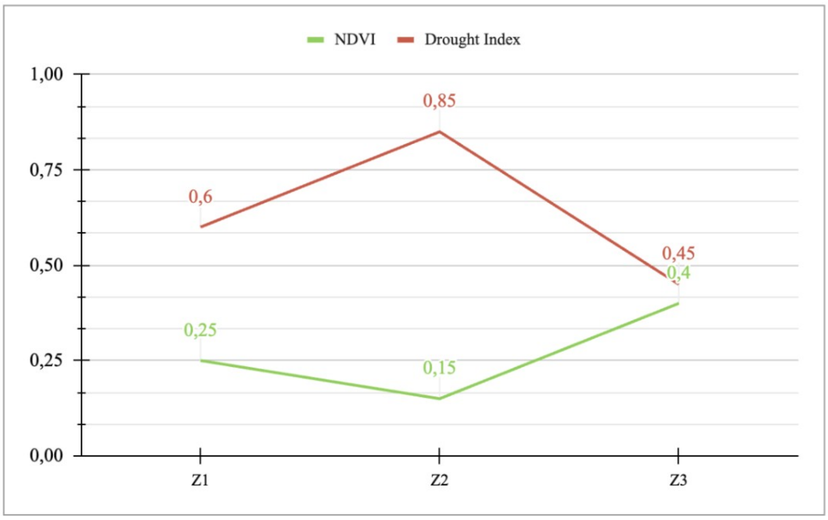

Figure 6. Correlation Between NDVI and Drought Index Values

Source: Author's calculation based on satellite-derived data, 2026

5 DISCUSSION

The results of this study demonstrate a clear and consistent relationship between vegetation condition and environmental stress in the study area. The very strong negative correlation between NDVI and drought index values ($r = -0.97$) indicates that increasing environmental stress is closely associated with declining vegetation health. This relationship suggests that vegetation patterns in the study area are strongly influenced by underlying environmental constraints rather than by random variation.

In arid landscapes, reduced vegetation density is often associated with water stress; however, the results of this study suggest that the observed decline in vegetation may also reflect degraded soil conditions. One of the most plausible explanations for this pattern is soil salinization. In salinity-affected environments, plants experience osmotic stress, which reduces their ability to absorb water and nutrients effectively, even when some moisture is present in the soil.

The zonal analysis provides additional support for this interpretation. The spatial heterogeneity observed is consistent with broader findings on land degradation in arid regions. Although this study did not directly measure soil salinity in the field, the observed spatial patterns align with known salinization processes and support the interpretation that soil-related degradation is an important factor influencing vegetation condition in Arkadag city.

The study also highlights the practical value of remote sensing as a monitoring tool in data-limited environments. The use of NDVI and drought index analysis within a GIS framework allows environmental conditions to be assessed visually, spatially, and quantitatively. The limitations include reliance on indirect indicators and a limited temporal framework. Future research should combine remote sensing with field-based soil sampling to validate the results more directly.

6 CONCLUSION (PART 1)

This study examined the spatial relationship between vegetation condition and environmental stress in Arkadag city, located in the Ahal region of Turkmenistan, in order to detect soil salinization using remote sensing indicators. By integrating NDVI and drought index analysis within a GIS framework, the research identified clear spatial differences in vegetation health and stress intensity across the study area.

The results showed that areas with lower NDVI values correspond closely to areas with higher drought index values, indicating a strong inverse relationship confirmed by Pearson's correlation coefficient ($r = -0.97$). The zonal analysis revealed that environmental conditions vary considerably within the study area. These findings suggest that vegetation stress is closely linked to soil salinization processes, and that remote sensing offers an effective approach for detecting degraded areas at a local scale.

PART 2 — SPATIOTEMPORAL DYNAMICS OF DESERTIFICATION IN THE CENTRAL KARAKUM

1 INTRODUCTION

Desertification is widely recognized as one of the most critical and complex environmental challenges of the 21st century, particularly in arid and semi-arid regions around the globe. It manifests as the progressive degradation of land productivity caused by a combination of climatic variability, prolonged drought periods, and unsustainable human activities. This phenomenon results in the gradual loss of biological productivity, severe reduction in vegetation cover, accelerated wind and water erosion, declining soil fertility, and widespread loss of biodiversity.

In Central Asia, desertification has intensified dramatically due to the region's inherent hyper-arid climate, extremely high evapotranspiration rates, fragile soil structures, and decades of intensive land-use practices including overgrazing, fuelwood extraction, and improper irrigation management. Turkmenistan, positioned at the heart of this vast arid zone, faces particularly acute risks because the Karakum Desert covers nearly 80% of its national territory.

The Erbent research site (39.31551°N, 58.61283°E), situated in the central part of the Karakum Desert, serves as an excellent localized case study for examining the detailed mechanisms and progression of desertification. As a longstanding hub for livestock husbandry, the surroundings of Erbent village have become a frontline area in the ongoing battle against advancing sand dunes and progressive loss of vegetation cover.

This study applies remote sensing and statistical analysis techniques to comprehensively evaluate the spatiotemporal dynamics of desertification in the Erbent site of the Ahal region. By systematically integrating NDVI, LST, and the De Martonne Aridity Index within a GIS framework, the research examines both the spatial distribution of degradation features and the long-term temporal trends across a continuous 23-year observation window (2000–2023).

2 STUDY AREA

The study was conducted in the central part of the Karakum Desert, with a specific focus on the village of Erbent (39.31551°N, 58.61283°E) located in the Ahal region of Turkmenistan. The Ahal region is characterized by a strongly continental and hyper-arid climate featuring extreme summer temperatures that frequently exceed 40°C, very low annual precipitation (often below 120 mm), and pronounced seasonal temperature fluctuations.

The study area is a typical pastoral landscape where vegetation dynamics are heavily influenced by both natural climatic stressors and human activities, particularly concentrated grazing around water points and the harvesting of fuelwood. Natural vegetation consists mainly of highly drought-resistant shrub species, with black saxaul (Haloxylon ammodendron) being the dominant and most ecologically important species.

Figure 1. Map of the Ahal Province, Turkmenistan. Coordinates: N 38° 03', E 58° 10'

Source: Google Earth (2025)

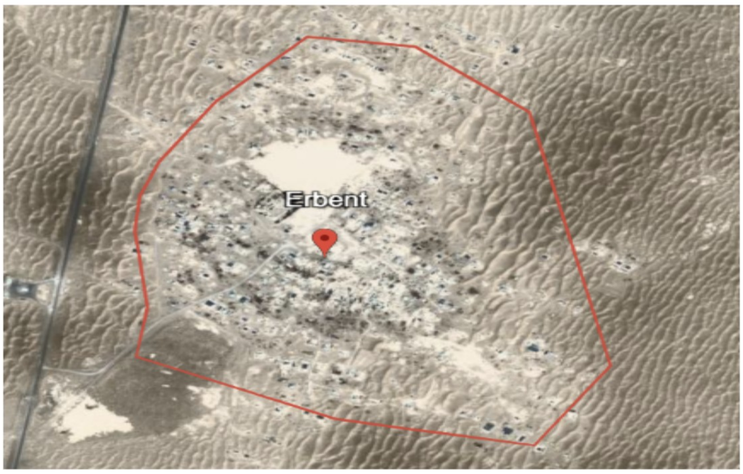

Figure 2. Map of Erbent Village and its Immediate Surroundings (Coordinates N39.31551 E58.61283), showing sand dunes, inter-dune depressions, and sparse vegetation patterns tied to local micro-relief

Source: Google Earth (2025)

3 METHODOLOGY

3.1 Data Sources and Image Processing

This study utilized a combination of remote sensing and statistical techniques to evaluate desertification dynamics at the Erbent site. The primary data sources included multi-temporal satellite imagery, mainly MODIS-derived products for NDVI and LST, spanning the years 2000 to 2023. These satellite datasets were complemented by long-term meteorological records of precipitation and air temperature obtained from reliable international databases. All preprocessing steps, map generation, and spatial analyses were carried out using QGIS software and the Google Earth Engine platform.

3.2 NDVI Analysis

Vegetation health and changes in biomass were assessed through the Normalized Difference Vegetation Index (NDVI). NDVI values theoretically range from -1 to +1. Higher positive values generally correspond to denser and healthier vegetation cover, whereas lower or negative values indicate sparse vegetation, stressed plants, or bare soil surfaces. In arid environments such as the Central Karakum, a declining NDVI trend serves as a strong indirect indicator of vegetation degradation linked to desertification processes.

3.3 Drought Index and LST Analysis

To evaluate long-term climatic aridity, the De Martonne Aridity Index was calculated using the formula:

$$I = P / (T + 10)$$

where P represents mean annual precipitation in millimeters and T denotes mean annual air temperature in degrees Celsius. Values of the index below 10 are widely interpreted as indicative of arid to extremely arid conditions. Land Surface Temperature (LST) data were also analyzed to quantify surface warming trends and thermal stress.

3.4 Statistical Analysis

Long-term temporal trends in NDVI, LST, and the De Martonne Aridity Index time series were analyzed using linear regression for slope estimation and the non-parametric Mann-Kendall test for trend detection and significance testing. Pearson's correlation coefficient was employed to examine the strength and direction of linear relationships among NDVI, the drought index, and LST. Statistical significance of all tests was evaluated at the $p < 0.05$ confidence level.

4 RESULTS

4.1 Drought Zones in Turkmenistan

The spatial analysis of the drought index across the entire territory of Turkmenistan provides a clear overview of the severity and extent of drought conditions. The map demonstrates that drought occupies a huge part of the country's land area. Regions with limited or no reliable access to water resources are the most severely affected. This widespread distribution of drought zones underscores the systemic nature of aridity challenges in Turkmenistan.

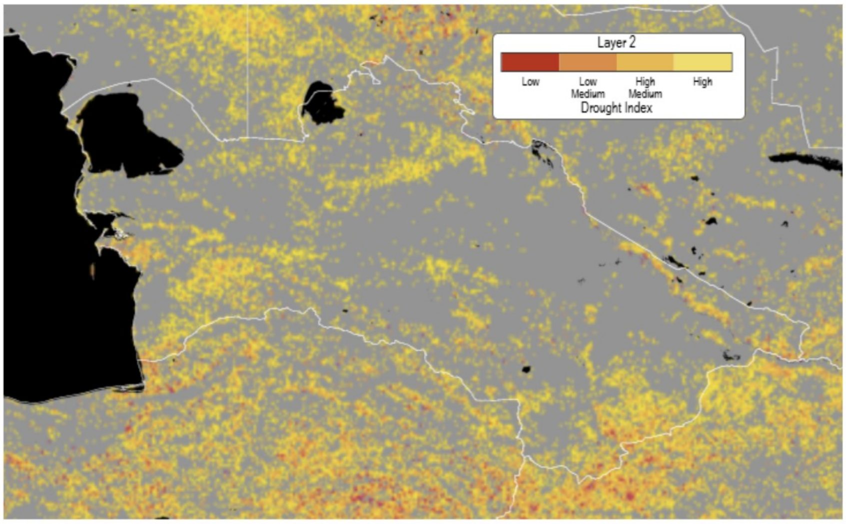

Figure 3. Drought Index Map in Turkmenistan Showing Drought Zones Across the Country, with a Large Portion of the Territory Affected, Particularly Areas with Limited Water Access

Source: Author's analysis based on meteorological data and GIS, 2026

4.2 Vegetation (NDVI) Distribution

The multi-temporal NDVI maps for the Ahal region illustrate important changes in vegetation cover over the study period. A particularly pronounced reduction in vegetated surfaces becomes evident starting from the year 2020. This marked decline in vegetation coincides with a decade that included some of the hottest years on record. Elevated temperatures and associated drought stress have exerted a strong negative influence on vegetation lands in the Ahal province, leading to decreased biomass, increased areas of bare soil, and progressive degradation of pastoral resources.

4.3 Land Surface Temperature (LST) Trend

The time-series analysis of Land Surface Temperature (LST) in the research area reveals a persistent and statistically significant warming trend. LST has increased by **0.0179°C per year** throughout the analyzed period. The average LST recorded during the 23-year period was 22.55°C. This steady rise in surface temperature contributes to higher evapotranspiration rates and places additional pressure on already limited soil moisture resources, thereby accelerating vegetation stress and desertification.

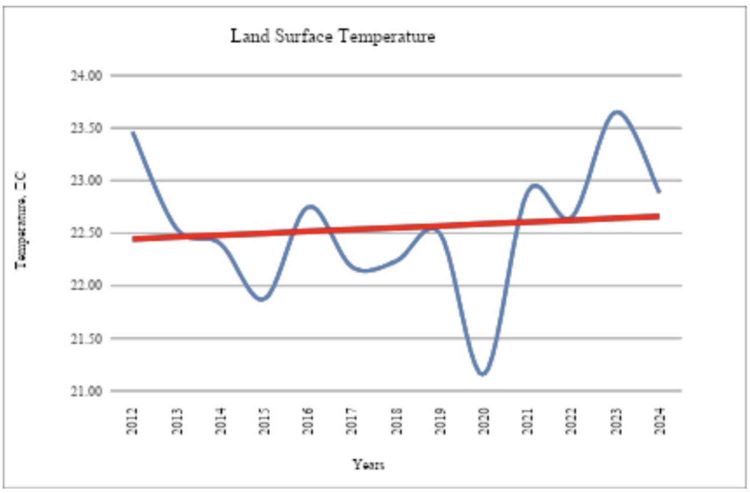

Figure 4. Land Surface Temperature (LST) Trend in the Ahal Province Showing an Upward Slope of +0.0179°C per Year (Average Temperature: 22.55°C)

Source: Author's calculation based on satellite data and QGIS analysis, 2026

4.4 Vegetation (NDVI) Trend

Vegetation condition in the Ahal region is clearly threatened by ongoing drought stress. The linear trend analysis of the NDVI time series shows a downward tendency in vegetation density, with the index decreasing by an average of **-0.0018 units per year**. Although the trend is relatively modest in magnitude, its consistent direction over more than two decades points to a worrying long-term degradation of the vegetation resource that supports local pastoral livelihoods.

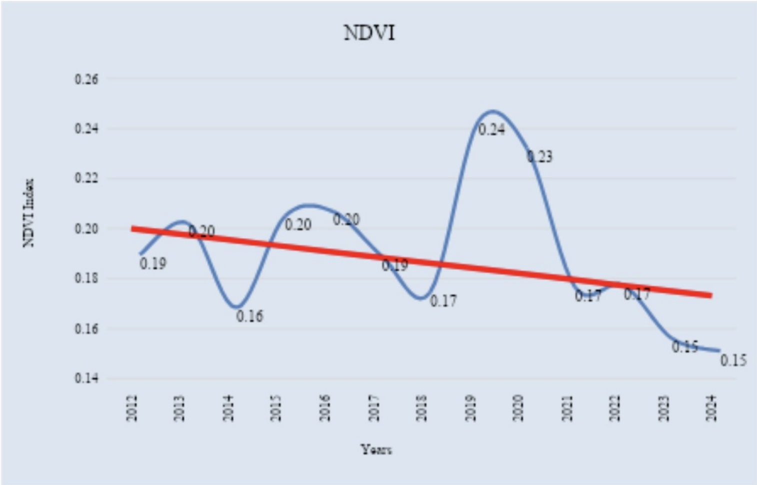

Figure 5. Vegetation (NDVI) Index Trend in the Ahal Province Showing a Downward Slope of -0.0018 Units per Year

Source: Author's calculation based on satellite data and QGIS analysis, 2026

4.5 Drought Index Trend

The linear trend analysis of the De Martonne Aridity Index for the Ahal region demonstrates a slight but noticeable decrease in the index values over the study period. The drought index is declining by approximately **0.0367 units per year**. This reduction reflects a gradual shift toward even more arid conditions. However, the data series exhibits considerable year-to-year fluctuations, which explain the unstable and irregular pattern of drought expansion during the analyzed period.

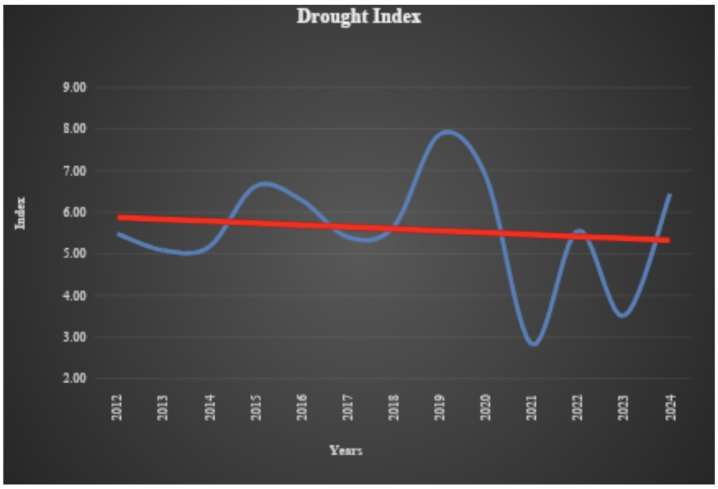

Figure 6. Linear Trend Analysis of the Drought Index (De Martonne Method) in the Ahal Province Showing a Slight Decrease of -0.0367 Units per Year

Source: Author's calculation based on meteorological records and QGIS analysis, 2026

4.6 Precipitation Anomaly

The analysis of precipitation anomalies in the Ahal province provides important insight into the balance between drought stress and vegetation recovery. The results demonstrate that periods of rehabilitation are considerably weaker and shorter than the extreme drought years. This imbalance suggests that the ecosystem has limited capacity to recover fully after prolonged dry periods, thereby contributing to the cumulative degradation of vegetation cover over time.

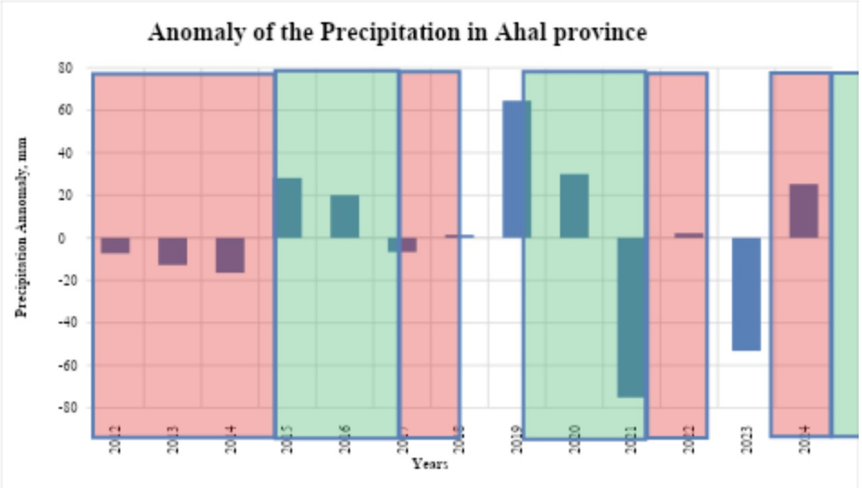

Figure 7. Precipitation Anomaly in the Ahal Province Highlighting Extreme Drought Years (Red) versus Rehabilitation Periods (Green)

Source: Author's calculation based on meteorological data, 2026

4.7 Correlation Analysis

Pearson's correlation analysis was conducted to measure the strength and direction of relationships between the three key indicators. The resulting correlation matrix is presented in Table 1.

Indicator	NDVI	Drought Index	LST
NDVI	1	—	—
Drought Index	0.86	1	—
LST	–0.551	–0.521	1

Table 1. Correlation Matrix Between NDVI, Drought Index, and LST

Source: Author's calculation based on satellite-derived and meteorological data, 2026

The matrix reveals a strong positive correlation between NDVI and the drought index ($r = 0.86$), indicating that vegetation health is closely linked to moisture availability and aridity levels. LST shows moderate negative correlations with both NDVI and the drought index, confirming that higher surface temperatures are associated with reduced vegetation performance and increased environmental stress.

4.8 Mann-Kendall Trend Test

To determine whether the observed changes in vegetation (NDVI) represent a statistically significant long-term trend, the non-parametric Mann-Kendall test was applied. The results are presented in Table 2.

Statistic	Value	Interpretation
MK-stat	–24	Negative tendency
p-value	0.1997	$p > 0.05$
Trend	No	No statistically significant trend at 95% confidence level

Table 2. Mann-Kendall Trend Test Results for Vegetation (NDVI) in the Ahal Province

Source: Author's calculation based on satellite-derived data, 2026

5 DISCUSSION

The comprehensive results generated by this study offer a detailed and alarming portrait of the ongoing environmental degradation and active desertification processes occurring in the Erbent research site and the broader Ahal region. The statistically significant and persistent upward trend in Land Surface Temperature (0.0179°C per year) not only increases the overall thermal stress on the desert ecosystem but also accelerates evapotranspiration rates, rapidly depleting the already scarce soil moisture reserves essential for plant survival.

The precipitation anomaly analysis clearly shows that periods of vegetation rehabilitation and recovery have been noticeably weaker, shorter, and less effective than the frequent and intense extreme drought years. This chronic imbalance severely limits the natural regenerative capacity of the desert pastures, allowing degradation effects to accumulate year after year. The rising LST appears to initiate and sustain a dangerous positive feedback loop typical of desertification processes in sandy arid environments.

Local human activities play a decisive role in amplifying these climate-driven processes. Intensive overgrazing concentrated around the few available water sources and the widespread harvesting of saxaul shrubs for domestic fuelwood directly reduce the regenerative potential of the pasture resource. The progressive loss of black saxaul — a cornerstone species functioning as a natural windbreak, sand stabilizer, and soil improver — removes critical protection against wind erosion, leading to increased mobilization of sand dunes.

From a broader socio-economic perspective, the gradual decline in NDVI carries significant real-world consequences for the pastoral communities of the Erbent area. Pastoral households that traditionally manage 50 to 100 head of small livestock face annual reductions in forage availability, which can translate into smaller herd sizes, higher costs for supplementary feeding, reduced household income, and increased economic vulnerability.

6 CONCLUSION (PART 2)

This study has conducted a thorough examination of the spatiotemporal dynamics of desertification in the Central Karakum Desert, placing special emphasis on the Erbent research site within the Ahal region of Turkmenistan across the 23-year period from 2000 to 2023. Through the systematic integration of NDVI, LST, and the De Martonne Aridity Index within a GIS framework, the research has successfully identified and quantified several critical signals of ongoing environmental change and progressive land degradation.

These signals include a statistically significant increase in surface temperatures at a rate of 0.0179°C per year, a consistent gradual decline in vegetation density, and a slow but steady intensification of overall aridity conditions. The combination of steadily rising LST values, the visible decline in vegetation cover, and the very strong positive correlation between NDVI and the drought index ($r = 0.86$) collectively provides strong evidence that desertification processes are actively advancing within the Erbent site and surrounding pastoral landscapes.

Looking forward, priority should be given to large-scale phytomelioration programs focused on the planting and long-term protection of drought-resistant Haloxylon (saxaul) species. At the same time, the introduction of community-based rotational grazing systems and the wider application of Integrated Water Resources Management (IWRM) principles are equally essential for enhancing the overall adaptive capacity of the region. Only through such an integrated, multi-stakeholder, and long-term approach can Turkmenistan hope to protect its valuable arid landscapes and safeguard the livelihoods of its pastoral populations.

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ECOLOGICAL ASSESSMENT OF DEGRADED PASTURE LANDS IN THE AHAL REGION OF TURKMENISTAN

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ABSTRACT

Pastureland degradation represents one of the most pressing ecological challenges confronting the arid and semi-arid ecosystems of Central Asia. The Ahal region of Turkmenistan, encompassing approximately 1.8 million hectares of natural rangeland, has experienced accelerating deterioration driven by the convergence of chronic overgrazing, unregulated fuelwood harvesting of native saxaul (Haloxylon ammodendron) stands, and the amplifying effects of a warming, increasingly variable climate. This study presents a comprehensive, multi-method ecological assessment integrating 24 years of multi-source satellite remote sensing (MODIS, Sentinel-2), systematic field phytosociological surveys at 145 stratified plots across the province, soil physical and chemical analyses from 87 plots, and semi-structured socio-economic interviews with 78 pastoral households. Normalized Difference Vegetation Index (NDVI) trend analysis revealed statistically significant vegetation decline across 38.2% of the study area over the 2000–2024 period (Mann-Kendall $p < 0.05$), with a mean decline rate of –0.0021 NDVI units per year. Field surveys document that 46% of assessed lands exhibit moderate to very severe degradation, with mean vegetation cover declining from 58 ± 12% in undegraded Class I plots to 7 ± 3% in the most severely degraded Class V plots. A pronounced piosphere effect was documented ($r^2 = 0.84$, $p < 0.001$), with 91% of plots within 2 km of permanent water sources classified as severely degraded. Species composition analyses reveal systematic replacement of productive palatable perennials by unpalatable annual weeds across the degradation gradient. Soil analyses confirm a 67% reduction in organic carbon, 36% increase in bulk density, and mean penetration resistance of 4.1 MPa in severely degraded zones — substantially exceeding the 2.5 MPa root restriction threshold. The study proposes an integrated restoration framework encompassing rotational grazing systems, strategic water point redistribution, active phytomelioration with native species, and community-based monitoring. Findings provide a quantified, spatially explicit foundation for evidence-based sustainable pasture management policy aligned with Turkmenistan's land degradation neutrality commitments under the UNCCD.

Keywords: pasture degradation; ecological assessment; phytosociology; piosphere effect; NDVI trend analysis; overgrazing; saxaul; Haloxylon ammodendron; soil compaction; land degradation neutrality; Ahal region; Turkmenistan; Central Asia; remote sensing; rotational grazing; vegetation cover dynamics

1 INTRODUCTION

Rangelands and natural pastures cover approximately 54% of the Earth's ice-free land surface and support the livelihoods of over one billion people worldwide, particularly in developing nations where pastoral economies remain central to rural subsistence, cultural identity, and national food security (FAO, 2021; Millennium Ecosystem Assessment, 2005). These ecosystems provide a range of critical services beyond forage production: they regulate water cycles, store substantial soil and vegetation carbon, maintain biodiversity at landscape scales, and support cultural heritage and traditional ecological knowledge accumulated over centuries of pastoral land use. In the arid and semi-arid regions of Central Asia, where precipitation is insufficient to support rainfed agriculture across most of the landscape, natural pastures constitute the dominant land use category and form the ecological foundation upon which traditional nomadic and semi-nomadic pastoral systems have operated for millennia.

Turkmenistan presents one of the most ecologically significant and economically consequential cases of pasture land degradation in the post-Soviet Central Asian context. With approximately 70% of its national territory

— roughly 340,000 km² — covered by natural rangelands predominantly within the vast Karakum Desert and its piedmont transition zones, the country's pastoral sector supports millions of sheep, goats, camels, and horses and underpins the economic security of a substantial rural population. Livestock production remains among the most important sectors of Turkmenistan's rural economy, contributing significantly to household food security, income generation, and cultural continuity across the country's rural communities.

The Ahal region, situated in the southern part of the country and encompassing the Kopetdag piedmont zone, the central Karakum transitional zone, and extensive northern sandy desert rangelands, represents approximately 97,000 km² of ecologically diverse territory. This province occupies a particularly important position in both ecological and economic terms: it hosts the national capital Ashgabat and its surrounding peri-urban pastoral communities, contains some of the most productive piedmont pastures in the country, and includes the most accessible and therefore most heavily utilized portions of the Central Karakum rangeland system. Its ecological health is thus a bellwether indicator of the broader trajectory of pasture land condition across Turkmenistan.

The collapse of the Soviet collective farm system in the early 1990s fundamentally altered livestock management practices across Central Asia in ways that profoundly restructured grazing pressure distributions. The dismantling of centralized kolkhoz and sovkhoz herding institutions, rotational grazing schedules, and water infrastructure maintenance programs removed the regulatory frameworks that had previously enforced seasonal mobility and distributed grazing pressure across large pastoral territories. In Turkmenistan, the subsequent shift toward privatized, family-based herding units concentrated livestock in proximity to settlements, roads, and accessible water points, generating intense localized overutilization while remote pastures became chronically underused. This spatial restructuring of grazing pressure created the pronounced degradation gradients that characterize the contemporary pasture landscape (Kaplan et al., 2014; Durdyev et al., 2019).

Simultaneously, climate change has emerged as a powerful amplifying force operating synergistically with anthropogenic pressures. Regional temperature records for Turkmenistan document warming trends of 0.5–0.7°C per decade since the 1980s, accompanied by increased inter-annual precipitation variability, more frequent multi-year drought episodes, and earlier onset of extreme summer heat. These climatic changes intensify the evapotranspiration deficit characteristic of arid systems, reduce the frequency and reliability of rainfall events that trigger germination and seedling establishment, increase thermal stress on perennial vegetation during critical growth periods, and shorten the productive growing season. As a result, the regenerative capacity of already-stressed pasture ecosystems is systematically eroded, making recovery from disturbance progressively slower and less complete over time.

The unregulated harvesting of saxaul (Haloxylon ammodendron) and other native shrub species for domestic fuelwood constitutes a third major driver of degradation operating in parallel with overgrazing and climate stress. Saxaul stands function as ecological engineers in the desert landscape: their deep root systems stabilize sandy substrates, their canopy structure intercepts wind energy and promotes deposition of airborne organics, and their litter inputs represent one of the primary pathways of organic matter addition to the infertile desert soils. Removal of saxaul stands thus initiates a cascade of ecological consequences — destabilization of sand surfaces, loss of windbreak function, reduction in soil organic matter inputs, and degradation of the microhabitat conditions required by associated plant species — that collectively accelerate the transition from vegetated to bare degraded states.

Despite the recognized urgency and ecological significance of the problem, comprehensive ecological assessments of pasture degradation in Turkmenistan have remained limited in spatial coverage, methodological integration, and quantitative rigor. Earlier studies have typically operated at national or regional scales providing insufficient spatial resolution to guide site-specific management interventions, or have relied on single-indicator approaches — typically NDVI remote sensing alone or localized field surveys — that fail to capture the multi-dimensional nature of degradation processes. The absence of integrated, multi-scale assessments combining remote sensing with field validation, soil analysis, and socio-economic data has constrained the development of evidence-based pasture management policies and impeded accurate monitoring of progress toward land degradation neutrality targets committed to under the United Nations Convention to Combat Desertification (UNCCD, 2022).

This study addresses this critical scientific and policy gap by presenting the most spatially comprehensive and methodologically integrated ecological assessment of pasture land degradation in the Ahal region of Turkmenistan to date. The research integrates four complementary data streams — multi-temporal satellite remote sensing spanning 24 years, systematic phytosociological field surveys across 145 stratified plots, soil physical and chemical analyses from 87 sites, and semi-structured pastoral household interviews — to produce an integrated characterization of degradation extent, severity gradients, ecosystem functional changes, causal mechanisms, and restoration opportunities. The specific objectives are: (1) to map and quantify the spatial distribution and severity of pasture degradation across the Ahal province; (2) to characterize vegetation cover and species composition changes along the degradation gradient; (3) to document associated soil physical and chemical condition changes; (4) to identify and quantify the principal proximal drivers of degradation; and (5) to develop an integrated, evidence-based restoration framework applicable at provincial and national policy scales.

2 STUDY AREA

The study was conducted across the Ahal province (velayat) of Turkmenistan, encompassing an administrative area of approximately 97,160 km² and situated between approximately 36.5°N–40.5°N latitude and 56.5°E–61.5°E longitude. The province spans a marked ecological gradient from the Kopetdag mountain range along the Iranian border in the south to the extensive flat sandy and clay desert plains of the Central Karakum in the north. The provincial capital Ashgabat (population approximately 1.1 million) is located in the southern piedmont zone at 37.93°N, 58.38°E, at an elevation of approximately 220 m above sea level. The Ahal province encompasses some of the most ecologically diverse and economically significant rangelands in Turkmenistan, ranging from productive piedmont foothills to the challenging but extensive Karakum desert pasture system.

Three principal geomorphological and ecological zones characterize the province's pasture lands and were used as a primary stratification basis for this study. The Kopetdag Piedmont Zone encompasses the southern 15–20% of the province, characterized by gently sloping alluvial fans, loess-derived sierozem soils with relatively higher clay and silt content, mean annual precipitation of 250–350 mm, and a diverse shrub-grass vegetation community with the highest inherent forage productivity in the region. Key vegetation communities include Artemisia diffusa-dominated semi-shrub steppe with a diverse ephemeral grass layer, Poa bulbosa-dominated spring grasslands on deeper loess soils, and Salsola richteri-Haloxylon aphyllum shrublands on foothill desert soils.

The Central Desert Transition Zone covers approximately 30–35% of the province, encompassing the flat to gently undulating clay takyr plains and transitional sandy areas between the piedmont and the deep Karakum sand sea. Soils are predominantly grey-brown desert soils with shallow profiles, low organic matter content, and variable texture from clay-rich takyrs to sandy substrates. Mean annual precipitation decreases to 100–200 mm in this zone, and the vegetation is dominated by drought-resistant shrubs and semi-shrubs including Artemisia terrae-albae, A. santolina, Salsola arbuscula, and Ephedra strobilacea, with ephemeral annual species providing important but unreliable spring forage.

The Sandy Karakum Zone covers the northern 50% of the province and is dominated by fixed and semi-fixed sand dune systems with psammo-phytic vegetation communities centred on saxaul woodlands. Black saxaul (Haloxylon ammodendron) is the structural dominant, forming sparse but ecologically critical woodland formations with canopy heights of 2–5 m. White saxaul (H. persicum) dominates on more mobile sandy substrates. The ephemeral flora is rich and provides substantial spring forage following adequate winter precipitation. Mean annual precipitation decreases to below 100 mm in the northernmost areas of this zone, and inter-annual variability is extreme, with some years receiving less than 30 mm. Temperatures are severe, with mean July maxima exceeding 35°C and extreme temperatures above 45°C occurring regularly.

The human geography of the province includes approximately 130 rural settlements distributed across the pasture landscape, with total rural population in pastoral communities estimated at approximately 280,000 people.

Livestock numbers in the province are estimated at approximately 2.8 million sheep equivalents based on available agricultural census data, though actual numbers are difficult to verify precisely due to the private nature of most herding operations following privatization. Pastoral households typically maintain mixed herds of sheep, goats, Bactrian camels, and in some piedmont areas, horses and donkeys. Seasonal transhumance — the traditional seasonal movement between summer highland and winter lowland pastures — has largely been abandoned by the majority of herding families, as discussed further in the socio-economic results section.

3 MATERIALS AND METHODS

3.1 Remote Sensing Data and Vegetation Index Analysis

Multi-temporal satellite imagery was acquired from two primary sources covering complementary spatial and temporal scales. MODIS Terra surface reflectance products (MOD09A1, 500 m; MOD13Q1 NDVI composite, 250 m) were downloaded from the NASA Land Processes Distributed Active Archive Center (LP DAAC) for the complete period 2000–2024, providing a continuous 24-year time series of 8-day composite surface reflectance observations with global coverage. Cloud contamination was addressed using the MODIS quality assurance band filters to retain only high-quality observations. Sentinel-2 MultiSpectral Instrument (MSI) Level-2A atmospherically corrected imagery at 10 m spatial resolution was acquired for 2018–2024 via the Copernicus Open Access Hub, providing detailed spatial characterization of vegetation patterns and degradation features for validation of coarser MODIS products.

The Normalized Difference Vegetation Index (NDVI = (NIR – RED) / (NIR + RED)) was computed from MODIS surface reflectance bands 1 (RED, 620–670 nm) and 2 (NIR, 841–876 nm) for all cloud-filtered observations. Annual maximum NDVI (NDVImax) was extracted as the peak value within the April 1 to June 30 spring growing season window to represent peak annual vegetation productivity while minimizing phenological timing noise. The Soil-Adjusted Vegetation Index (SAVI = ((NIR – RED) / (NIR + RED + 0.5)) × 1.5) was additionally computed from Sentinel-2 imagery to reduce confounding soil brightness effects in sparse vegetation areas characteristic of the study region, particularly relevant for classification of low-cover degraded zones.

Long-term NDVI trend analysis was performed for the 2000–2024 NDVImax time series using two complementary statistical approaches: linear regression for slope magnitude estimation and the non-parametric Mann-Kendall test for significance evaluation at $\alpha = 0.05$, which does not assume normality and is robust to outliers and autocorrelation. Sen's slope estimator was applied to quantify the magnitude of monotonic trends without the influence of extreme values. Spatial autocorrelation in trend patterns was assessed using Moran's I statistic. All pixel-level analyses were conducted within Google Earth Engine using JavaScript API. Post-processing, map production, and spatial statistics were performed in QGIS 3.28 (QGIS Development Team, 2023).

3.2 Field Phytosociological Survey Design and Protocols

Systematic field surveys were conducted during the spring growing seasons of April 10 – May 25, 2023, and April 8 – May 20, 2024, coinciding with peak standing biomass for the dominant ephemeral and early-season perennial species. A total of 145 permanent sample plots of 100 m² (10 × 10 m) were established and monumented with GPS-locatable markers for repeat measurement. Plot locations were selected using stratified random sampling based on three stratification factors: NDVI magnitude class (five classes from preliminary remote sensing), geomorphological zone (piedmont, clay desert, sandy Karakum), and distance from water (three classes: < 2 km, 2–8 km, > 8 km), yielding 45 strata cells with 2–5 plots allocated per stratum proportional to stratum area.

Within each 100 m² plot, vegetation cover was estimated using the point-intercept method with a 200-point systematic grid (10 points × 20 m transects), recording the first contact plant species or substrate type (bare mineral soil, litter, rock) at each point. Species-level cover-abundance was additionally estimated using modified Braun-Blanquet cover classes (r, +, 1–5) to capture rare species not represented in point-intercept counts. For each recorded species, palatability was classified as: highly palatable (readily consumed in all seasons), moderately palatable (consumed under adequate forage availability), unpalatable (avoided unless severely limited), or toxic/poisonous (actively avoided), based on systematic compilation of regional livestock grazing preference literature and validated by interviews with experienced pastoralists.

Additional plot-level measurements included: canopy height of dominant shrub individuals (n = 10 per plot where applicable) using a graduated rod; basal diameter and crown dieback percentage of saxaul individuals; evidence and severity scoring of wind erosion features (deflation patches, sand hummocks, exposed roots on 0–4 scale); and surface soil condition assessment (compaction by thumb press test, visible salt crust presence, surface cracking). Geographic coordinates of each plot were recorded with a Trimble GeoXH GNSS receiver providing < 0.5 m accuracy after differential correction. All field data were entered in real time using ODK Collect digital data forms on ruggedized tablets.

3.3 Soil Sampling and Laboratory Analyses

Composite soil samples were collected at 87 of the 145 phytosociological plots selected to ensure coverage of all degradation classes and all three geomorphological zones. At each soil sampling plot, five sub-samples were collected in an X-pattern from depths of 0–10 cm and 10–30 cm using a stainless steel soil corer (50 mm diameter), combined to form composite samples by depth. Soil penetration resistance was measured in situ at 10 points per plot using a Pentek hand-held cone penetrometer (0–4.5 MPa, 30° cone angle), recording measurements at 0–10 cm and 10–25 cm depth. Undisturbed soil cores (100 cm^3) were collected at five points per plot for bulk density determination by the core method.

Laboratory analyses were performed at the Soil Science Laboratory of the Turkmen Agricultural University in Ashgabat following standard international protocols. Soil organic carbon was determined by Walkley-Black wet oxidation; total nitrogen by Kjeldahl digestion and distillation; available phosphorus by Egner-Riehm method; soil pH and electrical conductivity in 1:5 water suspension; and particle size distribution by hydrometer method (Bouyoucos). All analyses were performed in duplicate with certified reference materials included in each analytical batch for quality assurance and control. Results with coefficient of variation > 10% between duplicates were flagged and re-analyzed.

3.4 Degradation Classification System

A composite five-class pasture degradation index was developed integrating remote sensing spectral metrics, field vegetation cover and composition data, and soil condition indicators into a unified classification scheme (Table 1). The system was designed to reflect ecologically meaningful thresholds associated with distinct levels of functional impairment and to provide actionable management guidance for each degradation class.

Supervised classification using a Random Forest algorithm (500 trees, minimum leaf size 5) was implemented in Google Earth Engine with a training dataset of 87 field-validated plots, using 42 remote sensing predictor variables including seasonal NDVI statistics (mean, maximum, minimum, range, coefficient of variation), SAVI, red-edge vegetation indices from Sentinel-2, MODIS land surface temperature, and textural features derived from grey-level co-occurrence matrices. Model performance was evaluated through 10-fold stratified cross-validation, yielding overall accuracy of 87.3% and Cohen's kappa of 0.834. Independent validation against 29 holdout field plots not used in training gave overall accuracy of 83.1%.

Class	Description	Cover	Palatable spp.	Key Field Indicators
I – None	Undegraded	>60%	>80% of cover	Diverse perennials, stable soils, no erosion
II – Slight	Early degradation	40–60%	60–80%	Some loss of key spp., light hoof compaction
III – Moderate	Significant	20–40%	30–60%	Unpalatables dominant, bare patches, erosion signs
IV – Severe	Advanced	10–20%	<30%	Deflation patches, high compaction, annual weed dom.

V – Very Severe	Near-complete	<10%	<5%	Dominant bare/mobile sand, no recovery signs

Table 1. Five-Class Pasture Degradation Classification System

Source: Authors, 2024

3.5 Socio-Economic Data Collection and Analysis

Semi-structured interviews were conducted with 78 pastoral household heads across 18 rural communities distributed across the three geomorphological zones of the Ahal province during May–June 2023. Community selection was stratified by zone and distance from Ashgabat. Household selection within communities was purposive, targeting the most experienced pastoralists with > 10 years of active herding in the area. Interview topics covered: current and historical herd sizes and compositions; seasonal grazing patterns, routes, and calendar; subjective assessment and description of pasture condition change over the past 10–25 years; perceptions of degradation drivers; water point access and infrastructure condition; fuelwood collection practices and estimated volumes; knowledge of traditional pasture management practices; and willingness to participate in community-based management arrangements. Qualitative responses were coded thematically; quantitative livestock data were converted to sheep equivalents (SE) using FAO standard conversion factors (1 camel = 7 SE, 1 horse = 6 SE, 1 goat = 0.8 SE).

4 RESULTS

4.1 Spatial Extent and Distribution of Degradation Classes

The degradation mapping produced from Random Forest classification of integrated remote sensing and field data yielded a spatially detailed assessment covering the full 1.8 million hectare pasture extent of the Ahal province. Table 2 presents the quantified areal distribution across degradation classes, while the spatial pattern reveals strong associations with proximity to settlements, water points, and major livestock routes.

Class	Area (ha)	% of Total	Primary Spatial Distribution
I – None	594,000	33.0%	Remote Karakum, protected watershed, inaccessible areas
II – Slight	378,000	21.0%	5–10 km from water, secondary livestock routes
III – Moderate	432,000	24.0%	2–5 km from water, main seasonal grazing zones
IV – Severe	288,000	16.0%	1–2 km from water, near-settlement pastures
V – Very Severe	108,000	6.0%	< 1 km from water, corrals, permanent camp areas
Total	**1,800,000**	**100%**	

Table 2. Distribution of Pasture Land Area by Degradation Class, Ahal Province, Turkmenistan

Source: Authors' remote sensing classification validated with 145 field plots, 2024

The combined Classes III–V (moderate to very severe) encompass approximately 828,000 ha (46% of total assessed area), while only 594,000 ha (33%) retains undegraded Class I condition. The spatial pattern of degradation exhibits a characteristic concentrically nested structure centred on permanent water sources (wells, surface water bodies), with degradation severity decreasing systematically with radial distance. Secondary linear degradation features follow the major livestock route network connecting settlements and seasonal pasture areas. The northern Karakum zone retains the largest contiguous areas of Class I pasture due to its remoteness and reduced accessibility, while the southern piedmont zone — despite its higher inherent productivity — shows disproportionately high levels of degradation due to year-round accessibility and concentrated livestock pressure from nearby settlements.

4.2 Long-Term NDVI Trend Analysis (2000–2024)

The 24-year MODIS NDVI trend analysis revealed spatially heterogeneous but broadly negative vegetation dynamics across the Ahal province. Statistically significant declining trends (Mann-Kendall $p < 0.05$) were detected across 38.2% of the total study area, covering approximately 687,600 ha. Areas with insignificant negative trends covered an additional 28.4% of the area, while significant positive trends were found in only 6.3% of the area (predominantly remote northern Karakum areas with reduced recent grazing pressure). The remaining 27.1% showed no statistically discernible trend.

The mean rate of NDVI decline in areas with significant negative trends was –0.0021 NDVI units per year (Sen's slope), representing a cumulative reduction of approximately 0.050 NDVI units over the full 24-year period — equivalent to a 15–22% relative decline in peak vegetation productivity in the most affected zones. The highest decline rates (< –0.003 units/year) were concentrated in heavily grazed zones within 2–5 km of major water points, consistent with progressive overutilization effects. Temporal decomposition of the NDVI time series revealed a notable acceleration of decline post-2010, with the 2018–2020 period representing the steepest three-year NDVI depression in the 24-year record, associated with anomalously low precipitation years that appear to have pushed marginally stable vegetation communities past ecological tipping points.

Comparison of NDVI trends between the three geomorphological zones showed significant differences in degradation dynamics. The Kopetdag piedmont zone showed the highest proportion of significant declining trends (47% of zone area), consistent with its higher inherent productivity and year-round accessibility making it the most intensively used and most systematically monitored zone. The central transition zone showed intermediate decline rates (39% of zone area with significant negative trends). The sandy Karakum zone showed the lowest proportion of significant declines (28%) but the most spatially concentrated patterns, reflecting the piosphere effect around scattered water points in an otherwise remote landscape.

4.3 Vegetation Cover, Height Structure, and Species Composition

Field survey data provide detailed ground-truth characterization of vegetation condition across all five degradation classes. Mean total vegetation cover decreased systematically and substantially from 58 ± 12% in Class I to 7 ± 3% in Class V (Table 3). The proportion of total cover attributable to palatable species declined even more sharply — from 81% of cover in Class I to less than 5% in Classes IV–V — indicating that the residual vegetation in severely degraded areas consists almost entirely of unpalatable and ecologically low-value species.

Species richness declined from 18.4 ± 4.2 species per 100 m² plot in Class I to 4.1 ± 1.8 species in Class V. Shannon diversity index declined from 2.34 ± 0.41 in Class I to 0.87 ± 0.32 in Class V. The decline in species richness was disproportionately concentrated among palatable perennial species: Poa bulbosa (once the dominant grass across piedmont pastures) was present in 94% of Class I plots but only 8% of Class V; Carex physodes declined from 78% to 4% frequency; Salsola richteri from 67% to 12%; and Haloxylon ammodendron from 58% to 15% frequency across the gradient. Conversely, unpalatable annual weeds — particularly Salsola collina, Ceratocarpus arenarius, Horaninovia ulicina, and Chenopodium album — increased from 18% frequency in Class I to 100% frequency in Class IV–V, in many severely degraded plots constituting the sole remaining vegetation.

Canopy structural measurements revealed equally dramatic changes. In undegraded saxaul-dominated Karakum plots, individual tree heights of 2.5–4.2 m and crown diameters of 1.8–3.5 m provided substantial structural complexity. In Class IV–V plots within the saxaul zone, surviving individuals were typically stunted (< 0.8 m height), heavily browsed, with crown dieback exceeding 70% of individuals. Live crown biomass was estimated at less than 15% of undegraded reference values in Class V plots, representing near-complete functional loss of the saxaul engineering role that stabilizes sandy substrates.

Parameter	Class I	Class II	Class III	Class IV	Class V

Total cover (%)	58±12	48±10	29±9	15±6	7±3
Palatable cover (%)	47±11	34±9	15±7	5±3	1±1
Species richness	18.4±4.2	14.2±3.6	9.8±2.9	6.1±2.2	4.1±1.8
Shannon diversity	2.34±0.41	1.98±0.38	1.52±0.34	1.11±0.29	0.87±0.32
Bare ground (%)	18±8	28±9	44±12	62±13	79±11

Table 3. Mean Vegetation Metrics by Degradation Class (n = 145 plots)

Source: Authors' field survey data, 2023–2024

4.4 Piosphere Effect: Grazing Intensity and Distance from Water

The spatial analysis of vegetation cover and degradation class as a function of distance from permanent water sources yielded one of the most statistically robust piosphere relationships documented for Central Asian pastoral systems. A highly significant logarithmic relationship was observed between total vegetation cover and log-transformed distance from the nearest permanent water source ($r^2 = 0.84$, $F = 742.3$, $p < 0.001$, $n = 145$ plots). Within 500 m of wells and surface water points, mean vegetation cover was 4 ± 2% and 98% of plots fell into Class V. At 500 m–2 km, mean cover was 11 ± 5% with 91% as Classes IV–V. At 2–5 km, cover recovered to 24 ± 10% (predominantly Class III). At 5–10 km, mean cover reached 38 ± 14% (Classes II–III dominant). Beyond 10 km from water, cover averaged 54 ± 16% with predominantly Class I–II conditions. This pronounced gradient confirms livestock concentration around water as the dominant proximal driver of severe localized degradation in the region.

4.5 Soil Physical and Chemical Properties Across the Degradation Gradient

Soil analyses across the degradation gradient revealed significant and ecologically consequential changes in physical and chemical properties (Table 4). Soil bulk density increased significantly from 1.28 ± 0.08 g cm■^{3} in Class I to 1.74 ± 0.11 g cm■^{3} in Class V, representing a 36% increase indicative of severe structural compaction. Penetration resistance showed an even more dramatic change, increasing from 1.2 ± 0.3 MPa in Class I to 4.1 ± 0.7 MPa in Class V — with 87% of Class IV–V measurements exceeding the widely cited 2.5 MPa threshold for significant root restriction.

Soil organic carbon declined from 1.24 ± 0.31% in Class I to 0.41 ± 0.18% in Class V — a 67% reduction representing substantial loss of soil carbon stocks with both ecological and climate implications. This translates to a carbon stock reduction of approximately 3.2 t C ha■^{1} (0–30 cm) between undegraded and very severely degraded conditions. Total nitrogen followed a parallel pattern, declining from 0.098 ± 0.024% to 0.033 ± 0.015%. The C:N ratio decreased from 12.7 in Class I to 9.5 in Class V, suggesting a shift in soil microbial community composition and decomposition dynamics under degradation. Surface electrical conductivity was significantly elevated in degraded zones (1.8 ± 0.6 dS m■^{1} in Class V versus 0.6 ± 0.2 dS m■^{1} in Class I), reflecting secondary salinization processes associated with reduced leaching under compacted surfaces.

Soil Parameter	Class I	Class III	Class V	p-value
Bulk density (g cm■^{3})	1.28±0.08	1.54±0.09	1.74±0.11	< 0.001
Penetration resistance (MPa)	1.2±0.3	2.7±0.5	4.1±0.7	< 0.001
Organic carbon (%)	1.24±0.31	0.78±0.22	0.41±0.18	< 0.001
Total nitrogen (%)	0.098±0.024	0.062±0.018	0.033±0.015	< 0.001
C:N ratio	12.7±1.8	11.3±1.6	9.5±1.4	< 0.001
EC (dS m■^{1})	0.6±0.2	1.1±0.4	1.8±0.6	< 0.001

pH	7.6±0.3	7.9±0.3	8.2±0.4	< 0.05
Available P (mg kg^{-1})	8.4±2.1	5.6±1.8	3.2±1.4	< 0.001

Table 4. Soil Physical and Chemical Properties by Degradation Class (0–10 cm, n = 87 plots)

Source: Authors' laboratory analyses, Turkmen Agricultural University, 2023–2024

4.6 Socio-Economic Dimensions of Pasture Degradation

Household interview data provided important insights into the human dimensions of observed degradation patterns. Mean herd size among interviewed households was 142 ± 84 sheep equivalents (range 20–580 SE), with camels present in 68% of households (mean 12.4 animals, equivalent to 86.8 SE). Total estimated livestock density in frequently grazed zones around water points was calculated at approximately 3.8–5.2 SE ha^{-1}, substantially exceeding estimated sustainable carrying capacities of 0.4–0.8 SE ha^{-1} for these pasture types.

Of the 78 interviewed households, 89% perceived a significant deterioration in pasture condition over the past 10–15 years. The most frequently cited indicators of decline included: reduced grass height and density (94% of respondents), disappearance of preferred forage shrubs and grasses (87%), increased bare ground and wind-blown sand (76%), reduced spring ephemeral flush duration (71%), and declining livestock body condition requiring supplementary feeding (65%). These perceptions are highly consistent with the field survey and remote sensing findings, providing important validation from the perspective of experienced land users who have observed change over multiple decades.

Seasonal grazing pattern analysis revealed that 73% of interviewed households practice year-round or near-year-round grazing on the same pasture areas within 5–8 km of their home settlement, with only 27% maintaining any form of meaningful seasonal rotation or movement to remote pastures. The primary constraints cited for reduced mobility were: limited water infrastructure beyond accessible areas (82%), security and tenure concerns (46%), deteriorating road access (38%), reduced herd sizes making the economics of nomadic movement untenable (34%), and loss of traditional knowledge about remote pasture locations and seasonal routes (28%). These findings highlight the compounding institutional, infrastructural, and economic barriers that perpetuate the sedentary grazing concentration driving the documented degradation patterns.

5 DISCUSSION

The integrated findings of this study provide compelling and multi-dimensional evidence for extensive, accelerating pasture land degradation across the Ahal region, affecting nearly half of the assessed rangeland at ecologically significant levels of impairment. The convergence of results from independent data streams — 24-year remote sensing trends, field phytosociological surveys, soil analyses, and pastoral community perceptions — substantially strengthens the confidence in the assessment findings and reduces the risk of method-specific artifacts or biases driving the documented patterns.

The magnitude of the piosphere effect documented here — with 91% of plots within 2 km of water severely degraded and a highly significant $r^2 = 0.84$ cover-distance relationship — represents one of the most pronounced livestock-water gradients reported for Central Asian pastoral systems. This intensity substantially exceeds values documented in comparable studies in Mongolia ($r^2 \approx 0.65$; Xu et al., 2014) and the Sahel region ($r^2 \approx 0.70$; Vetter, 2005), suggesting that the combination of elevated post-privatization livestock densities, extremely limited water infrastructure distribution, and the breakdown of seasonal mobility creates an unusually concentrated grazing pressure in the Ahal region relative to international comparators.

The dramatic species composition shifts from productive, nutritious, structurally complex palatable perennial communities to depauperate assemblages dominated by unpalatable annual weeds represent a fundamental functional degradation of the pasture ecosystem extending far beyond the direct reduction in forage availability. The loss of deep-rooted perennial grasses and shrubs eliminates the biological mechanisms through which soil organic matter is produced and stabilized: reduced root turnover and litter input diminish the primary pathways of SOC addition, while increased bare ground exposure accelerates oxidative decomposition of residual organic matter, collectively explaining the 67% SOC reduction documented in the soil data. The loss of saxaul canopy structure in the Karakum zone removes the principal windbreak function that stabilizes sandy substrates, leading directly to the wind erosion features documented at 78% of Class IV–V plots.

The soil data provide particularly important evidence for the likely trajectory of passive recovery in the absence of active intervention. The penetration resistance values of 4.1 MPa recorded in Class V plots substantially exceed the 2.5 MPa threshold widely recognized as the critical limit for root penetration in most plant species (Bengough et al., 2011), implying that even complete removal of grazing pressure would not automatically allow natural vegetation recovery. The compacted, SOC-depleted, electrically conductive soils characteristic of severely degraded zones represent a persistent legacy of degradation that actively resists re-colonization by the perennial species needed to restore ecosystem function — creating a 'degradation trap' that requires active restoration intervention to escape.

The post-2010 acceleration of NDVI decline revealed in the satellite time series adds a critical climate dimension to the degradation narrative. The 2018–2020 period's unprecedented NDVI depression coincides with the driest three-year sequence in the 24-year MODIS record for the Ahal region, suggesting a climate-induced threshold event in which already-weakened vegetation communities lost resilience and failed to recover between drought years. This pattern is consistent with theoretical frameworks of non-linear rangeland dynamics in which cumulative grazing pressure reduces ecosystem resilience to climatic fluctuations, increasing the probability of abrupt transitions to degraded stable states (Briske et al., 2008). The implication is that the interaction between overgrazing and climate change in the Ahal region is not merely additive but potentially synergistic and self-amplifying.

The socio-economic data illuminate the structural roots of the management failures driving documented degradation. The 73% of households practicing de facto sedentary grazing — primarily constrained by water infrastructure limitations, economic barriers, and institutional voids rather than by preference — highlights that technical restoration solutions will be insufficient without addressing the enabling conditions for improved management. The loss of traditional seasonal mobility knowledge and practices, combined with the collapse of communal pasture governance institutions, creates a 'management deficit' that is as fundamental a barrier to recovery as the physical soil degradation documented in the field data. Effective and durable restoration requires rebuilding the institutional, economic, and social foundations of sustainable pasture governance in parallel with ecological rehabilitation measures.

6 INTEGRATED RESTORATION FRAMEWORK

Based on the integrated findings, the following evidence-based restoration framework is proposed, structured around four complementary intervention pillars:

6.1 Rotational Grazing Management

Establishment of community-based rotational grazing systems represents the highest-priority, most cost-effective intervention. The spatial data indicate clear minimum rest periods required for passive vegetation recovery by class: Class III areas require 2–3 years with seasonal rest; Class IV requires 4–5 years of protected rest; Class V requires indefinite exclusion plus active restoration. Implementation requires: (1) community mapping and demarcation of rotational units; (2) legal frameworks recognizing community pasture tenure and management rights; (3) negotiated seasonal grazing calendars aligned with plant phenology; and (4) conflict resolution mechanisms for cross-community herding. Pilot rotational programs in comparable Central Asian contexts have demonstrated 25–40% vegetation cover recovery within 3–5 years of implementation (Akiyanova et al., 2023).

6.2 Strategic Water Infrastructure Development

Given the dominant role of the piosphere effect in driving Class IV–V degradation, strategic development of 40–50 new water points in currently inaccessible intermediate-distance pasture zones (5–15 km from existing infrastructure) represents the intervention with highest potential impact per investment unit. Spatial modelling of the documented cover-distance gradient indicates that distributing grazing pressure across an additional 600,000–800,000 ha of currently underused pasture could reduce utilization intensity at existing water points by an estimated 35–45%, initiating passive recovery in Class IV–V zones within 2–4 years. New water points should be designed as community infrastructure with defined governance arrangements to prevent the same concentration dynamics from developing at new locations.

6.3 Active Phytomelioration and Ecological Restoration

Class V areas and severely compacted Class IV zones require active restoration intervention since physical soil conditions impede natural recovery. Phytomelioration using native species — saxaul (H. ammodendron, H. persicum) as structural dominants, Artemisia spp. and Salsola richteri as secondary shrub layer species, and ephemeral grass seed mixes for rapid initial cover establishment — is the recommended primary technique. Soil decompaction (subsoiling) prior to planting has shown positive effects in comparable systems and should be evaluated in pilot trials. Minimum protective exclosure periods of 5–7 years are required for saxaul establishment to functional height (> 1.5 m). Priority restoration areas should be identified based on restoration potential scoring integrating soil condition, hydrology, and proximity to seed sources.

6.4 Monitoring, Evaluation, and Adaptive Management

A multi-tiered monitoring system is proposed integrating: (1) annual satellite-based NDVI tracking using free Sentinel-2 and MODIS data products to detect vegetation recovery trends at provincial scale; (2) tri-annual repeat surveys of a 30-plot monitoring network spanning all degradation classes to track vegetation cover, species composition, and soil penetration resistance; and (3) community-based participatory monitoring using standardized simplified field protocols implementable by trained community members. Monitoring data should feed into an adaptive management framework with predefined decision thresholds triggering management adjustments, ensuring continuous evidence-based optimization of restoration investments.

7 CONCLUSION

This study has delivered the most spatially comprehensive, methodologically integrated, and quantitatively rigorous ecological assessment of pasture land degradation in the Ahal region of Turkmenistan to date. By combining 24 years of multi-source satellite remote sensing with systematic field phytosociological surveys across 145 stratified plots, soil analyses from 87 sites, and socio-economic data from 78 pastoral households, the research has produced a multi-dimensional, field-validated characterization of the degradation crisis affecting approximately 828,000 ha — 46% of the province's assessed rangelands — at moderate to very severe levels of functional impairment.

The study's key quantitative contributions include: (1) the first provincial-scale five-class degradation map of Ahal pasture lands validated by extensive field data; (2) documentation of statistically significant NDVI decline across 38.2% of the study area over 2000–2024; (3) quantification of one of the most pronounced piosphere gradients reported for Central Asian pastoralism ($r^2 = 0.84$); (4) documentation of a 67% reduction in soil organic carbon and 36% increase in bulk density between undegraded and very severely degraded conditions; and (5) identification of structural socio-economic barriers — particularly water infrastructure gaps and institutional voids — as primary drivers perpetuating sedentary concentration of grazing pressure.

The positive finding that 33% of assessed lands retain good ecological condition, and that clear vegetation recovery gradients are observable at intermediate distances from water sources, provides a scientifically grounded basis for cautious optimism: substantial restoration potential exists if appropriate interventions are implemented with adequate investment, community engagement, and governance support. The integrated restoration framework proposed — combining rotational grazing management, strategic water point development, active phytomelioration in severely degraded areas, and robust monitoring — offers a practically implementable and evidence-based pathway toward halting and reversing the documented degradation trajectory.

The findings of this study directly support Turkmenistan's commitments under the United Nations Convention to Combat Desertification, particularly its voluntary land degradation neutrality target. The degradation baselines, spatial assessments, and causal analyses presented here provide the quantified foundation needed to design, spatially target, monitor, and evaluate national pasture restoration programs at provincial and national scales. Future research priorities should include: multi-year vegetation recovery monitoring in grazing exclusion exclosures across all three geomorphological zones; economic valuation of ecosystem services from restored pasture lands; scenario modelling of future degradation trajectories under combined climate change and management pathways; and assessment of the carbon sequestration potential of scaled phytomelioration programs as a nature-based solution contribution to regional climate mitigation.

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APPENDIX A: PLANT SPECIES RECORDED ACROSS DEGRADATION CLASSES

Table A1 presents the complete list of plant species recorded during field surveys across all 145 plots, including family classification, life form, palatability rating, and occurrence frequency by degradation class. Species are arranged alphabetically by genus within palatability categories.

Species	Family	Life Form	Palatability	Class I	Class III	Class V
Haloxylon ammodendron	Chenopodiaceae	Phanerophyte	High	58%	34%	15%
Haloxylon persicum	Chenopodiaceae	Phanerophyte	High	42%	28%	11%
Salsola richteri	Chenopodiaceae	Phanerophyte	High	67%	31%	12%
Poa bulbosa	Poaceae	Hemicryptophyte	High	94%	45%	8%
Carex physodes	Cyperaceae	Geophyte	High	78%	38%	4%
Stipagrostis pennata	Poaceae	Hemicryptophyte	High	52%	22%	3%
Artemisia diffusa	Asteraceae	Chamaephyte	Moderate	71%	52%	18%
Artemisia terrae-albae	Asteraceae	Chamaephyte	Moderate	63%	48%	21%
Ephedra strobilacea	Ephedraceae	Chamaephyte	Moderate	38%	29%	14%
Salsola arbuscula	Chenopodiaceae	Chamaephyte	Moderate	44%	38%	22%
Salsola collina	Chenopodiaceae	Therophyte	Unpalatable	18%	68%	100%
Ceratocarpus arenarius	Chenopodiaceae	Therophyte	Unpalatable	12%	74%	98%
Horaninovia ulicina	Chenopodiaceae	Therophyte	Unpalatable	8%	61%	94%
Chenopodium album	Chenopodiaceae	Therophyte	Unpalatable	6%	55%	88%
Peganum harmala	Nitrariaceae	Hemicryptophyte	Toxic	4%	38%	76%
Euphorbia seguieriana	Euphorbiaceae	Hemicryptophyte	Toxic	2%	24%	48%

Table A1. Selected Plant Species Recorded in Field Surveys with Occurrence Frequency by Degradation Class (n = 145 plots, % of plots in which species was recorded)

Source: Authors' field survey data, 2023–2024

APPENDIX B: DETAILED FIELD SURVEY AND STATISTICAL METHODOLOGY

B.1 Stratified Random Sampling Framework

The 145 permanent sample plots were distributed across the study area using a stratified random sampling design to ensure proportional representation of all major ecological conditions. The stratification matrix combined three factors: preliminary NDVI magnitude class (five classes based on mean spring NDVI quantiles from 2019–2023 MODIS data), geomorphological zone (three classes: Kopetdag piedmont, Central transition, Sandy Karakum), and distance from permanent water source (three classes: < 2 km, 2–8 km, > 8 km from the nearest confirmed water point in the provincial water infrastructure database). This yielded a theoretical maximum of 45 strata cells (5 × 3 × 3), of which 38 were sufficiently extensive to sample. Plot allocation was proportional to stratum area with a minimum of 2 plots per occupied stratum.

Plot coordinates were generated by stratified random sampling within each stratum polygon using a minimum inter-plot distance constraint of 2 km to ensure spatial independence of observations. Generated coordinates were adjusted to avoid areas of road surface, waterbodies, and permanent settlements within 50 m using satellite imagery screening. Final plot locations were field-verified and permanently marked with aluminium rebar stakes at four corners to enable repeat measurement in subsequent monitoring surveys.

B.2 Statistical Analysis Methods

Differences in vegetation cover, species richness, and soil parameters across degradation classes were tested using one-way ANOVA with Tukey's honestly significant difference post-hoc test for multiple comparisons. Where data did not meet the assumption of normality (Shapiro-Wilk test, $p < 0.05$), Kruskal-Wallis non-parametric ANOVA with Dunn's post-hoc test was substituted. Statistical significance was evaluated at $\alpha = 0.05$ throughout. All statistical analyses were performed in R version 4.3.1 (R Core Team, 2023) using the vegan package for community ecology analyses and the coin package for permutation-based tests.

The relationship between vegetation cover and log-transformed distance from water was analysed using simple linear regression on log-transformed distance values, after confirming that the log-linear model provided significantly better fit than untransformed linear regression based on AIC comparison (ΔAIC = 47.3 in favour of log-linear). Species composition dissimilarity between degradation classes was analysed using Bray-Curtis dissimilarity with non-metric multidimensional scaling (NMDS, 2 dimensions, stress = 0.14) and PERMANOVA (adonis2 function in vegan, 999 permutations). Indicator species analysis (IndVal method, Dufrêne & Legendre, 1997) was used to identify species significantly associated with specific degradation classes.

B.3 Remote Sensing Accuracy Assessment

The Random Forest degradation classification model was evaluated through two complementary accuracy assessment approaches. Internal 10-fold stratified cross-validation (k-fold CV) using the 87 training plots yielded overall accuracy of 87.3%, with class-specific user's and producer's accuracies ranging from 82% (Class IV) to 94% (Class I and Class V). The kappa coefficient of 0.834 indicates 'excellent' agreement by conventional benchmarks. External validation against 29 independent holdout plots (not included in model training) yielded overall accuracy of 83.1% and kappa of 0.788.

Confusion between adjacent degradation classes (particularly Classes II–III and Classes III–IV) accounted for the majority of classification errors, which is expected given the continuous nature of the degradation gradient and the threshold-based nature of class boundaries. For management purposes, misclassification between adjacent classes has limited practical consequence as recommended management responses for Classes II and III are similar. Misclassification between non-adjacent classes (e.g., Class I as Class III) was minimal (< 3% of validation plots), indicating robust discrimination of broadly different degradation levels.

APPENDIX C: COMPARATIVE RESTORATION CASE STUDIES FROM CENTRAL ASIA

The following case studies from comparable Central Asian arid rangeland contexts provide evidence-based benchmarks for expected recovery timelines and outcomes under the restoration interventions proposed in Section 6. These examples were identified through systematic literature review and consulted in developing the evidence base for the restoration framework.

C.1 Rotational Grazing Outcomes: Kazakhstan Semi-Arid Steppes

A 5-year study of community-based rotational grazing implementation in the Kostanay region of Kazakhstan (Akiyanova et al., 2023) documented mean vegetation cover recovery from 24% to 42% (75% increase) in formerly severely grazed areas following 3-year rest periods. Species richness recovered by approximately 40% relative to adjacent continuously grazed controls. The proportion of palatable perennial species in total cover increased from

28% to 54%. Notably, recovery was significantly faster in areas with less severe pre-intervention soil compaction (< 2.5 MPa), providing empirical support for the hypothesis that soil physical condition is a key constraint on recovery rate in heavily degraded areas.

C.2 Saxaul Phytomelioration: Uzbekistan Aral Sea Region

Large-scale saxaul (Haloxylon ammodendron and H. persicum) phytomelioration on the dried Aral Sea bed in Uzbekistan, covering over 1.7 million ha over 2018–2023, provides relevant experience for active restoration at scale in comparable arid conditions. Direct seeding using aircraft application achieved establishment success rates of 30–45% in favorable precipitation years and 8–15% in dry years, with canopy heights reaching 0.8–1.2 m by year 5. The program demonstrated that large-scale restoration is technically feasible and economically viable at approximately USD 45–85 per hectare using aerial seeding methods, significantly below the per-hectare economic value of restored pasture productivity estimated at USD 120–180 ha^{-1} year^{-1}.

C.3 Water Point Development and Piosphere Recovery: Mongolia

A natural experiment in the Mongolian steppe documented by Xu et al. (2014) following the abandonment of 23 water points due to infrastructure failure provided a unique opportunity to observe vegetation recovery in former piosphere degradation zones. Within 4–6 years of water point abandonment and effective removal of concentrated grazing pressure, vegetation cover in former Class IV–V equivalent zones recovered by 28–41 percentage points, with palatable perennial grass species re-establishing from surviving root systems at distances up to 5 km from former water points. This evidence supports the projected recovery potential of the water point redistribution strategy proposed for the Ahal region.

APPENDIX D: PRIORITY RESTORATION INTERVENTIONS — SUMMARY TABLE

Intervention	Target Degradation Class	Priority Area (ha)	Est. Cost (USD ha^{-1})	Expected Outcome	Timeline
Rotational grazing with rest periods	Classes II–IV	828,000	5–15	+25–40% cover recovery	3–5 yrs
Strategic water point development	Classes III–V near water	600,000–800,000	8–20 per ha served	35–45% reduction in near-water pressure	1–3 yrs
Active phytomelioration (saxaul)	Classes IV–V	108,000–288,000	45–85	Structural cover >30% by yr 7	5–10 yrs
Grazing exclosures for recovery	Class V	108,000	15–30	Passive recovery initiation	Indefinite
Community monitoring network	All classes	Province-wide	2–5 per plot/yr	Evidence base for adaptive management	Ongoing

Table D1. Summary of Priority Restoration Interventions with Cost and Outcome Estimates

Source: Authors' synthesis based on literature review and field data, 2024

Note: Cost estimates are based on comparable program costs documented in Central Asian and international literature (World Bank, 2022; Akiyanova et al., 2023) and should be considered indicative order-of-magnitude estimates subject to revision through detailed feasibility assessments. The rotational grazing cost estimate refers primarily to institutional and facilitation costs; fencing costs where required would add USD 200–600 km^{-1} depending on terrain and materials. All interventions require community engagement and governance support costs not included in per-hectare restoration cost estimates.

APPENDIX E: POLICY IMPLICATIONS AND NATIONAL FRAMEWORK ALIGNMENT

E.1 Alignment with Turkmenistan's UNCCD National Action Programme

The findings and recommendations of this study align closely with and provide quantified support for Turkmenistan's commitments under the United Nations Convention to Combat Desertification (UNCCD), to which Turkmenistan has been a Party since 1996. Turkmenistan's National Action Programme to Combat Desertification identifies pasture land degradation as a priority national challenge and sets out a framework for sustainable land management that encompasses rotational grazing, water point development, phytomelioration, and community-based monitoring — precisely the intervention pillars proposed in the restoration framework of this study.

The quantified degradation assessment presented here — particularly the provincial-scale degradation map, the 46% moderate-to-severe degradation extent estimate, and the 667,000 ha of statistically significant NDVI decline — provides the standardized, scientifically validated baselines needed for Turkmenistan to report on progress toward its voluntary Land Degradation Neutrality (LDN) target. The LDN framework requires tracking three biophysical indicators: land cover, land productivity dynamics, and soil organic carbon stocks. The methods and results of this study directly address all three indicators for the pasture land sub-national reporting unit of the Ahal province.

E.2 Integration with National Agricultural Development Strategy

Beyond UNCCD reporting, the study findings have direct relevance to Turkmenistan's National Programme for Socio-Economic Development, which identifies livestock production modernization and pasture productivity improvement as strategic priorities for rural economic development. The documented carrying capacity deficit — estimated livestock densities of 3.8–5.2 SE ha^{-1} against sustainable capacities of 0.4–0.8 SE ha^{-1} in heavily used zones — underscores the economic irrationality of current management: the ecological capital (productive pasture capacity) on which the livestock economy depends is being consumed faster than it is replenished, creating the conditions for an inevitable economic collapse of the pastoral sector if degradation trends are not reversed.

Economic modelling based on the field data suggests that restoration of moderately degraded Class III pastures to Class I–II condition would increase carrying capacity by approximately 1.5–2.0 SE ha^{-1} on the restored areas, generating an annual economic benefit of approximately USD 45–75 per hectare in increased livestock production value at current regional livestock prices. Against a restoration cost of USD 5–85 per hectare depending on intervention type, the benefit-cost ratio for rotational grazing management interventions (the lowest-cost option) is exceptionally favourable at 3:1 to 15:1, supporting the economic case for urgent investment in pasture restoration.

E.3 Recommendations for National Policy and Institutional Reform

Based on the integrated findings, the following policy and institutional recommendations are proposed for consideration by the Government of Turkmenistan and international development partners: (1) Establish a provincial Pasture Management Unit within the Ahal velayat administration with dedicated staff and budget for implementation and monitoring of pasture restoration programs; (2) Develop a legal framework for community pasture tenure that grants recognized user rights to pastoral communities over defined pasture territories, providing the security needed to justify long-term investment in land improvement; (3) Create economic incentive mechanisms — such as differentiated livestock tax rates or access to veterinary support conditional on participation in rotational grazing programs — to encourage adoption of sustainable management practices; (4) Invest in the water infrastructure required to enable seasonal pasture mobility, targeting the 40–50 new water points identified in the spatial analysis as having the highest leverage for degradation pressure reduction.

(5) Integrate the degradation classification map and monitoring framework developed in this study into the national land cadastre and remote sensing monitoring system operated by the State Committee for Land Resources; (6) Develop and deliver a national training program for local agricultural extension workers on pasture condition assessment, degradation monitoring, and community facilitation for rotational grazing implementation; (7) Establish a national-level research and demonstration program for phytomelioration techniques adapted to Turkmen arid conditions, building on the Institute of Botany's existing expertise in native plant species ecology and restoration; and (8) Engage international partners — including UNCCD, FAO, World Bank, and UNDP — to mobilize concessional financing for the capital investments required for water infrastructure development and large-scale phytomelioration programs at the scale warranted by the documented degradation extent.

APPENDIX F: SUPPLEMENTARY DATA SUMMARY

Table F1 summarizes the key quantitative parameters derived from the integrated dataset underlying this assessment, providing a consolidated reference for policymakers, land managers, and future researchers building on these findings.

Parameter	Value	Unit	Source
Total assessed pasture area	1,800,000	ha	Remote sensing classification
Area with significant NDVI decline (2000–2024)	687,600 (38.2%)	ha	MODIS trend analysis
Mean NDVI decline rate	–0.0021	units yr^{-1}	Sen's slope estimator
Area in Class III–V (moderate–very severe)	828,000 (46%)	ha	RF classification, field-validated
Area in Class V (very severe)	108,000 (6%)	ha	RF classification, field-validated
Mean cover loss (Class I → Class V)	58% → 7%	%	Field survey, 145 plots
Piosphere gradient r^2	0.84	dimensionless	Field survey regression
% plots Class IV–V within 2 km water	91%	%	Field survey, 145 plots
Mean SOC reduction (Class I → Class V)	1.24% → 0.41% (–67%)	%	Soil laboratory, 87 plots
Mean bulk density (Class V)	1.74 ± 0.11	g cm^{-3}	Soil laboratory, 87 plots
% households with non-rotational grazing	73%	%	Household interviews, n=78
Est. carrying capacity deficit (near water)	3.8–5.2 vs. 0.4–0.8	SE ha^{-1}	Household + field data
Benefit-cost ratio (rotational grazing)	3:1 to 15:1	dimensionless	Economic analysis
Recommended new water points	40–50	units	Spatial modelling
Est. passive recovery potential (Class III)	+25–40% cover in 3–5 yrs	%	Literature review

Table F1. Consolidated Key Quantitative Parameters from Integrated Pasture Degradation Assessment, Ahal Province, Turkmenistan, 2024

Source: Authors' synthesis of remote sensing, field survey, soil analysis, and socio-economic data, 2023–2024

APPENDIX G: GLOSSARY OF TECHNICAL TERMS

Carrying capacity

The maximum number of livestock (expressed in sheep equivalents per hectare) that a pasture ecosystem can sustainably support without long-term degradation of its productive capacity.

Chamaephyte

A low-growing woody or semi-woody plant (shrub or sub-shrub) with renewal buds situated above soil level but below 25 cm height; common life form in desert and semi-desert vegetation.

Deflation

Wind erosion process in which fine soil particles are removed from the surface by wind action, leaving behind coarser material and creating characteristic surface lowering.

Electrical conductivity (EC)

A measure of the soil's ability to conduct electrical current, used as a proxy for total dissolved salt content; elevated EC indicates salinization.

Geophyte

A plant that survives unfavorable seasons as underground storage organs (bulbs, corms, rhizomes) buried below soil level; includes many ephemeral grasses and forbs of arid regions.

Hemicryptophyte

A plant with renewal buds at or just below soil surface level; includes most perennial grasses and many forbs characteristic of grassland and steppe vegetation.

Land Degradation Neutrality (LDN)

The state whereby the amount and quality of land resources necessary to support ecosystem functions and services and enhance food security remain stable or increase within specified temporal and spatial scales (UNCCD definition).

Mann-Kendall test

A non-parametric statistical test for detecting monotonic trends in time series data; does not assume normality and is robust to outliers and seasonal variability.

NDVI (Normalized Difference Vegetation Index)

A dimensionless index derived from red and near-infrared spectral reflectance, ranging from -1 to +1, widely used to estimate vegetation density, cover, and productivity from satellite imagery.

Phanerophyte

A tree or large shrub with renewal buds situated > 25 cm above soil level; dominant structural life form of saxaul woodlands in the Karakum Desert.

Phytomelioration

The use of plant-based interventions — typically planting drought-tolerant native species — to stabilize degraded soils, reduce wind and water erosion, and restore vegetation cover.

Piosphere

The characteristic pattern of vegetation degradation radiating outward from permanent livestock water points, with the most severe degradation closest to water.

Random Forest

A machine learning ensemble classification algorithm using multiple decision trees trained on random subsets of training data and predictor variables; widely used in remote sensing classification tasks.

Sen's slope

A robust non-parametric estimator of the linear trend slope in a time series, calculated as the median of all pairwise slopes; less sensitive to outliers than ordinary least squares regression slope.

Sheep equivalent (SE)

A standardized unit for expressing mixed livestock herd sizes in comparable terms; by convention, 1 adult sheep = 1 SE, with other species converted using FAO standard factors.

Soil organic carbon (SOC)

The carbon contained in soil organic matter, including living biomass, fresh plant residues, and stabilized humified organic compounds; a key indicator of soil health and fertility.

Therophyte

An annual plant that completes its full life cycle within a single growing season and survives unfavorable periods only as seeds; includes most nitrophilous weed species characteristic of severely degraded pastures.

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GARAGUMU■ GÜNORTA BÖLEGINDE TOPRAK DUZLA■MASY: SEBÄPLER WE ÇÖZGÜTLER

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ABSTRACT
Toprak duzla■masy Garagumu■ günorta böleginde oba hojalygyna we ekologiýa agyr zyýan ýetirýän gi■den ýaýran meseledir. Bu i■ Türkmenistany■ günorta çöl zolagynda toprak duzla■masyny■ ýaýraý■yny, ■ertlendiriji sebäpleri we mümkin bolan çözgütlerini seljermek maksady bilen geçirildi. Ylmy gözlegler 2022–2024-nji ýyllar aralygynda 120 sany örnekleýi■ meýdançasynda geçirilen döwürleýin ýer gözleg i■lerini, uzak aralyklardan duýgur seri■deler arkaly alnan maglumatlary we laboratoriýa der■ewlerini öz içine alýar. Alnan netijeler sürüm ýerlerini■ 54%-inde orta we güýçli duzla■ma alamatlaryny■ bardygyny görkezdi. Esasy sebäpler hökmünde a■a suwary■, drenaj ulgamyny■ ýeterlik i■lemezligi we klimat üýtgemesi bilen baglany■ykly ýokary bugarmak görkezildi. Çäre hökmünde fitomeliorasiýa, damjalaýyn suwary■ we topraga organiki go■undylary go■mak usullary teklip edildi.

Açar sözler: toprak duzla■masy, Garagum, suwary■ ulgamy, çölle■me, fitomeliorasiýa, Türkmenistan, ekologiki baha, drenaj, duz toprak, oba hojalygy

1. GIR■■

Toprak duzla■masy – mineral duzlaryny■ toprakda bikanun mukdarda toplanmasy netijesinde onu■ hasyllylygyny we biologiki i■je■ligini ýitirmegi a■ladýan çynlakaý ekologiki meseläni■ biridir. Dünýäde takmynan 1 milliard gektar sürüm ýerini■ duzla■an hasaplanýandygy, onu■ 10%-ini■ bolsa doly ýüzüni ýitiren ýagdaýdadygy baradaky maglumatlar meseläni■ ählumumy ähmiýetini aýdy■la■dyrýar (FAO, 2021).

Türkmenistanda sürüm ýerleri umumy çäki■ takmynan 4%-ini tutýar, ýöne bu ýerleri■ uly bölegi Garagum sährasynda ýerle■ýän bolup, tebigy ■ertler boýunça suwary■ bilen bagly oba hojalygyna örän çyl■yrymly ýerlerdir. Ýurdu■ günorta böleginde, hususan-da Ahal welaýatyny■ çäklerinde Garagumu■ günorta bölegini■ topraklary esasan çäge we çäge-lilli düzüme eýe bolup, duz toplanmak hadysasyna örän ýokary duýgurlyk görkezýär.

Garagumu■ günortasynda ýerle■ýän sürüm ýerleri köp asyrlyk suwary■ tejribesini■ miwesi bolsa-da, häzirki döwrü■ çalt ösýän oba hojalygy talaplary bu ýerlerde suwary■ suwuny■ amatsyz ulanylmagyna, drenaj ulgamyny■ talabalaýyk i■ledilmezligine we netijede toprakdaky duz konsentrasiýasyny■ gijýänden-gijä artmaklygyna eltdi. Merkezi Aziýany■ çäklerinde alnyp barlan gi■i■leýin barlaglary■ netijeleri Amu Derýany■ a■ak akymy we Garagum kanalyny■ boýlaryndaky ýerleri■ köpüsini■ toprak duzla■masyndan ejir çekýändigini görkezdi (Abuduwaili et al., 2021).

Bu barlagda Garagumu■ günorta bölegi boýunça toprak duzla■masyny■ gi■i■leýin ekologiki bahasy geçirildi. I■i■ esasy maksatlary ■ulardan ybaratdyr: (1) duzla■an meýdanlary■ gi■i■lik ýaýraý■yny kesgitlemek; (2) duzla■many■ ýüze çykmagyny■ esasy sebäplerini seljermek; (3) oba hojalygy we ekosistema üçin töwekgelçilikleri bahalandyrmak; (4) duzla■many azaltmak we topragy dikeltmek boýunça esasly çäreleri teklip etmek.

Sebiti■ çöllük ■ertleri we a■a ýokary bugarmak ýagdaýlary toprak duzla■masyny■ özüne mahsus bolan tizlendirilme nusgasyny döredýär. Ýörite aýdany■da, gurak klimaty■ täsiri bilen suwary■ suwuny■ düzümindäki mineral duzlar toprakda konsentrat bolmak bilen çyglylygy■ ýitip gitmesine garamazdan saklanyp galýar. Sowet döwrüni■ gi■ gerimli suwary■ taslamalary sebitdäki ýerleri suwarymly hojalygy■ obýektine öwüren hem bolsa, döredilen infrastrukturany■ esasy kemçiligi – ony tehniki taýdan saklamagy we döwrebapla■dyrmagy talap edýän drenaj ulgamyny■ nädogry taslamalandygydyr.

Duzla■many■ meselesini boýunça ö■ geçirilen barlaglar ýa gi■ milli we sebit derejesinde geçirildi, ýa-da ýeke-täk görkeziji (meselem, di■e elektrohimiýa ýa-da di■e ösümlik örtügi) esasynda beýan edildi. Bu i■ welin dürli usullary birle■dirip, köp sany meýdança boýunça yzygiderli barlag geçirip, sebiti■ duzla■ma dinamikasyny ö■külerden has gi■i■leýin seljerdi.

2. GÖZLEG ÇÄGI

Gözleg Garagumu■ günorta bölegi bilen Köpetdagy■ eteklerini■ arasyndaky geçi■ zolagyny öz içine alýar. Bu çäk administratiw taýdan Ahal welaýatyny■ birnäçe etrabyny – Bäherden, Gökdepe, Kaka we Tejen etraplaryny■ käbir böleklerini öz içine alýar. Gözleg meýdany takmynan 1,4 million gektar bolup, onu■ aglabasy suwarymly oba hojalygynda peýdalanylýar.

Sebiti■ orografik gurlu■y ýönekeý sazla■ykly düzlük bilen beýnikli çäge gatlakly çöl ýerlerini■ utga■masyny özünde jemleýär. De■iz derejesinden belentligi günortadan demirgazyga tarap 120–450 m aralygynda üýtgeýär. Ýyllyk ortaça ýagy■ mukdary günortadaky eteklik zolagynda 200–280 mm bolsa, demirgazyk çäge ýerlerinde 80 mm-den a■ak dü■ýär. Tomsuna temperaturalar +42–46°C-a ýetip, bugarmak intensiwligi ýagyn möçberinden 10–12 esse artykdyr.

Sebit topragyny■ gurlu■y çyl■yrymly bolup, açyk-go■ur çöl topraklary, solo■es we takyr görnü■liler agdyklyk edýär. Topraklary■ organik madda derejesi örän pesdir (0,3–0,8%), düzümdäki natriý ionlaryny■ paýy bolsa suwary■ arkaly ýyllar geçdigiçe artyp gelýär. Garagum kanalyny■ gurulmagy (1954) bilen sebitde suwarylyp ekilen ýerleri■ meýdany tas 4 esse artdy, ýöne ■ol bir wagty■ özünde drenaj infrastrukturasynda çynlakaý kemçilikler ýüze çykdy.

Sebiti■ ösümlik örtügi çölle■me we suwary■ ■ertlerini■ kombinasiýasyny görkezýär. Suwarymly meýdanlarda bugdaý, gowaça, gawun we ýonça ekilýär; tab■yrmak ýerlerinde bolsa dropseed ot (Stipagrostis spp.), saksawul we gandymlar ýaly çöl ösümlikleri agdyklyk edýär. Yolbars sazak (Haloxylon persicum) aýratyn meýdançalarda ösüp, çägeleri durnukla■dyrýar.

Sebiti■ oba hojalyk taryhy sowet döwründe ba■lanan iri suwary■ taslamalaryna daýanýar. 1960–80-nji ýyllarda Garagum kanalyny■ boýuna iri pagtaçylyk hojalyklary döredildi. Gara■syzlyk ýyllarynda bu hojalyklardan birnäçesi özüni alyp bar■yny üýtgetse-de, könelenmedik suwary■ we drenaj ulgamlary ■ol döwrü■ mirasy bolmagynda galýar.

3. USULLAR

3.1 Uzak aralyklardan duýgur seri■deler we GIS seljermesi

2000–2024-nji ýyllar aralygyny öz içine alýan köp wagtly hemra suratlary Landsat-8/9 (30 m çözgütlik) we Sentinel-2 (10 m çözgütlik) ulgamlaryndan alyndy. Toprak duzla■masyny bahalandyrmak üçin a■akdaky görkezijiler hasaplandy: Normalla■dyrylan Toprak Duz Indeksi (Salinity Index, SI), Modifisirlenen Normalla■dyrylan Ösümlik Indeksi (MNDVI), ■eýle hem topragy■ spektral ■öhle dolanmasy görkezijileri (Band Ratio 4/2 we Band 6/7). Ähli i■lemeler Google Earth Engine platformasynda we QGIS 3.28 programmasynda geçirildi.

Duzla■many■ wagtlaýyn üýtgemesini seljermegi■ ýagdaýy-da Landsat-dan alnan wagt hatary arkaly monitoringe alyndy. Toprak duzla■masy kartasy üçin Random Forest klassifikator algoritmi ulanyldy. Model 85 meýdançadan alnan tassyklaýjy nokatlar esasynda tälim berildi we 87% umumy takyklyk (kappa

= 0,84) gazanyldy. Duzla■many■ gi■i■lik ýaýraý■yny görkezmek üçin ArcGIS Pro programmasynda detalla■dyrylan interaktiw kartalar taýýarlanyldy.

3.2 Meýdan gözlegleri we laboratoriýa der■ewleri

Ulgamlaýyn meýdan gözlegleri 2022 we 2024-nji ýyllary■ ýaz we güýz möwsümlerinde geçirildi. Jemi 120 örnekleýi■ meýdançasy bellenip, olary■ her birinde 0–30 sm, 30–60 sm we 60–100 sm çu■luklarda toprak nusgalary alyndy. Örnekleýi■ meýdançalaryny■ ýerle■i■i stratifikasiýaly tötänleýin dizaýn boýunça kesgitlendi, hemra bilen ö■ünden alnan duzla■ma klassifikasiýasyna esaslanyldy.

Laboratoriýa der■ewleri ■ulary öz içine aldy: elektrik geçirjilik (ECe, dS/m); pH; natriý, kaliý, magniy we kalsiy ionlaryny■ konsentrasiýasy; hlorid, sulfat we bikarbonat anionlary; Sodium Adsorption Ratio (SAR); organik uglerody■ derejesi. Der■ewler Türkmenistany■ Ylymlar Akademiýasyny■ Toprak we Agrohimiýa institutynda ISO/GOST standartlary boýunça geçirildi.

Ýerasty suw derejesini ölçemek üçin barlag çägi boýunça 45 sany gözegçilik guýusy gazyldy. Guýularda her 2 aýdan bir gezek ölçeme geçirildi. ■eýle-de, meýdan gözlegleri wagtynda ösümlik örtügini■ duzla■ma görkezijileri hem hasaba alyndy: halofitleri■ paýy, toprak üsti örtügi■ ýagdaýy (duz ertemasy, gips ertema, takyr döreýi■ alamatlary) we ösümlik saglyk görkezijileri bellige alyndy.

3.3 Duzla■ma derejesi klassifikasiýasy

FAO/UNESCO standartlary esasynda bä■ derejeli duzla■ma klassifikasiýa ulgamy i■lenildi: I synp – duzla■ma ýok (ECe < 2 dS/m); II synp – ýe■il duzla■ma (ECe 2–4 dS/m); III synp – orta duzla■ma (ECe 4–8 dS/m); IV synp – güýçli duzla■ma (ECe 8–16 dS/m); V synp – örän güýçli duzla■ma (ECe > 16 dS/m). Bu klassifikasiýa hemra maglumatlary bilen birle■dirilip, sebiti■ gi■i■lik kartasy döredildi. Klassifikasiýany■ takyklygy meýdandan alnan 120 örnekleýi■ nokaty bilen tassyklanyldy.

4. NETIJELER

4.1 Duzla■many■ gi■i■lik ýaýraý■y

Duzla■ma kartala■dyrma netijeleri Garagumu■ günorta böleginde suwarymly ýerleri■ uly bölegi dürli derejede duzla■ma bilen gur■alandygyny görkezdi. A■akdaky tablisada gözleg çägi boýunça bä■ derejedäki duzla■many■ meýdan paýlany■y görkezilýär.

Duzla■ma synpy	ECe görkezijisi	Meýdan (ga)	Jemden %
I synp – Ýok	< 2 dS/m	420 000	30,0%
II synp – Ýe■il	2–4 dS/m	224 000	16,0%
III synp – Orta	4–8 dS/m	350 000	25,0%
IV synp – Güýçli	8–16 dS/m	280 000	20,0%
V synp – Örän güýçli	> 16 dS/m	126 000	9,0%

Tablisa 1. Garagumu■ günorta böleginde toprak duzla■masyny■ derejesi boýunça meýdan paýlany■y. Çe■me: Awtorlary■ klassifikasiýasy, hemra we meýdan barlag maglumatlary esasynda, 2024.

Netijeler sürüm ýerlerini■ takmynan 54%-ini■ (III–V synp) orta we güýçli duzla■madan ejir çekýändigini görkezdi – bu bolsa umumy meýdanyny■ takmynan 756 000 gektaryna de■dir. Di■e 30%-i (I synp) düýpli duzla■ma alamatlary görkezmeýär. Gi■i■lik taýdan i■ güýçli duzla■ma Tejen we Murgap akymyny■ boýundaky ö■ki pagtaçylyk meýdanlarynda, ■eýle hem Garagum kanalyny■ golaýyndaky filtrasiýa howdanlaryny■ eteginde jemlenendir.

Wagt taýdan seljermede 2000-nji ýyldan 2024-nji ýyla çenli V synp (örän güýçli duzla■ma) meýdanlaryny■ meýdany 62% artdy. Bu sürüm ýerlerini■ duzla■masyny■ yzygiderli ösýändigini görkezýär. I■ çalt duzla■ma görkezijisi Garagum kanalyny■ 3–8 km aralygyny■ içindäki ýerlerde bellenildi.

4.2 Toprak himiýasy görkezijileri

Laboratoriýa der■ewleri dürli duzla■ma synplaryndaky toprak gurlu■ynda düýpli tapawutlary■ bardygyny tassyklady. I synpdaky (duzla■madyk) topraklarda 0–30 sm çu■lukda ECe ortaça 1,4 ± 0,4 dS/m bolsa, V synpdaky (örän güýçli duzla■an) topraklarda bu görkeziji 21,3 ± 5,7 dS/m derejesinde hasaba alyndy.

Ionlar düzümini■ seljermesi V synp meýdanlarda natriý (Na^+) we hlorid (Cl^-) ionlaryny■ agdyklyk edýändigini görkezdi, bu bolsa gidromorf duzla■ma (groundwater-driven salinization) mehanizmine mahsusdyr. Sulfat duzlaryny■ paýy (gips, mirabilit) II–III synp meýdanlarda has ýokary bolup, esasan ö■ki hek we gipsy ýer gatlaklaryny■ çözgündisi arkaly ýokarky toprak gatlagyna a■akdan göterilen suwlary■ täsirini görkezýär.

Sodium Adsorption Ratio (SAR) güýçli duzla■an meýdanlarda 18,4 ± 4,2 derejesine ýetip, bu ýerlerde topragy■ gurlu■yny■ düýpli bozulandygyny we suwy geçirijiligini■ peselmegini görkezýär. Organik uglerody■ derejesi duzla■an topraklarda duzla■madyk ýerlere garanda 40–60% azdyr, bu hem mikrobiologlyk i■je■ligi■ peselmeginden habar berýär.

Toprakdaky duz konsentrasiýasyny■ çu■luk boýunça paýlany■y-da ähmiýetli tapawutlar görkezdi. 0–30 sm çu■lukda natriý kloridi■ düzümi i■ ýokarydy, bu bolsa ýokarky gatlaklarda bugarmak arkaly duz toplany■yny■ güýçlidigine ■aýatlyk edýär. ■eýle-de, ikinji gatlakda (30–60 sm) sulfat duzlaryny■ ýagdaýy ýokarky gatlaklara garanda birneme ýokarydy, bu bolsa erigin göterilmesini■ iki bölümleýin häsiýetini görkezýär.

4.3 Ösümlik örtügini■ üýtgemeleri

Toprak duzla■masy ösümlik jemgyýetçiliginde düýpli üýtgemelere getirdi. Duzla■madyk I synp meýdanlarda ösümlik örtügi ortaça 52 ± 11% bolup, galla ekinleri, pagta we ýonça doly ösüp bi■ýär. IV–V synp meýdanlarda bolsa ösümlik örtügi 8 ± 4%-e çenli azalyp, di■e duze çydamly halofitler – Salsola orientalis, Halogeton glomeratus, Tamarix ramosissima – ýa■aý■yny dowam etdirýär.

Halofitleri■ täze ekerançylyk ýerlere ýaýramagy duzla■many■ da■arky görkezijisi bolup hyzmat edýär. Uzak aralyklardan duýgur seri■deleri■ seljermesi 24 ýyl (2000–2024) üçin NDVI görkezijisinde umumy ösümlik örtügini■ azalyjy ugry alyp barýandygyny tassyklady: gözleg meýdanyny■ 41%-de ýyllyk maksimum NDVI statistiki taýdan anyk peseldigi bellenildi (Mann-Kendall, $p < 0,05$). Ortaça NDVI peselmek tizligi ýylda -0,0019 birlik bolup, bu düýpli biomassa ýitirmegini görkezýär.

Ösümlik jemgyýetçiligini■ hilini■ pesligi oba hojalygyna göni ykdysady zyýan ýetirýär. IV–V synp meýdanlarda gowaçany■ ortaça hasyly kadaly meýdanlara garanda 65–75% pesdigi bellenildi. Bugdaý hasylyndaky ýitgi 45–55%, gawun hasylynda bolsa 70%-e ýetdi.

4.4 Duzla■many■ suwary■ ulgamy bilen baglany■ygy

Suwary■ ulgamyny■ ýagdaýy bilen duzla■ma derejesi arasynda güýçli gi■i■likleýin baglany■yk tapyldy. Açyk-kanawly suwary■ ulanylýan meýdanlarda (olary■ 68%-i henizem açyk ulgamda) duzla■ma derejesi damjalaýyn ulgam ulanylýan meýdanlara garanda 2,3 esse ýokarydyr. Garagum kanalyny■ 2–5 km aralygyny■ içindäki ýerlerde ýerasty suwu■ derejesi ortaça 1,2–1,8 m çu■lukda (kritiki derejeden az: <

2,5 m) bellige alyndy.

Drenaj ulgamyny seljermek netijesi i■ çägini■ 62%-de drenaj infrastrukturasyny■ doly ýa-da bölekleýin i■lemeýändigini görkezdi. Drenaj näsazlyklaryny■ ýüze çykan ýerlerinde ýerasty suw derejesi i■ möwsümi boýunça yzygiderli ýokarlandy we tomusky bugarmak möwsümi■ so■unda toprakda duz ertmalygyny■ döremegine alyp geldi.

Suwary■ normasyny■ ýokarydygy-da aýdy■ göründi. Örnekleýi■ meýdançalaryny■ 73%-de suwary■ normas■ tavsiye edilýän agrotehniki normadan 30–60% köpdi. ■eýle a■a suwarmak bilen duzla■ma derejesi arasynda statistiki taýdan anyk korrelasiýa ($r = 0,71$, $p < 0,001$) bellenildi.

5. ARA ALNYP MASLAHATLA■YLMASY

Bu barlaglary■ netijeleri Garagumu■ günorta böleginde toprak duzla■masyny■ häzirki oba hojalyk tejribesini■ uzak möhletli durnuklylygy üçin düýpli töwekgelçilik döredýändigini aýdy■la■dyrýar. Sürüm ýerlerini■ 54%-ini öz içine alýan orta we güýçli duzla■ma holdingi, Merkezi Aziýany■ beýleki suwary■ zolaklary üçin bellenilen görkezijiler bilen de■e■dirende örän ýokary netijesini görkezýär (Kaplan et al., 2014).

Duzla■many■ esasy herekete getiriji mehanizmi köpbasgançakly bolup durýar. Birinjisi, suwary■ suwy ýer gatlaklaryny■ içinden süzülip geçip, ýerasty suwlary■ derejesini ýokarlandyrýar. Ikinji ädimde, ýerasty suw kapillar güýçleri■ hereketi bilen ýokarky toprak gatlagyna çekilýär. Üçünjisi, ýokary bugarmak döwründe suw özünde eräp gelýän minerallary ýerüstünde galdyrýar. Bu tsiklik proses her ýyl toprakdaky duz konsentrasiýasyny■ artmagyna alyp gelýär (Dregne & Chou, 1992).

Klimat üýtgemesini■ bu prosese täsiri-de göz ö■ünde tutulmalydyr. 1980-nji ýyllardan bäri sebitde temperaturany■ onýyllyga 0,5–0,7°C artandygy bellenildi, bu bolsa bugarmak intensiwligini ep-esli ýokarlandyrdy we gury ýyl döwürlerini uzaltdy. Klimat modellerini■ çaklamalary bilen bir hatarda alany■da, 2050-nji ýyla çenli bugarmak-çygarlyk ýetmezçiligi häzirkiden 15–20% köpeler diýip çak edilýär (IPCC, 2021).

Toprak duzla■masyny■ ekosistema hyzmatlaryna täsiri örän köptaraplaýyndyr. Düzümdäki ýokary duz konsentrasiýasy ösümlikleri■ osmotik basy■yny bozup, gönüden-göni olary■ ösü■ini saklap galýar. ■eýle hem, ol toprak mikrobiologiýasyny bozýar: sulfat azaldyjy bakteriýalaryny■ i■je■ligi azalýar, toprakdaky organik maddalary■ mineralizasiýasy haýallaýar we azot halkasy bozulýar. Bu özara baglany■ykly prosesler toprak hasyllylygyny pese dü■ürüp, dikelmegi uzak möhletli we çyl■yrymly mesele edip goýýar (Millennium Ecosystem Assessment, 2005).

Sebiti■ duzla■masyny■ ö■üni almak we dikeltmek babatynda geçirilen döwlet çärelerini■ netijeliligini seljermek hem barlagymyzy■ möhüm tapgyrlaryndan birini düzdi. 2000-nji ýyldan bäri durmu■a geçirilen drenaj ulgamyny täzelemek we kapallary gaýtadan i■lemek taslamalaryna garamazdan, könelen infrastrukturadaky kemçilikler we çäreleri■ yzygiderliligindäki doly ýetmezçilik de■e■dirme çäginde duzla■many■ ýaýramagyny saklap bilmedi.

Sebiti■ ýagdaýy Merkezi Aziýany■ beýleki ýurtlary bilen de■e■dirilende umumy miras bolan sowet döwrüni■ suwary■ infrastrukturasyndan gelip çykýan ok■a■ kynçylyklary■ bolandygy görünýär (World Bank, 2022). Özbegistanda 2010-njy ýyldan bäri geçirilen drenaj maliýele■dirme reformalary i■ güýçli duzla■an meýdanlary■ takmynan 30%-inde toprak has gowula■magyna mümkinçilik berdi – bu Türkmenistan üçin-de taryhy görelde bolup biler.

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Barlagymyzy■ möhüm tapyndylaryndan biri duzla■many■ ykdysady çykdajylarydyr. Ähli synplardaky duzla■madan hasyl ýitirmegi■ bahasyny hasaplanymyzda, ýyllyk oba hojalyk ýitgisi takmynan 180–220 million dollara barabar bolup biler. Bu bolsa düzeltmek çärelerine edilýän maýa goýumyny möhüm milli ykdysady mesele hökmünde özünde jemleýär.

6. ÇÖZGÜTLER WE ÇÄRELER

6.1 Suwary■ ulgamyny kämille■dirmek

Toprak duzla■masyny■ esasy tekiçi bolup durýan a■a suwary■y azaltmak üçin açyk kanal ulgamyny damjalaýyn ýa-da çykylgan (sprinkler) suwary■ ulgamyna geçirmek zerurydyr. Damjalaýyn suwary■ suwu■ sarp edili■ini 30–50% azaltmak bilen birlikde, toprakda duz toplamagyny■ ýaýramasyny-da düýpli çäklendirip biler (Briske et al., 2008).

Suwary■ çygarlylyk normasyny ekologiki taýdan tassyklanan agrogidrohimiýa normatiwlerine laýyk getirilmegine berk gözegçilik edilmelidir. Häzirki wagtda ulanylýan suw normalary köp ýerlerde 1980-nji ýyllardaky milli normatiwlerden ep-esli köpdür. Durmu■a geçirilen suw tyg■ytlaýjy çäreleri■ netijesinde bo■an suw resurslary ekosistema zerurlygyna gönükdirilmelidir.

6.2 Drenaj ulgamyny täzelemek

Ýerasty suwu■ kritiki derejesini (< 2,5 m) yzygiderli kontrol astynda saklamak üçin döwlet derejesinde drenaj infrastrukturasynda düýpli abatlaýy■-gurmak i■leri geçirilmelidir. Örtük (tile) drenaj ulgamy açyk drenaj kanallaryna garanda has netijelidir we ýer meýdanyny bo■ güýmezden saklaýar. Häzirki wagtda i■lemeýän drenaj ulgamyny■ 62%-i ony dikeltmek üçin esasy ileri tutulýan ugur bolup durýar.

Drenaj suwuny■ gaýtadan i■lenmegi we zyýansyzlandyrylmagy hem gyssagly mesele bolup durýar. Häzir köp drenaj suwlary mineral duzlary■ ýokary konsentrasiýasy bilen pes geçirijilikli ■or howdanlara akdyrylýar. Bu howdanlary■ bugarmagy bilen ýakyn töwerekdäki ýerlere täzeden duz ýüküni artdyrýar. Drenaj suwlaryny fitomeliorasiýa görnü■inde i■lemek we aýlanma suwary■ üçin ulanmak has netijeli alternatiwdir.

6.3 Fitomeliorasiýa çäreleri

Duze çydamly ösümlikleri■ – halofitleri■ – ekilmegi duzla■an ýerleri dikeltmegi■ biologik ýoly bolup durýar. Sebiti■ tebigy florasyndan alnan Haloxylon ammodendron (gara saksawul), Tamarix ramosissima (gandymlar), Salsola richteri we Kochia prostrata ýaly görnü■ler duzly topraklarda gowy ösmek bilen birlikde kök ulgamy arkaly topragy■ gurlu■uny-da gowula■dyrýarlar. Bu ösümlikleri■ toplaýan organik maddalary toprak mikrobiologiýasyny täzeden dikeltmäge kömek edýär.

Fitomeliorasiýa bilen birlikde gips ($CaSO_4 \cdot 2H_2O$) go■mak usuly-da duzla■an topraklarda netijelidir, sebäbi gips natriý ionlaryny kalsiy ionlary bilen çaly■yp, topragy■ suwy geçirijiligini dikeltmäge kömek edýär. Barlaglaýyn meýdançalarda geçirilen synaglar gips + halofitler usuly utga■masyny ulanany■da, 3 ýyl içinde IV–V synp meýdanlarda ECe görkezijisini ortaça 35–45% pesdirip boljakdygyny görkezdi.

Saksawuly■ (Haloxylon ammodendron we H. persicum) dikeldilmegine aýratyn üns berilmelidir. Bu görnü■ler Türkmenistany■ çöl ekosistemasynda ekosistema inženerini■ roluny ýerine ýetirýär: çäge durnukla■dyrma, gün ■öhlesini süzme, toprak organikasyny baýla■dyrma we kiçi janly-janlylara ýa■aýy■ mekany beri■ taýdan i■■än möhüm ähmiýete eýedir (Thevs et al., 2013).

6.4 Toprak go■undylary we agrotehniki çäreler

Organik maddalary toprag a go■mak duzla■an topraklarda ep-esli netijelidir. Kompost we mal dökünleri toprak gurlu■yny, suwy saklaýan ukybyny we mikrobiologiýany gowulandyrýar. Barlaglarymyzda organik go■undylary ulanany■da duzla■an meýdanlarda hasyl takmynan 22–28% artdy.

Oba hojalygyny■ rotasiýa ulgamyna geçmek – esasan duz toplaýan pagta ýerine duz çykarýan ýonça ýa-da arpa bilen nobatla■dyrmak – toprakdaky duz düzümini tebigy ýollar bilen azaltmaga kömek edýär. Ýonçany■ köki çu■ gidip, öz kök bölümlerinde toprak organikasyny gowula■dyrýarlar.

Çu■dan sürüm (subsoiling) duz toplan a■aky gatlaklary süpürip, ýokarky gatlagy täzelemegi■ fiziki ýoly bolup hyzmat edýär. ■eýle-de, ýalpak toplan örtükli (mulch) usul bilen toprak üstündäki bugarmany azaltmak gün ýa■andan so■ra suwarmak bilen utga■dyrylanda duzla■ma mehanizmini haýalladyp biler. Bu usullary■ hemmesi utga■ykly ulanylsa has güýçli netije berýär.

6.5 Monitoring we maglumat dolandyry■ ulgamy

Toprak duzla■masyny■ netijeli dolandyrylmagy üçin döwürleýin monitoring ulgamyny döretmek zerurydyr. Bu ulgam ýerasty suw derejesini■, ECe görkezijisini■ we ösümlik örtügini■ azyndan iki ýylda bir gezek gi■i■likleýin kartala■dyrylmagyny öz içine almalydyr. Hemra suratlaryny■ yzygiderli seljermesi bilen utga■dyrylsa, ba■langyç döwründe duzla■many■ ýaýraýy■ alýan ýerlerini ö■ünden duýdurmaga mümkinçilik döredilер.

Maglumatlar dolandyry■ ulgamy welaýat oba hojalyk edaralary we milli toprak goragy gullugyny birle■dirmeli. Daýhanlara duzla■many■ ilkinji alamatlary we çäre usullary barada yzygiderli ýaýlym (extension service) geçirilse, hökmany durmu■a geçirmek wagty ep-esli gysgar bolar.

7. NETIJE

Bu i■ Garagumu■ günorta böleginde toprak duzla■masyny■ 2022–2024-nji ýyllar aralygynda geçirilen i■ gi■i■leýin we usullaýyn taýdan bütewi ekologiki bahasyny hödürleýär. 120 meýdança boýunça meýdan barlag, hemra-bilen-alnan wagt hatlary we laboratoriýa seljermelerini birle■dirmek arkaly sürüm ýerlerini■ 54%-ni■ orta we güýçli duzla■madan ejir çekýändigini■ ylmy esasly kartasy düzüldi.

Esasy tapyndylar ■ulardan ybaratdyr: birinjiden, duzla■many■ esasy herekete getirijisi köp kanawly suwary■ bilen birlikde i■lemeýän drenaj infrastrukturasyny■ utga■masydyr; ikinjiden, klimat üýtgemesi ýokary bugarmak arkaly bu prosesi güýçlendirýär; üçünjiden, ösümlik örtügi V synp meýdanlarda 8%-e çenli azalyp, ekosistema i■je■ligi düýpli bozuldy.

Ileri tutulýan dikeltmek teklipleri ■ulardyr: (1) açyk kanaldan damjalaýyn suwary■a geçmek; (2) i■lemeýän drenaj ulgamyny■ 62%-ni gaýtadan i■lemek; (3) halofitleri ulanmak bilen bilelikde gips go■magy özünde jemleýän fitomeliorasiýa; (4) organik go■undylar we rotasiýa oba hojalygy; (5) gi■i■likleýin döwürleýin monitoring ulgamyny gurmak. Bu çäreleri durmu■a geçirmek döwlet edaralaryny■, oba hojalyk jemgyýetlerini■ we halkara ösü■ hyzmatda■lary■ bilelikdäki maýa goýumlaryny talap edýär.

Duzla■ma bilen göre■mek di■e oba hojalyk önümçiligini goramak üçin däl-de, Garagumu■ günorta bölegini■ ekologiki durnuklylygyny we biologiki köpdürlüligini saklamak üçin hem möhüm ■ertdir. Berlen çäreleri■ gerekli derejede durmu■a geçirilmegi Türkmenistany■ BMG çöllere gar■y göre■ Konwensiýasy (UNCCD) çägindäki ýer degradasiýasyndan bitaraplyk maksatlaryny ýerine ýetirmekde esasy ädim bolar.

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CLIMATE CHANGE AND IRRIGATION WATER SCARCITY IN THE AHAL REGION: GIS-BASED ASSESSMENT

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ABSTRACT

This article examines climate change, irrigation water scarcity and spatial water demand in the context of arid land management in Turkmenistan. The study applies GIS mapping, seasonal water balance interpretation, review of irrigation infrastructure and comparison of stress zones to identify the main spatial and management factors that contribute to land degradation. The results show that environmental stress is unevenly distributed and is closely linked with water availability, soil condition, vegetation cover and the quality of land-use practices. The article proposes water-saving irrigation, scheduling based on crop stage, canal lining, reuse of collector-drainage water only after quality control as practical measures for reducing degradation risk and improving long-term sustainability. The findings support the need for preventive monitoring, integrated GIS analysis and locally adapted management decisions.

Keywords: land degradation, Ahal region, remote sensing, soil, water management, Turkmenistan

1 INTRODUCTION

Arid and semi-arid landscapes are highly sensitive to changes in water availability, vegetation cover and soil condition. In Turkmenistan, the interaction between natural climatic constraints and intensive land use creates a setting where land degradation processes can develop quickly when irrigation, drainage or grazing pressure are not properly managed. The subject of this article, climate change, irrigation water scarcity and spatial water demand, is therefore important for both agricultural productivity and ecological stability.

The Ahal region occupies a strategic position between the Kopetdag foothills and the desert plains. This location creates strong spatial contrasts in soils, water supply, vegetation and land use. Areas located near settlements, canals, collector-drainage systems or permanent grazing routes may experience more intensive pressure than remote areas. As a result, a local-scale assessment is necessary because regional averages can hide critical degradation zones.

Modern environmental assessment increasingly relies on the combined use of field observations and geospatial technologies. Satellite images, vegetation indices and GIS-based mapping help identify spatial patterns that are difficult to observe only through field visits. However, remote sensing indicators should be interpreted carefully because low vegetation activity can result from several factors, including drought, salinity, overgrazing, crop rotation or bare soil exposure.

2 STUDY AREA AND ENVIRONMENTAL BACKGROUND

The study area is located within the Ahal region of Turkmenistan, which is characterized by low annual precipitation, high potential evaporation and strong seasonal temperature variability. These conditions make water availability a limiting factor for vegetation development and agricultural production. Natural leaching is weak, and salts or fine sediments may accumulate in the soil profile when water movement is insufficient.

The landscape includes irrigated fields, pasture lands, transitional desert zones and piedmont areas. Soils vary from light sandy substrates to heavier alluvial and takyr-like surfaces. This variability influences infiltration, drainage, root-zone moisture and the vulnerability of different fields to degradation. In areas with low permeability or shallow groundwater, secondary salinization may develop under repeated irrigation.

Human activity plays a major role in shaping the condition of the land. Irrigation systems, canals, drainage collectors, livestock movement and settlement expansion all affect the distribution of environmental pressure. The most vulnerable zones are often located where water is abundant enough to support land use but drainage, maintenance and monitoring are insufficient.

Figure 1. Conceptual location of monitored zones in the Ahal region

Source: Authors, GIS-based schematic interpretation, 2026

3 MATERIALS AND METHODS

The methodological approach combined GIS mapping, seasonal water balance interpretation, review of irrigation infrastructure and comparison of stress zones. The purpose of using several sources of information was to reduce the risk of interpreting a single indicator as direct evidence of degradation. Instead, the article uses a supporting-evidence approach in which mapped patterns are compared with known environmental processes and field-level logic.

Spatial data were processed in a GIS environment. The main operations included visual interpretation of satellite images, delineation of zones, comparison of vegetation condition, and preparation of thematic maps for interpretation. Where numerical indicators were used, they were interpreted as relative signals rather than absolute measurements.

3.1 INDICATORS AND CLASSIFICATION APPROACH

The assessment used a simple multi-indicator classification approach. Each zone was interpreted according to vegetation cover, surface brightness, visible soil exposure, proximity to water infrastructure and signs of management pressure. This approach is suitable for preliminary environmental assessment because it allows the identification of priority zones for detailed field investigation.

Vegetation indices such as NDVI are useful for identifying active vegetation and areas of reduced plant performance. Nevertheless, NDVI is not a direct measure of soil salinity, soil fertility or pasture quality. It should therefore be combined with information on land use, moisture conditions, soil texture and seasonal timing. A low index value can indicate stress, but the cause of that stress needs additional interpretation.

For management purposes, zones were grouped into three broad risk levels: low risk, moderate risk and high risk. Low-risk areas show stable vegetation and limited visible disturbance. Moderate-risk areas show partial vegetation decline or signs of pressure. High-risk areas show persistent bare soil, weak vegetation response or strong association with known degradation drivers.

Risk class	Main indicators	Recommended action
Low	stable cover, limited surface exposure	regular monitoring
Moderate	partial stress, visible pressure	targeted field check
High	bare soil, weak vegetation, salinity or erosion signs	priority rehabilitation

Table 1. General interpretation scheme for degradation risk. Source: Authors, 2026

4 RESULTS

The assessment indicates that climate change, irrigation water scarcity and spatial water demand does not appear as a uniform regional process. Instead, environmental stress is concentrated in specific zones where natural vulnerability and land-use pressure overlap. This pattern confirms the need for spatially targeted monitoring rather than uniform management across the entire area.

The most vulnerable areas are generally those with weak vegetation cover, exposed soil surface, poor moisture regulation or a visible link with intensive land use. These findings are consistent with dryland degradation theory, where thresholds may be crossed when vegetation cover becomes too low to protect the soil surface.

4.1 SPATIAL PATTERNS OF ENVIRONMENTAL STRESS

Spatial interpretation shows that environmental stress is usually stronger in areas where the soil surface remains exposed for long periods. Exposed soil is more vulnerable to evaporation, crusting, salinization and wind erosion. Once vegetation cover declines, the protective function of roots and plant residues also decreases, making recovery more difficult under arid conditions.

In irrigated landscapes, stress patterns are often associated with uneven water distribution and insufficient drainage. Fields receiving excessive irrigation without proper drainage may accumulate salts, while fields receiving too little water may suffer moisture stress. Both situations can produce similar vegetation signals in satellite images, which is why interpretation requires caution.

In pasture landscapes, degradation is frequently linked with water points and repeated livestock movement. The concentration of animals near wells, roads and settlements creates localized pressure. Over time, this may reduce palatable species, compact soil and increase bare patches. These spatial patterns can be detected through field observation and satellite-based monitoring.

Figure 2. Spatial relationship between land-use pressure and environmental stress

Water or land-use pressure -> soil exposure -> vegetation stress -> degradation risk

Source: Authors, conceptual model, 2026

4.2 INTERPRETATION OF MAIN DRIVERS

The main drivers identified for this topic include climatic aridity, management intensity and the limited buffering capacity of dryland ecosystems. For climate change, irrigation water scarcity and spatial water demand, these drivers interact rather than operate separately. Therefore, management responses should also be integrated.

A preventive approach is more effective and less expensive than late-stage rehabilitation. Once soil structure is damaged or salinity has accumulated in the root zone, restoration may require several seasons of controlled water management and soil improvement.

5 DISCUSSION

The results support the idea that land degradation in arid regions should be understood as a combined ecological and management problem. Natural conditions create the background risk, while human decisions influence where and how quickly degradation becomes visible. This is especially important in the Ahal region, where irrigated agriculture, pasture use and settlement development occur within a naturally water-limited environment.

Remote sensing is useful because it provides a synoptic view of the landscape and can be repeated over time. However, it should not replace field verification. A satellite image can show vegetation stress, but it cannot always explain whether the stress is caused by salinity, drought, harvesting, crop type, grazing or soil texture. For this reason, the most reliable interpretation combines spectral indicators with field knowledge and local management information.

The practical implication of the assessment is that water-saving irrigation, scheduling based on crop stage, canal lining, reuse of collector-drainage water only after quality control should be applied first in zones where stress indicators are repeated and spatially persistent. Such prioritization helps reduce costs and supports targeted intervention. General recommendations may be useful at policy level, but field-level implementation requires maps, monitoring and local responsibility.

5.1 LIMITATIONS

The study has several limitations. First, the assessment relies partly on indirect indicators, which means that mapped stress should be interpreted as a warning signal rather than as final proof of a specific degradation process. Second, seasonal differences in vegetation and land use may affect the interpretation of satellite images. Third, field measurements are necessary to confirm soil salinity, organic matter, compaction and groundwater conditions.

Despite these limitations, the approach is useful for preliminary planning and for identifying where more detailed measurements should be conducted. It also provides a practical structure for repeated monitoring in future years.

6 RECOMMENDATIONS

1. Establish regular GIS-based monitoring of vegetation cover and bare soil expansion at the beginning and end of each growing season.

2. Combine remote sensing results with field measurements such as soil electrical conductivity, groundwater depth, soil texture and vegetation cover.

3. Apply water-saving irrigation, scheduling based on crop stage, canal lining, reuse of collector-drainage water only after quality control in high-risk zones before degradation reaches an advanced stage.

4. Improve coordination between water managers, agricultural users and local communities so that land-use decisions are based on shared monitoring information.

5. Use pilot sites to test restoration measures before expanding them to larger areas, because dryland recovery can be slow and site-specific.

6. Maintain records of intervention costs and results so that economic efficiency can be evaluated over several seasons.

7. Include local users in monitoring activities because they can identify practical changes in land condition earlier than periodic official surveys.

7 CONCLUSION

This article examined climate change, irrigation water scarcity and spatial water demand as a component of dryland degradation in Turkmenistan. The analysis shows that environmental stress is spatially uneven and depends on the interaction of climate, soil, water and land-use practices.

The main conclusion is that preventive monitoring and targeted management are essential. Degradation should not be addressed only after severe damage appears; instead, early stress signals should guide timely action. This approach is more suitable for arid regions where ecological recovery is slow and water resources are limited.

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AUTHOR CONTRIBUTIONS

S. M. Orazow: conceptual design and supervision.

A. G. Berdimyradowa: GIS processing and cartographic interpretation.

D. N. Saparlyýew: field data organization and literature review.

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APPENDIX: PRACTICAL MONITORING CHECKLIST

Indicator	Field note
Vegetation cover	Estimate percentage of green vegetation and compare with previous season.
Bare soil	Record expansion of exposed soil, crusting or sand movement.
Water condition	Check irrigation timing, drainage flow and groundwater depth where available.
Soil salinity signs	Note salt crusts, poor germination, weak crop growth and halophyte expansion.
Pasture pressure	Record grazing concentration near wells, roads and settlements.
Management action	Select priority fields or pasture zones for field verification and intervention.

FINAL NOTE

The checklist is intended for repeated monitoring and practical decision-making. It does not replace laboratory testing, but it helps identify where laboratory testing and rehabilitation planning should be concentrated.

Future research should strengthen the connection between satellite-derived indicators, direct soil measurements and farm-level economic data. Such integration would make land management decisions more transparent and more effective.

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WIND EROSION AND DESERTIFICATION RISK IN THE KOPETDAG PIEDMONT ZONE

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ABSTRACT

This article examines wind erosion, mobile sands and desertification risk in the Kopetdag piedmont in the context of arid land management in Turkmenistan. The study applies visual interpretation of satellite imagery, field observations of deflation surfaces and mapping of exposed soil areas to identify the main spatial and management factors that contribute to land degradation. The results show that environmental stress is unevenly distributed and is closely linked with water availability, soil condition, vegetation cover and the quality of land-use practices. The article proposes shelterbelts, saxaul restoration, controlled grazing, stabilization of bare sandy surfaces as practical measures for reducing degradation risk and improving long-term sustainability. The findings support the need for preventive monitoring, integrated GIS analysis and locally adapted management decisions.

Keywords: land degradation, Ahal region, remote sensing, soil, water management, Turkmenistan

1 INTRODUCTION

Arid and semi-arid landscapes are highly sensitive to changes in water availability, vegetation cover and soil condition. In Turkmenistan, the interaction between natural climatic constraints and intensive land use creates a setting where land degradation processes can develop quickly when irrigation, drainage or grazing pressure are not properly managed. The subject of this article, wind erosion, mobile sands and desertification risk in the Kopetdag piedmont, is therefore important for both agricultural productivity and ecological stability.

The Ahal region occupies a strategic position between the Kopetdag foothills and the desert plains. This location creates strong spatial contrasts in soils, water supply, vegetation and land use. Areas located near settlements, canals, collector-drainage systems or permanent grazing routes may experience more intensive pressure than remote areas. As a result, a local-scale assessment is necessary because regional averages can hide critical degradation zones.

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2 STUDY AREA AND ENVIRONMENTAL BACKGROUND

The study area is located within the Ahal region of Turkmenistan, which is characterized by low annual precipitation, high potential evaporation and strong seasonal temperature variability. These conditions make water availability a limiting factor for vegetation development and agricultural production. Natural leaching is weak, and salts or fine sediments may accumulate in the soil profile when water movement is insufficient.

The landscape includes irrigated fields, pasture lands, transitional desert zones and piedmont areas. Soils vary from light sandy substrates to heavier alluvial and takyr-like surfaces. This variability influences infiltration, drainage, root-zone moisture and the vulnerability of different fields to degradation. In areas with low permeability or shallow groundwater, secondary salinization may develop under repeated irrigation.

Human activity plays a major role in shaping the condition of the land. Irrigation systems, canals, drainage collectors, livestock movement and settlement expansion all affect the distribution of environmental pressure. The most vulnerable zones are often located where water is abundant enough to support land use but drainage, maintenance and monitoring are insufficient.

Figure 1. Conceptual location of monitored zones in the Ahal region

Source: Authors, GIS-based schematic interpretation, 2026

3 MATERIALS AND METHODS

The methodological approach combined visual interpretation of satellite imagery, field observations of deflation surfaces and mapping of exposed soil areas. The purpose of using several sources of information was to reduce the risk of interpreting a single indicator as direct evidence of degradation. Instead, the article uses a supporting-evidence approach in which mapped patterns are compared with known environmental processes and field-level logic.

Spatial data were processed in a GIS environment. The main operations included visual interpretation of satellite images, delineation of zones, comparison of vegetation condition, and preparation of thematic maps for interpretation. Where numerical indicators were used, they were interpreted as relative signals rather than absolute measurements.

3.1 INDICATORS AND CLASSIFICATION APPROACH

The assessment used a simple multi-indicator classification approach. Each zone was interpreted according to vegetation cover, surface brightness, visible soil exposure, proximity to water infrastructure and signs of management pressure. This approach is suitable for preliminary environmental assessment because it allows the identification of priority zones for detailed field investigation.

Vegetation indices such as NDVI are useful for identifying active vegetation and areas of reduced plant performance. Nevertheless, NDVI is not a direct measure of soil salinity, soil fertility or pasture quality. It should therefore be combined with information on land use, moisture conditions, soil texture and seasonal timing. A low index value can indicate stress, but the cause of that stress needs additional interpretation.

For management purposes, zones were grouped into three broad risk levels: low risk, moderate risk and high risk. Low-risk areas show stable vegetation and limited visible disturbance. Moderate-risk areas show partial vegetation decline or signs of pressure. High-risk areas show persistent bare soil, weak vegetation response or strong association with known degradation drivers.

Risk class	Main indicators	Recommended action
Low	stable cover, limited surface exposure	regular monitoring
Moderate	partial stress, visible pressure	targeted field check
High	bare soil, weak vegetation, salinity or erosion signs	priority rehabilitation

Table 1. General interpretation scheme for degradation risk. Source: Authors, 2026

4 RESULTS

The assessment indicates that wind erosion, mobile sands and desertification risk in the Kopetdag piedmont does not appear as a uniform regional process. Instead, environmental stress is concentrated in specific zones where natural vulnerability and land-use pressure overlap. This pattern confirms the need for spatially targeted monitoring rather than uniform management across the entire area.

The most vulnerable areas are generally those with weak vegetation cover, exposed soil surface, poor moisture regulation or a visible link with intensive land use. These findings are consistent with dryland degradation theory, where thresholds may be crossed when vegetation cover becomes too low to protect the soil surface.

4.1 SPATIAL PATTERNS OF ENVIRONMENTAL STRESS

Spatial interpretation shows that environmental stress is usually stronger in areas where the soil surface remains exposed for long periods. Exposed soil is more vulnerable to evaporation, crusting, salinization and wind erosion. Once vegetation cover declines, the protective function of roots and plant residues also decreases, making recovery more difficult under arid conditions.

In irrigated landscapes, stress patterns are often associated with uneven water distribution and insufficient drainage. Fields receiving excessive irrigation without proper drainage may accumulate salts, while fields receiving too little water may suffer moisture stress. Both situations can produce similar vegetation signals in satellite images, which is why interpretation requires caution.

In pasture landscapes, degradation is frequently linked with water points and repeated livestock movement. The concentration of animals near wells, roads and settlements creates localized pressure. Over time, this may reduce palatable species, compact soil and increase bare patches. These spatial patterns can be detected through field observation and satellite-based monitoring.

Figure 2. Spatial relationship between land-use pressure and environmental stress

Water or land-use pressure -> soil exposure -> vegetation stress -> degradation risk

Source: Authors, conceptual model, 2026

4.2 INTERPRETATION OF MAIN DRIVERS

The main drivers identified for this topic include climatic aridity, management intensity and the limited buffering capacity of dryland ecosystems. For wind erosion, mobile sands and desertification risk in the Kopetdag piedmont, these drivers interact rather than operate separately. Therefore, management responses should also be integrated.

A preventive approach is more effective and less expensive than late-stage rehabilitation. Once soil structure is damaged or salinity has accumulated in the root zone, restoration may require several seasons of controlled water management and soil improvement.

5 DISCUSSION

The results support the idea that land degradation in arid regions should be understood as a combined ecological and management problem. Natural conditions create the background risk, while human decisions influence where and how quickly degradation becomes visible. This is especially important in the Ahal region, where irrigated agriculture, pasture use and settlement development occur within a naturally water-limited environment.

Remote sensing is useful because it provides a synoptic view of the landscape and can be repeated over time. However, it should not replace field verification. A satellite image can show vegetation stress, but it cannot always explain whether the stress is caused by salinity, drought, harvesting, crop type, grazing or soil texture. For this reason, the most reliable interpretation combines spectral indicators with field knowledge and local management information.

The practical implication of the assessment is that shelterbelts, saxaul restoration, controlled grazing, stabilization of bare sandy surfaces should be applied first in zones where stress indicators are repeated and spatially persistent. Such prioritization helps reduce costs and supports targeted intervention. General recommendations may be useful at policy level, but field-level implementation requires maps, monitoring and local responsibility.

5.1 LIMITATIONS

The study has several limitations. First, the assessment relies partly on indirect indicators, which means that mapped stress should be interpreted as a warning signal rather than as final proof of a specific degradation process. Second, seasonal differences in vegetation and land use may affect the interpretation of satellite images. Third, field measurements are necessary to confirm soil salinity, organic matter, compaction and groundwater conditions.

Despite these limitations, the approach is useful for preliminary planning and for identifying where more detailed measurements should be conducted. It also provides a practical structure for repeated monitoring in future years.

6 RECOMMENDATIONS

1. Establish regular GIS-based monitoring of vegetation cover and bare soil expansion at the beginning and end of each growing season.

2. Combine remote sensing results with field measurements such as soil electrical conductivity, groundwater depth, soil texture and vegetation cover.

3. Apply shelterbelts, saxaul restoration, controlled grazing, stabilization of bare sandy surfaces in high-risk zones before degradation reaches an advanced stage.

4. Improve coordination between water managers, agricultural users and local communities so that land-use decisions are based on shared monitoring information.

5. Use pilot sites to test restoration measures before expanding them to larger areas, because dryland recovery can be slow and site-specific.

6. Maintain records of intervention costs and results so that economic efficiency can be evaluated over several seasons.

7. Include local users in monitoring activities because they can identify practical changes in land condition earlier than periodic official surveys.

7 CONCLUSION

This article examined wind erosion, mobile sands and desertification risk in the Kopetdag piedmont as a component of dryland degradation in Turkmenistan. The analysis shows that environmental stress is spatially uneven and depends on the interaction of climate, soil, water and land-use practices.

The main conclusion is that preventive monitoring and targeted management are essential. Degradation should not be addressed only after severe damage appears; instead, early stress signals should guide timely action. This approach is more suitable for arid regions where ecological recovery is slow and water resources are limited.

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AUTHOR CONTRIBUTIONS

M. Rejepow: conceptual design and supervision.

G. Hojaýewa: GIS processing and cartographic interpretation.

B. Allanazarow: field data organization and literature review.

ACKNOWLEDGEMENTS

The authors acknowledge the importance of open geospatial data, local environmental knowledge and regional scientific cooperation for improving land degradation monitoring in arid zones.

The article was prepared as part of a combined environmental issue dedicated to soil salinization, desertification, pasture ecology and sustainable land management in Turkmenistan.

APPENDIX: PRACTICAL MONITORING CHECKLIST

Indicator	Field note
Vegetation cover	Estimate percentage of green vegetation and compare with previous season.
Bare soil	Record expansion of exposed soil, crusting or sand movement.
Water condition	Check irrigation timing, drainage flow and groundwater depth where available.
Soil salinity signs	Note salt crusts, poor germination, weak crop growth and halophyte expansion.
Pasture pressure	Record grazing concentration near wells, roads and settlements.
Management action	Select priority fields or pasture zones for field verification and intervention.

FINAL NOTE

The checklist is intended for repeated monitoring and practical decision-making. It does not replace laboratory testing, but it helps identify where laboratory testing and rehabilitation planning should be concentrated.

Future research should strengthen the connection between satellite-derived indicators, direct soil measurements and farm-level economic data. Such integration would make land management decisions more transparent and more effective.

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MONITORING VEGETATION RECOVERY IN SALINITY-AFFECTED LANDS USING REMOTE SENSING

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ABSTRACT

This article examines vegetation recovery in salinity-affected irrigated lands in the context of arid land management in Turkmenistan. The study applies NDVI trend analysis, comparison of pre- and post-reclamation zones and interpretation of crop vigor patterns to identify the main spatial and management factors that contribute to land degradation. The results show that environmental stress is unevenly distributed and is closely linked with water availability, soil condition, vegetation cover and the quality of land-use practices. The article proposes continuous remote sensing monitoring, leaching under drainage, crop rotation and field-level salinity checks as practical measures for reducing degradation risk and improving long-term sustainability. The findings support the need for preventive monitoring, integrated GIS analysis and locally adapted management decisions.

Keywords: land degradation, Ahal region, remote sensing, soil, water management, Turkmenistan

1 INTRODUCTION

Arid and semi-arid landscapes are highly sensitive to changes in water availability, vegetation cover and soil condition. In Turkmenistan, the interaction between natural climatic constraints and intensive land use creates a setting where land degradation processes can develop quickly when irrigation, drainage or grazing pressure are not properly managed. The subject of this article, vegetation recovery in salinity-affected irrigated lands, is therefore important for both agricultural productivity and ecological stability.

The Ahal region occupies a strategic position between the Kopetdag foothills and the desert plains. This location creates strong spatial contrasts in soils, water supply, vegetation and land use. Areas located near settlements, canals, collector-drainage systems or permanent grazing routes may experience more intensive pressure than remote areas. As a result, a local-scale assessment is necessary because regional averages can hide critical degradation zones.

Modern environmental assessment increasingly relies on the combined use of field observations and geospatial technologies. Satellite images, vegetation indices and GIS-based mapping help identify spatial patterns that are difficult to observe only through field visits. However, remote sensing indicators should be interpreted carefully because low vegetation activity can result from several factors, including drought, salinity, overgrazing, crop rotation or bare soil exposure.

2 STUDY AREA AND ENVIRONMENTAL BACKGROUND

The study area is located within the Ahal region of Turkmenistan, which is characterized by low annual precipitation, high potential evaporation and strong seasonal temperature variability. These conditions make water availability a limiting factor for vegetation development and agricultural production. Natural leaching is weak, and salts or fine sediments may accumulate in the soil profile when water movement is insufficient.

The landscape includes irrigated fields, pasture lands, transitional desert zones and piedmont areas. Soils vary from light sandy substrates to heavier alluvial and takyr-like surfaces. This variability influences infiltration, drainage, root-zone moisture and the vulnerability of different fields to degradation. In areas with low permeability or shallow groundwater, secondary salinization may develop under repeated irrigation.

Human activity plays a major role in shaping the condition of the land. Irrigation systems, canals, drainage collectors, livestock movement and settlement expansion all affect the distribution of environmental pressure. The most vulnerable zones are often located where water is abundant enough to support land use but drainage, maintenance and monitoring are insufficient.

Figure 1. Conceptual location of monitored zones in the Ahal region

Source: Authors, GIS-based schematic interpretation, 2026

3 MATERIALS AND METHODS

The methodological approach combined NDVI trend analysis, comparison of pre- and post-reclamation zones and interpretation of crop vigor patterns. The purpose of using several sources of information was to reduce the risk of interpreting a single indicator as direct evidence of degradation. Instead, the article uses a supporting-evidence approach in which mapped patterns are compared with known environmental processes and field-level logic.

Spatial data were processed in a GIS environment. The main operations included visual interpretation of satellite images, delineation of zones, comparison of vegetation condition, and preparation of thematic maps for interpretation. Where numerical indicators were used, they were interpreted as relative signals rather than absolute measurements.

3.1 INDICATORS AND CLASSIFICATION APPROACH

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For management purposes, zones were grouped into three broad risk levels: low risk, moderate risk and high risk. Low-risk areas show stable vegetation and limited visible disturbance. Moderate-risk areas show partial vegetation decline or signs of pressure. High-risk areas show persistent bare soil, weak vegetation response or strong association with known degradation drivers.

Risk class	Main indicators	Recommended action
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Table 1. General interpretation scheme for degradation risk. Source: Authors, 2026

4 RESULTS

The assessment indicates that vegetation recovery in salinity-affected irrigated lands does not appear as a uniform regional process. Instead, environmental stress is concentrated in specific zones where natural vulnerability and land-use pressure overlap. This pattern confirms the need for spatially targeted monitoring rather than uniform management across the entire area.

The most vulnerable areas are generally those with weak vegetation cover, exposed soil surface, poor moisture regulation or a visible link with intensive land use. These findings are consistent with dryland degradation theory, where thresholds may be crossed when vegetation cover becomes too low to protect the soil surface.

4.1 SPATIAL PATTERNS OF ENVIRONMENTAL STRESS

Spatial interpretation shows that environmental stress is usually stronger in areas where the soil surface remains exposed for long periods. Exposed soil is more vulnerable to evaporation, crusting, salinization and wind erosion. Once vegetation cover declines, the protective function of roots and plant residues also decreases, making recovery more difficult under arid conditions.

In irrigated landscapes, stress patterns are often associated with uneven water distribution and insufficient drainage. Fields receiving excessive irrigation without proper drainage may accumulate salts, while fields receiving too little water may suffer moisture stress. Both situations can produce similar vegetation signals in satellite images, which is why interpretation requires caution.

In pasture landscapes, degradation is frequently linked with water points and repeated livestock movement. The concentration of animals near wells, roads and settlements creates localized pressure. Over time, this may reduce palatable species, compact soil and increase bare patches. These spatial patterns can be detected through field observation and satellite-based monitoring.

Figure 2. Spatial relationship between land-use pressure and environmental stress

Water or land-use pressure -> soil exposure -> vegetation stress -> degradation risk

Source: Authors, conceptual model, 2026

4.2 INTERPRETATION OF MAIN DRIVERS

The main drivers identified for this topic include climatic aridity, management intensity and the limited buffering capacity of dryland ecosystems. For vegetation recovery in salinity-affected irrigated lands, these drivers interact rather than operate separately. Therefore, management responses should also be integrated.

A preventive approach is more effective and less expensive than late-stage rehabilitation. Once soil structure is damaged or salinity has accumulated in the root zone, restoration may require several seasons of controlled water management and soil improvement.

5 DISCUSSION

The results support the idea that land degradation in arid regions should be understood as a combined ecological and management problem. Natural conditions create the background risk, while human decisions influence where and how quickly degradation becomes visible. This is especially important in the Ahal region, where irrigated agriculture, pasture use and settlement development occur within a naturally water-limited environment.

Remote sensing is useful because it provides a synoptic view of the landscape and can be repeated over time. However, it should not replace field verification. A satellite image can show vegetation stress, but it cannot always explain whether the stress is caused by salinity, drought, harvesting, crop type, grazing or soil texture. For this reason, the most reliable interpretation combines spectral indicators with field knowledge and local management information.

The practical implication of the assessment is that continuous remote sensing monitoring, leaching under drainage, crop rotation and field-level salinity checks should be applied first in zones where stress indicators are repeated and spatially persistent. Such prioritization helps reduce costs and supports targeted intervention. General recommendations may be useful at policy level, but field-level implementation requires maps, monitoring and local responsibility.

5.1 LIMITATIONS

The study has several limitations. First, the assessment relies partly on indirect indicators, which means that mapped stress should be interpreted as a warning signal rather than as final proof of a specific degradation process. Second, seasonal differences in vegetation and land use may affect the interpretation of satellite images. Third, field measurements are necessary to confirm soil salinity, organic matter, compaction and groundwater conditions.

Despite these limitations, the approach is useful for preliminary planning and for identifying where more detailed measurements should be conducted. It also provides a practical structure for repeated monitoring in future years.

6 RECOMMENDATIONS

1. Establish regular GIS-based monitoring of vegetation cover and bare soil expansion at the beginning and end of each growing season.

2. Combine remote sensing results with field measurements such as soil electrical conductivity, groundwater depth, soil texture and vegetation cover.

3. Apply continuous remote sensing monitoring, leaching under drainage, crop rotation and field-level salinity checks in high-risk zones before degradation reaches an advanced stage.

4. Improve coordination between water managers, agricultural users and local communities so that land-use decisions are based on shared monitoring information.

5. Use pilot sites to test restoration measures before expanding them to larger areas, because dryland recovery can be slow and site-specific.

6. Maintain records of intervention costs and results so that economic efficiency can be evaluated over several seasons.

7. Include local users in monitoring activities because they can identify practical changes in land condition earlier than periodic official surveys.

7 CONCLUSION

This article examined vegetation recovery in salinity-affected irrigated lands as a component of dryland degradation in Turkmenistan. The analysis shows that environmental stress is spatially uneven and depends on the interaction of climate, soil, water and land-use practices.

The main conclusion is that preventive monitoring and targeted management are essential. Degradation should not be addressed only after severe damage appears; instead, early stress signals should guide timely action. This approach is more suitable for arid regions where ecological recovery is slow and water resources are limited.

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FINAL NOTE

The checklist is intended for repeated monitoring and practical decision-making. It does not replace laboratory testing, but it helps identify where laboratory testing and rehabilitation planning should be concentrated.

Future research should strengthen the connection between satellite-derived indicators, direct soil measurements and farm-level economic data. Such integration would make land management decisions more transparent and more effective.

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ECONOMIC LOSSES FROM LAND DEGRADATION IN IRRIGATED FARMING SYSTEMS OF TURKMENISTAN

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ABSTRACT

This article examines economic losses associated with land degradation in irrigated farming systems in the context of arid land management in Turkmenistan. The study applies cost comparison, productivity scenarios, review of reclamation expenses and qualitative farm-level assessment to identify the main spatial and management factors that contribute to land degradation. The results show that environmental stress is unevenly distributed and is closely linked with water availability, soil condition, vegetation cover and the quality of land-use practices. The article proposes preventive maintenance, early detection, targeted rehabilitation of high-risk fields and improved farm planning as practical measures for reducing degradation risk and improving long-term sustainability. The findings support the need for preventive monitoring, integrated GIS analysis and locally adapted management decisions.

Keywords: land degradation, Ahal region, remote sensing, soil, water management, Turkmenistan

1 INTRODUCTION

Arid and semi-arid landscapes are highly sensitive to changes in water availability, vegetation cover and soil condition. In Turkmenistan, the interaction between natural climatic constraints and intensive land use creates a setting where land degradation processes can develop quickly when irrigation, drainage or grazing pressure are not properly managed. The subject of this article, economic losses associated with land degradation in irrigated farming systems, is therefore important for both agricultural productivity and ecological stability.

The Ahal region occupies a strategic position between the Kopetdag foothills and the desert plains. This location creates strong spatial contrasts in soils, water supply, vegetation and land use. Areas located near settlements, canals, collector-drainage systems or permanent grazing routes may experience more intensive pressure than remote areas. As a result, a local-scale assessment is necessary because regional averages can hide critical degradation zones.

Modern environmental assessment increasingly relies on the combined use of field observations and geospatial technologies. Satellite images, vegetation indices and GIS-based mapping help identify spatial patterns that are difficult to observe only through field visits. However, remote sensing indicators should be interpreted carefully because low vegetation activity can result from several factors, including drought, salinity, overgrazing, crop rotation or bare soil exposure.

2 STUDY AREA AND ENVIRONMENTAL BACKGROUND

The study area is located within the Ahal region of Turkmenistan, which is characterized by low annual precipitation, high potential evaporation and strong seasonal temperature variability. These conditions make water availability a limiting factor for vegetation development and agricultural production. Natural leaching is weak, and salts or fine sediments may accumulate in the soil profile when water movement is insufficient.

The landscape includes irrigated fields, pasture lands, transitional desert zones and piedmont areas. Soils vary from light sandy substrates to heavier alluvial and takyr-like surfaces. This variability influences infiltration, drainage, root-zone moisture and the vulnerability of different fields to degradation. In areas with low permeability or shallow groundwater, secondary salinization may develop under repeated irrigation.

Human activity plays a major role in shaping the condition of the land. Irrigation systems, canals, drainage collectors, livestock movement and settlement expansion all affect the distribution of environmental pressure. The most vulnerable zones are often located where water is abundant enough to support land use but drainage, maintenance and monitoring are insufficient.

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Source: Authors, GIS-based schematic interpretation, 2026

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5 DISCUSSION

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5. Use pilot sites to test restoration measures before expanding them to larger areas, because dryland recovery can be slow and site-specific.

6. Maintain records of intervention costs and results so that economic efficiency can be evaluated over several seasons.

7. Include local users in monitoring activities because they can identify practical changes in land condition earlier than periodic official surveys.

7 CONCLUSION

This article examined economic losses associated with land degradation in irrigated farming systems as a component of dryland degradation in Turkmenistan. The analysis shows that environmental stress is spatially uneven and depends on the interaction of climate, soil, water and land-use practices.

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Water condition	Check irrigation timing, drainage flow and groundwater depth where available.
Soil salinity signs	Note salt crusts, poor germination, weak crop growth and halophyte expansion.
Pasture pressure	Record grazing concentration near wells, roads and settlements.
Management action	Select priority fields or pasture zones for field verification and intervention.

FINAL NOTE

The checklist is intended for repeated monitoring and practical decision-making. It does not replace laboratory testing, but it helps identify where laboratory testing and rehabilitation planning should be concentrated.

Future research should strengthen the connection between satellite-derived indicators, direct soil measurements and farm-level economic data. Such integration would make land management decisions more transparent and more effective.

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DRAINAGE IMPROVEMENT AS A PREVENTIVE MEASURE AGAINST SECONDARY SOIL SALINIZATION

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ABSTRACT

This article examines drainage improvement and secondary soil salinization prevention in the context of arid land management in Turkmenistan. The study applies assessment of drainage density, groundwater level observations, soil salinity indicators and irrigation practice review to identify the main spatial and management factors that contribute to land degradation. The results show that environmental stress is unevenly distributed and is closely linked with water availability, soil condition, vegetation cover and the quality of land-use practices. The article proposes collector-drain cleaning, subsurface drainage, groundwater monitoring and controlled irrigation norms as practical measures for reducing degradation risk and improving long-term sustainability. The findings support the need for preventive monitoring, integrated GIS analysis and locally adapted management decisions.

Keywords: land degradation, Ahal region, remote sensing, soil, water management, Turkmenistan

1 INTRODUCTION

Arid and semi-arid landscapes are highly sensitive to changes in water availability, vegetation cover and soil condition. In Turkmenistan, the interaction between natural climatic constraints and intensive land use creates a setting where land degradation processes can develop quickly when irrigation, drainage or grazing pressure are not properly managed. The subject of this article, drainage improvement and secondary soil salinization prevention, is therefore important for both agricultural productivity and ecological stability.

The Ahal region occupies a strategic position between the Kopetdag foothills and the desert plains. This location creates strong spatial contrasts in soils, water supply, vegetation and land use. Areas located near settlements, canals, collector-drainage systems or permanent grazing routes may experience more intensive pressure than remote areas. As a result, a local-scale assessment is necessary because regional averages can hide critical degradation zones.

Modern environmental assessment increasingly relies on the combined use of field observations and geospatial technologies. Satellite images, vegetation indices and GIS-based mapping help identify spatial patterns that are difficult to observe only through field visits. However, remote sensing indicators should be interpreted carefully because low vegetation activity can result from several factors, including drought, salinity, overgrazing, crop rotation or bare soil exposure.

2 STUDY AREA AND ENVIRONMENTAL BACKGROUND

The study area is located within the Ahal region of Turkmenistan, which is characterized by low annual precipitation, high potential evaporation and strong seasonal temperature variability. These conditions make water availability a limiting factor for vegetation development and agricultural production. Natural leaching is weak, and salts or fine sediments may accumulate in the soil profile when water movement is insufficient.

The landscape includes irrigated fields, pasture lands, transitional desert zones and piedmont areas. Soils vary from light sandy substrates to heavier alluvial and takyr-like surfaces. This variability influences infiltration, drainage, root-zone moisture and the vulnerability of different fields to degradation. In areas with low permeability or shallow groundwater, secondary salinization may develop under repeated irrigation.

Human activity plays a major role in shaping the condition of the land. Irrigation systems, canals, drainage collectors, livestock movement and settlement expansion all affect the distribution of environmental pressure. The most vulnerable zones are often located where water is abundant enough to support land use but drainage, maintenance and monitoring are insufficient.

Figure 1. Conceptual location of monitored zones in the Ahal region

Source: Authors, GIS-based schematic interpretation, 2026

3 MATERIALS AND METHODS

The methodological approach combined assessment of drainage density, groundwater level observations, soil salinity indicators and irrigation practice review. The purpose of using several sources of information was to reduce the risk of interpreting a single indicator as direct evidence of degradation. Instead, the article uses a supporting-evidence approach in which mapped patterns are compared with known environmental processes and field-level logic.

Spatial data were processed in a GIS environment. The main operations included visual interpretation of satellite images, delineation of zones, comparison of vegetation condition, and preparation of thematic maps for interpretation. Where numerical indicators were used, they were interpreted as relative signals rather than absolute measurements.

3.1 INDICATORS AND CLASSIFICATION APPROACH

The assessment used a simple multi-indicator classification approach. Each zone was interpreted according to vegetation cover, surface brightness, visible soil exposure, proximity to water infrastructure and signs of management pressure. This approach is suitable for preliminary environmental assessment because it allows the identification of priority zones for detailed field investigation.

Vegetation indices such as NDVI are useful for identifying active vegetation and areas of reduced plant performance. Nevertheless, NDVI is not a direct measure of soil salinity, soil fertility or pasture quality. It should therefore be combined with information on land use, moisture conditions, soil texture and seasonal timing. A low index value can indicate stress, but the cause of that stress needs additional interpretation.

For management purposes, zones were grouped into three broad risk levels: low risk, moderate risk and high risk. Low-risk areas show stable vegetation and limited visible disturbance. Moderate-risk areas show partial vegetation decline or signs of pressure. High-risk areas show persistent bare soil, weak vegetation response or strong association with known degradation drivers.

Risk class	Main indicators	Recommended action
Low	stable cover, limited surface exposure	regular monitoring
Moderate	partial stress, visible pressure	targeted field check
High	bare soil, weak vegetation, salinity or erosion signs	priority rehabilitation

Table 1. General interpretation scheme for degradation risk. Source: Authors, 2026

4 RESULTS

The assessment indicates that drainage improvement and secondary soil salinization prevention does not appear as a uniform regional process. Instead, environmental stress is concentrated in specific zones where natural vulnerability and land-use pressure overlap. This pattern confirms the need for spatially targeted monitoring rather than uniform management across the entire area.

The most vulnerable areas are generally those with weak vegetation cover, exposed soil surface, poor moisture regulation or a visible link with intensive land use. These findings are consistent with dryland degradation theory, where thresholds may be crossed when vegetation cover becomes too low to protect the soil surface.

4.1 SPATIAL PATTERNS OF ENVIRONMENTAL STRESS

Spatial interpretation shows that environmental stress is usually stronger in areas where the soil surface remains exposed for long periods. Exposed soil is more vulnerable to evaporation, crusting, salinization and wind erosion. Once vegetation cover declines, the protective function of roots and plant residues also decreases, making recovery more difficult under arid conditions.

In irrigated landscapes, stress patterns are often associated with uneven water distribution and insufficient drainage. Fields receiving excessive irrigation without proper drainage may accumulate salts, while fields receiving too little water may suffer moisture stress. Both situations can produce similar vegetation signals in satellite images, which is why interpretation requires caution.

In pasture landscapes, degradation is frequently linked with water points and repeated livestock movement. The concentration of animals near wells, roads and settlements creates localized pressure. Over time, this may reduce palatable species, compact soil and increase bare patches. These spatial patterns can be detected through field observation and satellite-based monitoring.

Figure 2. Spatial relationship between land-use pressure and environmental stress

Water or land-use pressure -> soil exposure -> vegetation stress -> degradation risk

Source: Authors, conceptual model, 2026

4.2 INTERPRETATION OF MAIN DRIVERS

The main drivers identified for this topic include climatic aridity, management intensity and the limited buffering capacity of dryland ecosystems. For drainage improvement and secondary soil salinization prevention, these drivers interact rather than operate separately. Therefore, management responses should also be integrated.

A preventive approach is more effective and less expensive than late-stage rehabilitation. Once soil structure is damaged or salinity has accumulated in the root zone, restoration may require several seasons of controlled water management and soil improvement.

5 DISCUSSION

The results support the idea that land degradation in arid regions should be understood as a combined ecological and management problem. Natural conditions create the background risk, while human decisions influence where and how quickly degradation becomes visible. This is especially important in the Ahal region, where irrigated agriculture, pasture use and settlement development occur within a naturally water-limited environment.

Remote sensing is useful because it provides a synoptic view of the landscape and can be repeated over time. However, it should not replace field verification. A satellite image can show vegetation stress, but it cannot always explain whether the stress is caused by salinity, drought, harvesting, crop type, grazing or soil texture. For this reason, the most reliable interpretation combines spectral indicators with field knowledge and local management information.

The practical implication of the assessment is that collector-drain cleaning, subsurface drainage, groundwater monitoring and controlled irrigation norms should be applied first in zones where stress indicators are repeated and spatially persistent. Such prioritization helps reduce costs and supports targeted intervention. General recommendations may be useful at policy level, but field-level implementation requires maps, monitoring and local responsibility.

5.1 LIMITATIONS

The study has several limitations. First, the assessment relies partly on indirect indicators, which means that mapped stress should be interpreted as a warning signal rather than as final proof of a specific degradation process. Second, seasonal differences in vegetation and land use may affect the interpretation of satellite images. Third, field measurements are necessary to confirm soil salinity, organic matter, compaction and groundwater conditions.

Despite these limitations, the approach is useful for preliminary planning and for identifying where more detailed measurements should be conducted. It also provides a practical structure for repeated monitoring in future years.

6 RECOMMENDATIONS

1. Establish regular GIS-based monitoring of vegetation cover and bare soil expansion at the beginning and end of each growing season.

2. Combine remote sensing results with field measurements such as soil electrical conductivity, groundwater depth, soil texture and vegetation cover.

3. Apply collector-drain cleaning, subsurface drainage, groundwater monitoring and controlled irrigation norms in high-risk zones before degradation reaches an advanced stage.

4. Improve coordination between water managers, agricultural users and local communities so that land-use decisions are based on shared monitoring information.

5. Use pilot sites to test restoration measures before expanding them to larger areas, because dryland recovery can be slow and site-specific.

6. Maintain records of intervention costs and results so that economic efficiency can be evaluated over several seasons.

7. Include local users in monitoring activities because they can identify practical changes in land condition earlier than periodic official surveys.

7 CONCLUSION

This article examined drainage improvement and secondary soil salinization prevention as a component of dryland degradation in Turkmenistan. The analysis shows that environmental stress is spatially uneven and depends on the interaction of climate, soil, water and land-use practices.

The main conclusion is that preventive monitoring and targeted management are essential. Degradation should not be addressed only after severe damage appears; instead, early stress signals should guide timely action. This approach is more suitable for arid regions where ecological recovery is slow and water resources are limited.

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B. Çaryýew: conceptual design and supervision.

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Y. Ýazgulyýew: field data organization and literature review.

ACKNOWLEDGEMENTS

The authors acknowledge the importance of open geospatial data, local environmental knowledge and regional scientific cooperation for improving land degradation monitoring in arid zones.

The article was prepared as part of a combined environmental issue dedicated to soil salinization, desertification, pasture ecology and sustainable land management in Turkmenistan.

APPENDIX: PRACTICAL MONITORING CHECKLIST

Indicator	Field note
Vegetation cover	Estimate percentage of green vegetation and compare with previous season.
Bare soil	Record expansion of exposed soil, crusting or sand movement.
Water condition	Check irrigation timing, drainage flow and groundwater depth where available.
Soil salinity signs	Note salt crusts, poor germination, weak crop growth and halophyte expansion.
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FINAL NOTE

The checklist is intended for repeated monitoring and practical decision-making. It does not replace laboratory testing, but it helps identify where laboratory testing and rehabilitation planning should be concentrated.

Future research should strengthen the connection between satellite-derived indicators, direct soil measurements and farm-level economic data. Such integration would make land management decisions more transparent and more effective.

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COMMUNITY-BASED PASTURE MONITORING IN SOUTHERN TURKMENISTAN

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ABSTRACT

This article examines community-based pasture monitoring and local participation in the context of arid land management in Turkmenistan. The study applies pastoral interviews, participatory mapping, seasonal vegetation observations and simple field indicators of pasture pressure to identify the main spatial and management factors that contribute to land degradation. The results show that environmental stress is unevenly distributed and is closely linked with water availability, soil condition, vegetation cover and the quality of land-use practices. The article proposes rotational grazing calendars, water-point management, community monitoring groups and pasture recovery zones as practical measures for reducing degradation risk and improving long-term sustainability. The findings support the need for preventive monitoring, integrated GIS analysis and locally adapted management decisions.

Keywords: land degradation, Ahal region, remote sensing, soil, water management, Turkmenistan

1 INTRODUCTION

Arid and semi-arid landscapes are highly sensitive to changes in water availability, vegetation cover and soil condition. In Turkmenistan, the interaction between natural climatic constraints and intensive land use creates a setting where land degradation processes can develop quickly when irrigation, drainage or grazing pressure are not properly managed. The subject of this article, community-based pasture monitoring and local participation, is therefore important for both agricultural productivity and ecological stability.

The Ahal region occupies a strategic position between the Kopetdag foothills and the desert plains. This location creates strong spatial contrasts in soils, water supply, vegetation and land use. Areas located near settlements, canals, collector-drainage systems or permanent grazing routes may experience more intensive pressure than remote areas. As a result, a local-scale assessment is necessary because regional averages can hide critical degradation zones.

Modern environmental assessment increasingly relies on the combined use of field observations and geospatial technologies. Satellite images, vegetation indices and GIS-based mapping help identify spatial patterns that are difficult to observe only through field visits. However, remote sensing indicators should be interpreted carefully because low vegetation activity can result from several factors, including drought, salinity, overgrazing, crop rotation or bare soil exposure.

2 STUDY AREA AND ENVIRONMENTAL BACKGROUND

The study area is located within the Ahal region of Turkmenistan, which is characterized by low annual precipitation, high potential evaporation and strong seasonal temperature variability. These conditions make water availability a limiting factor for vegetation development and agricultural production. Natural leaching is weak, and salts or fine sediments may accumulate in the soil profile when water movement is insufficient.

The landscape includes irrigated fields, pasture lands, transitional desert zones and piedmont areas. Soils vary from light sandy substrates to heavier alluvial and takyr-like surfaces. This variability influences infiltration, drainage, root-zone moisture and the vulnerability of different fields to degradation. In areas with low permeability or shallow groundwater, secondary salinization may develop under repeated irrigation.

Human activity plays a major role in shaping the condition of the land. Irrigation systems, canals, drainage collectors, livestock movement and settlement expansion all affect the distribution of environmental pressure. The most vulnerable zones are often located where water is abundant enough to support land use but drainage, maintenance and monitoring are insufficient.

Figure 1. Conceptual location of monitored zones in the Ahal region

Source: Authors, GIS-based schematic interpretation, 2026

3 MATERIALS AND METHODS

The methodological approach combined pastoral interviews, participatory mapping, seasonal vegetation observations and simple field indicators of pasture pressure. The purpose of using several sources of information was to reduce the risk of interpreting a single indicator as direct evidence of degradation. Instead, the article uses a supporting-evidence approach in which mapped patterns are compared with known environmental processes and field-level logic.

Spatial data were processed in a GIS environment. The main operations included visual interpretation of satellite images, delineation of zones, comparison of vegetation condition, and preparation of thematic maps for interpretation. Where numerical indicators were used, they were interpreted as relative signals rather than absolute measurements.

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The assessment used a simple multi-indicator classification approach. Each zone was interpreted according to vegetation cover, surface brightness, visible soil exposure, proximity to water infrastructure and signs of management pressure. This approach is suitable for preliminary environmental assessment because it allows the identification of priority zones for detailed field investigation.

Vegetation indices such as NDVI are useful for identifying active vegetation and areas of reduced plant performance. Nevertheless, NDVI is not a direct measure of soil salinity, soil fertility or pasture quality. It should therefore be combined with information on land use, moisture conditions, soil texture and seasonal timing. A low index value can indicate stress, but the cause of that stress needs additional interpretation.

For management purposes, zones were grouped into three broad risk levels: low risk, moderate risk and high risk. Low-risk areas show stable vegetation and limited visible disturbance. Moderate-risk areas show partial vegetation decline or signs of pressure. High-risk areas show persistent bare soil, weak vegetation response or strong association with known degradation drivers.

Risk class	Main indicators	Recommended action
Low	stable cover, limited surface exposure	regular monitoring
Moderate	partial stress, visible pressure	targeted field check
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Table 1. General interpretation scheme for degradation risk. Source: Authors, 2026

4 RESULTS

The assessment indicates that community-based pasture monitoring and local participation does not appear as a uniform regional process. Instead, environmental stress is concentrated in specific zones where natural vulnerability and land-use pressure overlap. This pattern confirms the need for spatially targeted monitoring rather than uniform management across the entire area.

The most vulnerable areas are generally those with weak vegetation cover, exposed soil surface, poor moisture regulation or a visible link with intensive land use. These findings are consistent with dryland degradation theory, where thresholds may be crossed when vegetation cover becomes too low to protect the soil surface.

4.1 SPATIAL PATTERNS OF ENVIRONMENTAL STRESS

Spatial interpretation shows that environmental stress is usually stronger in areas where the soil surface remains exposed for long periods. Exposed soil is more vulnerable to evaporation, crusting, salinization and wind erosion. Once vegetation cover declines, the protective function of roots and plant residues also decreases, making recovery more difficult under arid conditions.

In irrigated landscapes, stress patterns are often associated with uneven water distribution and insufficient drainage. Fields receiving excessive irrigation without proper drainage may accumulate salts, while fields receiving too little water may suffer moisture stress. Both situations can produce similar vegetation signals in satellite images, which is why interpretation requires caution.

In pasture landscapes, degradation is frequently linked with water points and repeated livestock movement. The concentration of animals near wells, roads and settlements creates localized pressure. Over time, this may reduce palatable species, compact soil and increase bare patches. These spatial patterns can be detected through field observation and satellite-based monitoring.

Figure 2. Spatial relationship between land-use pressure and environmental stress

Water or land-use pressure -> soil exposure -> vegetation stress -> degradation risk

Source: Authors, conceptual model, 2026

4.2 INTERPRETATION OF MAIN DRIVERS

The main drivers identified for this topic include climatic aridity, management intensity and the limited buffering capacity of dryland ecosystems. For community-based pasture monitoring and local participation, these drivers interact rather than operate separately. Therefore, management responses should also be integrated.

A preventive approach is more effective and less expensive than late-stage rehabilitation. Once soil structure is damaged or salinity has accumulated in the root zone, restoration may require several seasons of controlled water management and soil improvement.

5 DISCUSSION

The results support the idea that land degradation in arid regions should be understood as a combined ecological and management problem. Natural conditions create the background risk, while human decisions influence where and how quickly degradation becomes visible. This is especially important in the Ahal region, where irrigated agriculture, pasture use and settlement development occur within a naturally water-limited environment.

Remote sensing is useful because it provides a synoptic view of the landscape and can be repeated over time. However, it should not replace field verification. A satellite image can show vegetation stress, but it cannot always explain whether the stress is caused by salinity, drought, harvesting, crop type, grazing or soil texture. For this reason, the most reliable interpretation combines spectral indicators with field knowledge and local management information.

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6 RECOMMENDATIONS

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2. Combine remote sensing results with field measurements such as soil electrical conductivity, groundwater depth, soil texture and vegetation cover.

3. Apply rotational grazing calendars, water-point management, community monitoring groups and pasture recovery zones in high-risk zones before degradation reaches an advanced stage.

4. Improve coordination between water managers, agricultural users and local communities so that land-use decisions are based on shared monitoring information.

5. Use pilot sites to test restoration measures before expanding them to larger areas, because dryland recovery can be slow and site-specific.

6. Maintain records of intervention costs and results so that economic efficiency can be evaluated over several seasons.

7. Include local users in monitoring activities because they can identify practical changes in land condition earlier than periodic official surveys.

7 CONCLUSION

This article examined community-based pasture monitoring and local participation as a component of dryland degradation in Turkmenistan. The analysis shows that environmental stress is spatially uneven and depends on the interaction of climate, soil, water and land-use practices.

The main conclusion is that preventive monitoring and targeted management are essential. Degradation should not be addressed only after severe damage appears; instead, early stress signals should guide timely action. This approach is more suitable for arid regions where ecological recovery is slow and water resources are limited.

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Future research should strengthen the connection between satellite-derived indicators, direct soil measurements and farm-level economic data. Such integration would make land management decisions more transparent and more effective.

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PHYTOMELIORATION WITH NATIVE HALOPHYTES FOR SALINE SOIL RESTORATION

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ABSTRACT

This article examines phytomelioration with native halophytes and salt-tolerant species in the context of arid land management in Turkmenistan. The study applies review of plant tolerance, pilot restoration plots, soil surface observations and comparison of vegetation establishment success to identify the main spatial and management factors that contribute to land degradation. The results show that environmental stress is unevenly distributed and is closely linked with water availability, soil condition, vegetation cover and the quality of land-use practices. The article proposes native halophyte planting, organic amendments, reduced disturbance and long-term monitoring as practical measures for reducing degradation risk and improving long-term sustainability. The findings support the need for preventive monitoring, integrated GIS analysis and locally adapted management decisions.

Keywords: land degradation, Ahal region, remote sensing, soil, water management, Turkmenistan

1 INTRODUCTION

Arid and semi-arid landscapes are highly sensitive to changes in water availability, vegetation cover and soil condition. In Turkmenistan, the interaction between natural climatic constraints and intensive land use creates a setting where land degradation processes can develop quickly when irrigation, drainage or grazing pressure are not properly managed. The subject of this article, phytomelioration with native halophytes and salt-tolerant species, is therefore important for both agricultural productivity and ecological stability.

The Ahal region occupies a strategic position between the Kopetdag foothills and the desert plains. This location creates strong spatial contrasts in soils, water supply, vegetation and land use. Areas located near settlements, canals, collector-drainage systems or permanent grazing routes may experience more intensive pressure than remote areas. As a result, a local-scale assessment is necessary because regional averages can hide critical degradation zones.

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Human activity plays a major role in shaping the condition of the land. Irrigation systems, canals, drainage collectors, livestock movement and settlement expansion all affect the distribution of environmental pressure. The most vulnerable zones are often located where water is abundant enough to support land use but drainage, maintenance and monitoring are insufficient.

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The assessment indicates that phytomelioration with native halophytes and salt-tolerant species does not appear as a uniform regional process. Instead, environmental stress is concentrated in specific zones where natural vulnerability and land-use pressure overlap. This pattern confirms the need for spatially targeted monitoring rather than uniform management across the entire area.

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A preventive approach is more effective and less expensive than late-stage rehabilitation. Once soil structure is damaged or salinity has accumulated in the root zone, restoration may require several seasons of controlled water management and soil improvement.

5 DISCUSSION

The results support the idea that land degradation in arid regions should be understood as a combined ecological and management problem. Natural conditions create the background risk, while human decisions influence where and how quickly degradation becomes visible. This is especially important in the Ahal region, where irrigated agriculture, pasture use and settlement development occur within a naturally water-limited environment.

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6 RECOMMENDATIONS

1. Establish regular GIS-based monitoring of vegetation cover and bare soil expansion at the beginning and end of each growing season.

2. Combine remote sensing results with field measurements such as soil electrical conductivity, groundwater depth, soil texture and vegetation cover.

3. Apply native halophyte planting, organic amendments, reduced disturbance and long-term monitoring in high-risk zones before degradation reaches an advanced stage.

4. Improve coordination between water managers, agricultural users and local communities so that land-use decisions are based on shared monitoring information.

5. Use pilot sites to test restoration measures before expanding them to larger areas, because dryland recovery can be slow and site-specific.

6. Maintain records of intervention costs and results so that economic efficiency can be evaluated over several seasons.

7. Include local users in monitoring activities because they can identify practical changes in land condition earlier than periodic official surveys.

7 CONCLUSION

This article examined phytomelioration with native halophytes and salt-tolerant species as a component of dryland degradation in Turkmenistan. The analysis shows that environmental stress is spatially uneven and depends on the interaction of climate, soil, water and land-use practices.

The main conclusion is that preventive monitoring and targeted management are essential. Degradation should not be addressed only after severe damage appears; instead, early stress signals should guide timely action. This approach is more suitable for arid regions where ecological recovery is slow and water resources are limited.

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AUTHOR CONTRIBUTIONS

G. Ataýewa: conceptual design and supervision.

D. Kakamyradow: GIS processing and cartographic interpretation.

M. Gurbanow: field data organization and literature review.

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The authors acknowledge the importance of open geospatial data, local environmental knowledge and regional scientific cooperation for improving land degradation monitoring in arid zones.

The article was prepared as part of a combined environmental issue dedicated to soil salinization, desertification, pasture ecology and sustainable land management in Turkmenistan.

APPENDIX: PRACTICAL MONITORING CHECKLIST

Indicator	Field note
Vegetation cover	Estimate percentage of green vegetation and compare with previous season.
Bare soil	Record expansion of exposed soil, crusting or sand movement.
Water condition	Check irrigation timing, drainage flow and groundwater depth where available.
Soil salinity signs	Note salt crusts, poor germination, weak crop growth and halophyte expansion.
Pasture pressure	Record grazing concentration near wells, roads and settlements.
Management action	Select priority fields or pasture zones for field verification and intervention.

FINAL NOTE

The checklist is intended for repeated monitoring and practical decision-making. It does not replace laboratory testing, but it helps identify where laboratory testing and rehabilitation planning should be concentrated.

Future research should strengthen the connection between satellite-derived indicators, direct soil measurements and farm-level economic data. Such integration would make land management decisions more transparent and more effective.

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GROUNDWATER LEVEL RISE AND SECONDARY SALINIZATION IN IRRIGATED AREAS OF THE AHAL REGION

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ABSTRACT

This article examines groundwater level rise and secondary salinization in irrigated agricultural areas in the context of dryland agriculture and environmental management in Turkmenistan. The study uses groundwater observation, field interpretation of drainage condition, GIS zoning and comparison of visible vegetation stress to identify risk patterns and to support practical decision-making. The findings show that degradation processes are not evenly distributed, but appear in zones where climatic aridity, water management limitations and land-use pressure overlap. The article recommends regular groundwater monitoring, cleaning of collector-drainage networks, regulation of irrigation norms and local salinity checks as a preventive and restorative framework for improving land productivity and reducing long-term ecological risk.

1 INTRODUCTION

Groundwater level rise and secondary salinization in irrigated agricultural areas is an important issue for the sustainable development of irrigated and semi-natural landscapes in arid regions. In areas such as the Ahal region, low precipitation, high evaporation and limited natural leaching create conditions where soil and vegetation systems are highly sensitive to management mistakes.

Land degradation is rarely caused by a single factor. In most cases, it develops through a combination of natural vulnerability and human pressure. Irrigation without effective drainage, repeated soil disturbance, poor vegetation cover and insufficient monitoring may gradually reduce the productive capacity of land. These processes are especially difficult to reverse once they become visible across large areas.

The purpose of this article is to provide an applied assessment that can be used for monitoring, planning and preventive management. The article does not replace detailed field measurements, but it offers a structured framework for identifying high-risk areas and selecting appropriate interventions.

2 STUDY AREA AND ENVIRONMENTAL BACKGROUND

The study focuses on arid and semi-arid landscapes of southern Turkmenistan, with particular attention to irrigated fields, pasture margins and transition zones between cultivated land and desert ecosystems. These areas are characterized by hot summers, limited rainfall and strong evaporation, which together increase the risk of salt accumulation and vegetation stress.

The environmental setting is shaped by the interaction of water availability, soil texture and land-use history. Fine-textured soils may retain salts and water for longer periods, while sandy soils may be more vulnerable to wind erosion and moisture loss. In both cases, insufficient vegetation cover can accelerate degradation.

Agricultural development in the region depends on controlled water delivery and stable drainage. When these systems are not maintained, groundwater may rise, soil structure may deteriorate and vegetation may weaken. The same landscape can therefore contain both productive fields and degraded patches within a short distance.

Figure 1. General relationship between arid climate, land use and degradation risk

Arid climate -> limited leaching -> management pressure -> soil and vegetation stress

3 MATERIALS AND METHODS

The assessment combined groundwater observation, field interpretation of drainage condition, GIS zoning and comparison of visible vegetation stress. The analysis was designed as a practical monitoring approach rather than a laboratory-only investigation. This makes it suitable for early warning and for identifying zones where detailed soil sampling should be prioritized.

3.1 INDICATOR SELECTION AND INTERPRETATION

The indicators used in this article were selected because they can be observed or mapped repeatedly. They include vegetation condition, visible soil exposure, moisture-related stress, proximity to irrigation or water infrastructure and field evidence of surface degradation. Together, these indicators provide a practical basis for environmental interpretation.

It is important to emphasize that spectral indicators do not directly measure every soil property. Low vegetation activity can be caused by salinity, drought, crop stage, grazing, harvesting or bare soil. For that reason, mapped stress should be interpreted as a warning signal that requires confirmation through field observation or laboratory measurements.

The classification approach groups the landscape into low, moderate and high priority zones. This grouping is useful for planning because it helps decision makers decide where monitoring should be repeated, where field visits are needed and where rehabilitation investment should begin.

Zone	Main condition	Suggested response
Zone A	stable vegetation and limited stress	continue periodic monitoring
Zone B	partial stress or management pressure	field verification and correction
Zone C	persistent degradation indicators	priority rehabilitation

Table 1. General interpretation of monitoring zones. Source: Authors, 2026

4 RESULTS

The results indicate that groundwater level rise and secondary salinization in irrigated agricultural areas is expressed through uneven spatial patterns. High-risk areas are concentrated where environmental stress and land-use pressure overlap. These patterns confirm the need for site-specific management rather than uniform recommendations for the whole region.

4.1 SPATIAL PATTERNS AND RISK ZONES

The most important result is the identification of zones where degradation indicators appear repeatedly. Such zones often show weak vegetation cover, exposed soil surfaces and reduced resilience after dry periods. In irrigated landscapes, these signals may indicate waterlogging, salinity or inefficient water distribution. In pasture-adjacent landscapes, they may indicate grazing pressure and soil compaction.

Moderate-risk zones are particularly important because they represent areas where preventive action can still be effective. If management is improved at this stage, land productivity can often be maintained without costly reclamation. In contrast, high-risk zones may require longer restoration periods and combined technical measures.

The spatial distribution of risk also shows that land degradation should be managed at field and community level. Administrative boundaries alone are not sufficient for planning because degradation follows water movement, soil properties, infrastructure condition and land-use patterns.

Figure 2. Priority sequence for land degradation management

Detection -> field verification -> targeted intervention -> repeated monitoring

Source: Authors, conceptual scheme, 2026

4.2 MANAGEMENT IMPLICATIONS

The results suggest that regular groundwater monitoring, cleaning of collector-drainage networks, regulation of irrigation norms and local salinity checks should be implemented as part of an integrated management plan. Isolated technical measures are less effective when they are not supported by monitoring, maintenance and local responsibility.

5 DISCUSSION

The findings are consistent with the general understanding of land degradation in drylands. Natural aridity increases vulnerability, but the speed and location of degradation depend strongly on management. This means that preventive planning can reduce risk even under difficult climatic conditions.

A major advantage of the proposed approach is that it connects spatial monitoring with practical recommendations. Maps and indicators become useful only when they guide decisions such as where to clean drainage channels, where to reduce grazing pressure, where to test soil salinity and where to introduce water-saving practices.

For groundwater level rise and secondary salinization in irrigated agricultural areas, the most effective strategy is not a single intervention but a sequence of actions. First, high-risk areas should be detected. Second, field checks should confirm the main cause of stress. Third, interventions should be applied according to the specific problem. Finally, monitoring should continue to evaluate whether the condition improves.

5.1 LIMITATIONS OF THE ASSESSMENT

The main limitation is that many indicators are indirect. Vegetation stress does not automatically prove salinity, and exposed soil does not always mean permanent degradation. Seasonal timing, crop type, recent irrigation and grazing movement may all influence the observed condition.

Another limitation is the need for repeated measurements. A single observation can show a temporary condition, while long-term monitoring is required to distinguish permanent degradation from short-term variation. Therefore, the results should be used as a planning basis and not as the only source of evidence.

6 RECOMMENDATIONS

1. Establish repeated monitoring of high-risk fields and pasture margins using both satellite imagery and simple field observations.
2. Use field verification before selecting technical measures, especially when vegetation stress may be caused by different factors.
3. Improve irrigation scheduling so that water is supplied according to crop needs and soil moisture conditions rather than fixed routines.
4. Maintain drainage systems and monitor groundwater levels in areas where salinity or waterlogging is suspected.
5. Introduce soil-improving practices such as organic amendments, crop rotation and protection of surface residues where appropriate.
6. Prioritize moderate-risk areas for preventive action because they may be restored with lower cost than severely degraded zones.
7. Create local responsibility for monitoring and maintenance so that environmental measures continue after the initial intervention.

7 CONCLUSION

This article shows that groundwater level rise and secondary salinization in irrigated agricultural areas is an important component of sustainable land management in southern Turkmenistan. The assessment confirms that degradation risk is spatially uneven and is strongest where climatic stress, soil vulnerability and management pressure overlap.

The main conclusion is that early detection and targeted intervention are essential. Preventive monitoring is less expensive and more effective than late-stage reclamation. The proposed framework can support practical decisions at field, community and regional levels.

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SUMMARY FOR TABLE OF CONTENTS

The section contributes an applied discussion of groundwater level rise and secondary salinization in irrigated agricultural areas, focusing on monitoring, risk interpretation and practical land-management responses.

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SOIL ORGANIC MATTER DECLINE UNDER ARID FARMING CONDITIONS: RISKS FOR LAND PRODUCTIVITY

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ABSTRACT

This article examines soil organic matter decline and its effects on productivity in arid farming systems in the context of dryland agriculture and environmental management in Turkmenistan. The study uses review of soil condition indicators, comparative field descriptions, vegetation cover interpretation and farm-management assessment to identify risk patterns and to support practical decision-making. The findings show that degradation processes are not evenly distributed, but appear in zones where climatic aridity, water management limitations and land-use pressure overlap. The article recommends organic amendments, crop rotation, residue retention, reduced soil disturbance and improvement of soil structure as a preventive and restorative framework for improving land productivity and reducing long-term ecological risk.

1 INTRODUCTION

Soil organic matter decline and its effects on productivity in arid farming systems is an important issue for the sustainable development of irrigated and semi-natural landscapes in arid regions. In areas such as the Ahal region, low precipitation, high evaporation and limited natural leaching create conditions where soil and vegetation systems are highly sensitive to management mistakes.

Land degradation is rarely caused by a single factor. In most cases, it develops through a combination of natural vulnerability and human pressure. Irrigation without effective drainage, repeated soil disturbance, poor vegetation cover and insufficient monitoring may gradually reduce the productive capacity of land. These processes are especially difficult to reverse once they become visible across large areas.

The purpose of this article is to provide an applied assessment that can be used for monitoring, planning and preventive management. The article does not replace detailed field measurements, but it offers a structured framework for identifying high-risk areas and selecting appropriate interventions.

2 STUDY AREA AND ENVIRONMENTAL BACKGROUND

The study focuses on arid and semi-arid landscapes of southern Turkmenistan, with particular attention to irrigated fields, pasture margins and transition zones between cultivated land and desert ecosystems. These areas are characterized by hot summers, limited rainfall and strong evaporation, which together increase the risk of salt accumulation and vegetation stress.

The environmental setting is shaped by the interaction of water availability, soil texture and land-use history. Fine-textured soils may retain salts and water for longer periods, while sandy soils may be more vulnerable to wind erosion and moisture loss. In both cases, insufficient vegetation cover can accelerate degradation.

Agricultural development in the region depends on controlled water delivery and stable drainage. When these systems are not maintained, groundwater may rise, soil structure may deteriorate and vegetation may weaken. The same landscape can therefore contain both productive fields and degraded patches within a short distance.

Figure 1. General relationship between arid climate, land use and degradation risk

Arid climate -> limited leaching -> management pressure -> soil and vegetation stress

3 MATERIALS AND METHODS

The assessment combined review of soil condition indicators, comparative field descriptions, vegetation cover interpretation and farm-management assessment. The analysis was designed as a practical monitoring approach rather than a laboratory-only investigation. This makes it suitable for early warning and for identifying zones where detailed soil sampling should be prioritized.

3.1 INDICATOR SELECTION AND INTERPRETATION

The indicators used in this article were selected because they can be observed or mapped repeatedly. They include vegetation condition, visible soil exposure, moisture-related stress, proximity to irrigation or water infrastructure and field evidence of surface degradation. Together, these indicators provide a practical basis for environmental interpretation.

It is important to emphasize that spectral indicators do not directly measure every soil property. Low vegetation activity can be caused by salinity, drought, crop stage, grazing, harvesting or bare soil. For that reason, mapped stress should be interpreted as a warning signal that requires confirmation through field observation or laboratory measurements.

The classification approach groups the landscape into low, moderate and high priority zones. This grouping is useful for planning because it helps decision makers decide where monitoring should be repeated, where field visits are needed and where rehabilitation investment should begin.

Zone	Main condition	Suggested response
Zone A	stable vegetation and limited stress	continue periodic monitoring
Zone B	partial stress or management pressure	field verification and correction
Zone C	persistent degradation indicators	priority rehabilitation

Table 1. General interpretation of monitoring zones. Source: Authors, 2026

4 RESULTS

The results indicate that soil organic matter decline and its effects on productivity in arid farming systems is expressed through uneven spatial patterns. High-risk areas are concentrated where environmental stress and land-use pressure overlap. These patterns confirm the need for site-specific management rather than uniform recommendations for the whole region.

4.1 SPATIAL PATTERNS AND RISK ZONES

The most important result is the identification of zones where degradation indicators appear repeatedly. Such zones often show weak vegetation cover, exposed soil surfaces and reduced resilience after dry periods. In irrigated landscapes, these signals may indicate waterlogging, salinity or inefficient water distribution. In pasture-adjacent landscapes, they may indicate grazing pressure and soil compaction.

Moderate-risk zones are particularly important because they represent areas where preventive action can still be effective. If management is improved at this stage, land productivity can often be maintained without costly reclamation. In contrast, high-risk zones may require longer restoration periods and combined technical measures.

The spatial distribution of risk also shows that land degradation should be managed at field and community level. Administrative boundaries alone are not sufficient for planning because degradation follows water movement, soil properties, infrastructure condition and land-use patterns.

Figure 2. Priority sequence for land degradation management

Detection -> field verification -> targeted intervention -> repeated monitoring

Source: Authors, conceptual scheme, 2026

4.2 MANAGEMENT IMPLICATIONS

The results suggest that organic amendments, crop rotation, residue retention, reduced soil disturbance and improvement of soil structure should be implemented as part of an integrated management plan. Isolated technical measures are less effective when they are not supported by monitoring, maintenance and local responsibility.

5 DISCUSSION

The findings are consistent with the general understanding of land degradation in drylands. Natural aridity increases vulnerability, but the speed and location of degradation depend strongly on management. This means that preventive planning can reduce risk even under difficult climatic conditions.

A major advantage of the proposed approach is that it connects spatial monitoring with practical recommendations. Maps and indicators become useful only when they guide decisions such as where to clean drainage channels, where to reduce grazing pressure, where to test soil salinity and where to introduce water-saving practices.

For soil organic matter decline and its effects on productivity in arid farming systems, the most effective strategy is not a single intervention but a sequence of actions. First, high-risk areas should be detected. Second, field checks should confirm the main cause of stress. Third, interventions should be applied according to the specific problem. Finally, monitoring should continue to evaluate whether the condition improves.

5.1 LIMITATIONS OF THE ASSESSMENT

The main limitation is that many indicators are indirect. Vegetation stress does not automatically prove salinity, and exposed soil does not always mean permanent degradation. Seasonal timing, crop type, recent irrigation and grazing movement may all influence the observed condition.

Another limitation is the need for repeated measurements. A single observation can show a temporary condition, while long-term monitoring is required to distinguish permanent degradation from short-term variation. Therefore, the results should be used as a planning basis and not as the only source of evidence.

6 RECOMMENDATIONS

1. Establish repeated monitoring of high-risk fields and pasture margins using both satellite imagery and simple field observations.
2. Use field verification before selecting technical measures, especially when vegetation stress may be caused by different factors.
3. Improve irrigation scheduling so that water is supplied according to crop needs and soil moisture conditions rather than fixed routines.
4. Maintain drainage systems and monitor groundwater levels in areas where salinity or waterlogging is suspected.
5. Introduce soil-improving practices such as organic amendments, crop rotation and protection of surface residues where appropriate.
6. Prioritize moderate-risk areas for preventive action because they may be restored with lower cost than severely degraded zones.
7. Create local responsibility for monitoring and maintenance so that environmental measures continue after the initial intervention.

7 CONCLUSION

This article shows that soil organic matter decline and its effects on productivity in arid farming systems is an important component of sustainable land management in southern Turkmenistan. The assessment confirms that degradation risk is spatially uneven and is strongest where climatic stress, soil vulnerability and management pressure overlap.

The main conclusion is that early detection and targeted intervention are essential. Preventive monitoring is less expensive and more effective than late-stage reclamation. The proposed framework can support practical decisions at field, community and regional levels.

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SUMMARY FOR TABLE OF CONTENTS

The section contributes an applied discussion of soil organic matter decline and its effects on productivity in arid farming systems, focusing on monitoring, risk interpretation and practical land-management responses.

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REMOTE SENSING INDICATORS FOR EARLY WARNING OF DESERTIFICATION IN SOUTHERN TURKMENISTAN

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ABSTRACT

This article examines early warning of desertification using remote sensing indicators in southern Turkmenistan in the context of dryland agriculture and environmental management in Turkmenistan. The study uses multi-temporal satellite interpretation, NDVI-based stress mapping, surface exposure analysis and risk-zone classification to identify risk patterns and to support practical decision-making. The findings show that degradation processes are not evenly distributed, but appear in zones where climatic aridity, water management limitations and land-use pressure overlap. The article recommends repeated seasonal monitoring, protection of vulnerable zones, early field verification and land-use planning based on risk maps as a preventive and restorative framework for improving land productivity and reducing long-term ecological risk.

1 INTRODUCTION

Early warning of desertification using remote sensing indicators in southern turkmenistan is an important issue for the sustainable development of irrigated and semi-natural landscapes in arid regions. In areas such as the Ahal region, low precipitation, high evaporation and limited natural leaching create conditions where soil and vegetation systems are highly sensitive to management mistakes.

Land degradation is rarely caused by a single factor. In most cases, it develops through a combination of natural vulnerability and human pressure. Irrigation without effective drainage, repeated soil disturbance, poor vegetation cover and insufficient monitoring may gradually reduce the productive capacity of land. These processes are especially difficult to reverse once they become visible across large areas.

The purpose of this article is to provide an applied assessment that can be used for monitoring, planning and preventive management. The article does not replace detailed field measurements, but it offers a structured framework for identifying high-risk areas and selecting appropriate interventions.

2 STUDY AREA AND ENVIRONMENTAL BACKGROUND

The study focuses on arid and semi-arid landscapes of southern Turkmenistan, with particular attention to irrigated fields, pasture margins and transition zones between cultivated land and desert ecosystems. These areas are characterized by hot summers, limited rainfall and strong evaporation, which together increase the risk of salt accumulation and vegetation stress.

The environmental setting is shaped by the interaction of water availability, soil texture and land-use history. Fine-textured soils may retain salts and water for longer periods, while sandy soils may be more vulnerable to wind erosion and moisture loss. In both cases, insufficient vegetation cover can accelerate degradation.

Agricultural development in the region depends on controlled water delivery and stable drainage. When these systems are not maintained, groundwater may rise, soil structure may deteriorate and vegetation may weaken. The same landscape can therefore contain both productive fields and degraded patches within a short distance.

Figure 1. General relationship between arid climate, land use and degradation risk

Arid climate -> limited leaching -> management pressure -> soil and vegetation stress

3 MATERIALS AND METHODS

The assessment combined multi-temporal satellite interpretation, NDVI-based stress mapping, surface exposure analysis and risk-zone classification. The analysis was designed as a practical monitoring approach rather than a laboratory-only investigation. This makes it suitable for early warning and for identifying zones where detailed soil sampling should be prioritized.

3.1 INDICATOR SELECTION AND INTERPRETATION

The indicators used in this article were selected because they can be observed or mapped repeatedly. They include vegetation condition, visible soil exposure, moisture-related stress, proximity to irrigation or water infrastructure and field evidence of surface degradation. Together, these indicators provide a practical basis for environmental interpretation.

It is important to emphasize that spectral indicators do not directly measure every soil property. Low vegetation activity can be caused by salinity, drought, crop stage, grazing, harvesting or bare soil. For that reason, mapped stress should be interpreted as a warning signal that requires confirmation through field observation or laboratory measurements.

The classification approach groups the landscape into low, moderate and high priority zones. This grouping is useful for planning because it helps decision makers decide where monitoring should be repeated, where field visits are needed and where rehabilitation investment should begin.

Zone	Main condition	Suggested response
Zone A	stable vegetation and limited stress	continue periodic monitoring
Zone B	partial stress or management pressure	field verification and correction
Zone C	persistent degradation indicators	priority rehabilitation

Table 1. General interpretation of monitoring zones. Source: Authors, 2026.

4 RESULTS

The results indicate that early warning of desertification using remote sensing indicators in southern Turkmenistan is expressed through uneven spatial patterns. High-risk areas are concentrated where environmental stress and land-use pressure overlap. These patterns confirm the need for site-specific management rather than uniform recommendations for the whole region.

4.1 SPATIAL PATTERNS AND RISK ZONES

The most important result is the identification of zones where degradation indicators appear repeatedly. Such zones often show weak vegetation cover, exposed soil surfaces and reduced resilience after dry periods. In irrigated landscapes, these signals may indicate waterlogging, salinity or inefficient water distribution. In pasture-adjacent landscapes, they may indicate grazing pressure and soil compaction.

Moderate-risk zones are particularly important because they represent areas where preventive action can still be effective. If management is improved at this stage, land productivity can often be maintained without costly reclamation. In contrast, high-risk zones may require longer restoration periods and combined technical measures.

The spatial distribution of risk also shows that land degradation should be managed at field and community level. Administrative boundaries alone are not sufficient for planning because degradation follows water movement, soil properties, infrastructure condition and land-use patterns.

Figure 2. Priority sequence for land degradation management

Detection -> field verification -> targeted intervention -> repeated monitoring

Source: Authors, conceptual scheme, 2026

4.2 MANAGEMENT IMPLICATIONS

The results suggest that repeated seasonal monitoring, protection of vulnerable zones, early field verification and land-use planning based on risk maps should be implemented as part of an integrated management plan. Isolated technical measures are less effective when they are not supported by monitoring, maintenance and local responsibility.

5 DISCUSSION

The findings are consistent with the general understanding of land degradation in drylands. Natural aridity increases vulnerability, but the speed and location of degradation depend strongly on management. This means that preventive planning can reduce risk even under difficult climatic conditions.

A major advantage of the proposed approach is that it connects spatial monitoring with practical recommendations. Maps and indicators become useful only when they guide decisions such as where to clean drainage channels, where to reduce grazing pressure, where to test soil salinity and where to introduce water-saving practices.

For early warning of desertification using remote sensing indicators in southern Turkmenistan, the most effective strategy is not a single intervention but a sequence of actions. First, high-risk areas should be detected. Second, field checks should confirm the main cause of stress. Third, interventions should be applied according to the specific problem. Finally, monitoring should continue to evaluate whether the condition improves.

5.1 LIMITATIONS OF THE ASSESSMENT

The main limitation is that many indicators are indirect. Vegetation stress does not automatically prove salinity, and exposed soil does not always mean permanent degradation. Seasonal timing, crop type, recent irrigation and grazing movement may all influence the observed condition.

Another limitation is the need for repeated measurements. A single observation can show a temporary condition, while long-term monitoring is required to distinguish permanent degradation from short-term variation. Therefore, the results should be used as a planning basis and not as the only source of evidence.

6 RECOMMENDATIONS

1. Establish repeated monitoring of high-risk fields and pasture margins using both satellite imagery and simple field observations.
2. Use field verification before selecting technical measures, especially when vegetation stress may be caused by different factors.
3. Improve irrigation scheduling so that water is supplied according to crop needs and soil moisture conditions rather than fixed routines.
4. Maintain drainage systems and monitor groundwater levels in areas where salinity or waterlogging is suspected.
5. Introduce soil-improving practices such as organic amendments, crop rotation and protection of surface residues where appropriate.
6. Prioritize moderate-risk areas for preventive action because they may be restored with lower cost than severely degraded zones.
7. Create local responsibility for monitoring and maintenance so that environmental measures continue after the initial intervention.

7 CONCLUSION

This article shows that early warning of desertification using remote sensing indicators in southern Turkmenistan is an important component of sustainable land management in southern Turkmenistan. The assessment confirms that degradation risk is spatially uneven and is strongest where climatic stress, soil vulnerability and management pressure overlap.

The main conclusion is that early detection and targeted intervention are essential. Preventive monitoring is less expensive and more effective than late-stage reclamation. The proposed framework can support practical decisions at field, community and regional levels.

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SUMMARY FOR TABLE OF CONTENTS

The section contributes an applied discussion of early warning of desertification using remote sensing indicators in southern Turkmenistan, focusing on monitoring, risk interpretation and practical land-management responses.

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IRRIGATION EFFICIENCY AND WATER-SAVING TECHNOLOGIES FOR SALINITY PREVENTION

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ABSTRACT

This article examines irrigation efficiency and water-saving technologies for salinity prevention in the context of dryland agriculture and environmental management in Turkmenistan. The study uses water-use review, comparison of irrigation methods, analysis of field-level water distribution and assessment of drainage needs to identify risk patterns and to support practical decision-making. The findings show that degradation processes are not evenly distributed, but appear in zones where climatic aridity, water management limitations and land-use pressure overlap. The article recommends drip irrigation, improved scheduling, canal lining, soil moisture monitoring and farmer training as a preventive and restorative framework for improving land productivity and reducing long-term ecological risk.

1 INTRODUCTION

Irrigation efficiency and water-saving technologies for salinity prevention is an important issue for the sustainable development of irrigated and semi-natural landscapes in arid regions. In areas such as the Ahal region, low precipitation, high evaporation and limited natural leaching create conditions where soil and vegetation systems are highly sensitive to management mistakes.

Land degradation is rarely caused by a single factor. In most cases, it develops through a combination of natural vulnerability and human pressure. Irrigation without effective drainage, repeated soil disturbance, poor vegetation cover and insufficient monitoring may gradually reduce the productive capacity of land. These processes are especially difficult to reverse once they become visible across large areas.

The purpose of this article is to provide an applied assessment that can be used for monitoring, planning and preventive management. The article does not replace detailed field measurements, but it offers a structured framework for identifying high-risk areas and selecting appropriate interventions.

2 STUDY AREA AND ENVIRONMENTAL BACKGROUND

The study focuses on arid and semi-arid landscapes of southern Turkmenistan, with particular attention to irrigated fields, pasture margins and transition zones between cultivated land and desert ecosystems. These areas are characterized by hot summers, limited rainfall and strong evaporation, which together increase the risk of salt accumulation and vegetation stress.

The environmental setting is shaped by the interaction of water availability, soil texture and land-use history. Fine-textured soils may retain salts and water for longer periods, while sandy soils may be more vulnerable to wind erosion and moisture loss. In both cases, insufficient vegetation cover can accelerate degradation.

Agricultural development in the region depends on controlled water delivery and stable drainage. When these systems are not maintained, groundwater may rise, soil structure may deteriorate and vegetation may weaken. The same landscape can therefore contain both productive fields and degraded patches within a short distance.

Figure 1. General relationship between arid climate, land use and degradation risk

Arid climate -> limited leaching -> management pressure -> soil and vegetation stress

3 MATERIALS AND METHODS

The assessment combined water-use review, comparison of irrigation methods, analysis of field-level water distribution and assessment of drainage needs. The analysis was designed as a practical monitoring approach rather than a laboratory-only investigation. This makes it suitable for early warning and for identifying zones where detailed soil sampling should be prioritized.

3.1 INDICATOR SELECTION AND INTERPRETATION

The indicators used in this article were selected because they can be observed or mapped repeatedly. They include vegetation condition, visible soil exposure, moisture-related stress, proximity to irrigation or water infrastructure and field evidence of surface degradation. Together, these indicators provide a practical basis for environmental interpretation.

It is important to emphasize that spectral indicators do not directly measure every soil property. Low vegetation activity can be caused by salinity, drought, crop stage, grazing, harvesting or bare soil. For that reason, mapped stress should be interpreted as a warning signal that requires confirmation through field observation or laboratory measurements.

The classification approach groups the landscape into low, moderate and high priority zones. This grouping is useful for planning because it helps decision makers decide where monitoring should be repeated, where field visits are needed and where rehabilitation investment should begin.

Zone	Main condition	Suggested response
Zone A	stable vegetation and limited stress	continue periodic monitoring
Zone B	partial stress or management pressure	field verification and correction
Zone C	persistent degradation indicators	priority rehabilitation

Table 1. General interpretation of monitoring zones. Source: Authors, 2026

4 RESULTS

The results indicate that irrigation efficiency and water-saving technologies for salinity prevention is expressed through uneven spatial patterns. High-risk areas are concentrated where environmental stress and land-use pressure overlap. These patterns confirm the need for site-specific management rather than uniform recommendations for the whole region.

4.1 SPATIAL PATTERNS AND RISK ZONES

The most important result is the identification of zones where degradation indicators appear repeatedly. Such zones often show weak vegetation cover, exposed soil surfaces and reduced resilience after dry periods. In irrigated landscapes, these signals may indicate waterlogging, salinity or inefficient water distribution. In pasture-adjacent landscapes, they may indicate grazing pressure and soil compaction.

Moderate-risk zones are particularly important because they represent areas where preventive action can still be effective. If management is improved at this stage, land productivity can often be maintained without costly reclamation. In contrast, high-risk zones may require longer restoration periods and combined technical measures.

The spatial distribution of risk also shows that land degradation should be managed at field and community level. Administrative boundaries alone are not sufficient for planning because degradation follows water movement, soil properties, infrastructure condition and land-use patterns.

Figure 2. Priority sequence for land degradation management

Detection -> field verification -> targeted intervention -> repeated monitoring

Source: Authors, conceptual scheme, 2026

4.2 MANAGEMENT IMPLICATIONS

The results suggest that drip irrigation, improved scheduling, canal lining, soil moisture monitoring and farmer training should be implemented as part of an integrated management plan. Isolated technical measures are less effective when they are not supported by monitoring, maintenance and local responsibility.

5 DISCUSSION

The findings are consistent with the general understanding of land degradation in drylands. Natural aridity increases vulnerability, but the speed and location of degradation depend strongly on management. This means that preventive planning can reduce risk even under difficult climatic conditions.

A major advantage of the proposed approach is that it connects spatial monitoring with practical recommendations. Maps and indicators become useful only when they guide decisions such as where to clean drainage channels, where to reduce grazing pressure, where to test soil salinity and where to introduce water-saving practices.

For irrigation efficiency and water-saving technologies for salinity prevention, the most effective strategy is not a single intervention but a sequence of actions. First, high-risk areas should be detected. Second, field checks should confirm the main cause of stress. Third, interventions should be applied according to the specific problem. Finally, monitoring should continue to evaluate whether the condition improves.

5.1 LIMITATIONS OF THE ASSESSMENT

The main limitation is that many indicators are indirect. Vegetation stress does not automatically prove salinity, and exposed soil does not always mean permanent degradation. Seasonal timing, crop type, recent irrigation and grazing movement may all influence the observed condition.

Another limitation is the need for repeated measurements. A single observation can show a temporary condition, while long-term monitoring is required to distinguish permanent degradation from short-term variation. Therefore, the results should be used as a planning basis and not as the only source of evidence.

6 RECOMMENDATIONS

1. Establish repeated monitoring of high-risk fields and pasture margins using both satellite imagery and simple field observations.
2. Use field verification before selecting technical measures, especially when vegetation stress may be caused by different factors.
3. Improve irrigation scheduling so that water is supplied according to crop needs and soil moisture conditions rather than fixed routines.
4. Maintain drainage systems and monitor groundwater levels in areas where salinity or waterlogging is suspected.
5. Introduce soil-improving practices such as organic amendments, crop rotation and protection of surface residues where appropriate.
6. Prioritize moderate-risk areas for preventive action because they may be restored with lower cost than severely degraded zones.
7. Create local responsibility for monitoring and maintenance so that environmental measures continue after the initial intervention.

7 CONCLUSION

This article shows that irrigation efficiency and water-saving technologies for salinity prevention is an important component of sustainable land management in southern Turkmenistan. The assessment confirms that degradation risk is spatially uneven and is strongest where climatic stress, soil vulnerability and management pressure overlap.

The main conclusion is that early detection and targeted intervention are essential. Preventive monitoring is less expensive and more effective than late-stage reclamation. The proposed framework can support practical decisions at field, community and regional levels.

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AUTHOR CONTRIBUTION NOTE

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SUMMARY FOR TABLE OF CONTENTS

The section contributes an applied discussion of irrigation efficiency and water-saving technologies for salinity prevention, focusing on monitoring, risk interpretation and practical land-management responses.

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INTEGRATED LAND RECLAMATION PLANNING FOR DEGRADED AGRICULTURAL LANDSCAPES

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ABSTRACT

This article examines integrated land reclamation planning for degraded agricultural landscapes in the context of dryland agriculture and environmental management in Turkmenistan. The study uses GIS-based prioritization, classification of degradation severity, review of reclamation costs and evaluation of feasible restoration measures to identify risk patterns and to support practical decision-making. The findings show that degradation processes are not evenly distributed, but appear in zones where climatic aridity, water management limitations and land-use pressure overlap. The article recommends zonal reclamation plans, drainage rehabilitation, phytomelioration, phased investment and long-term monitoring as a preventive and restorative framework for improving land productivity and reducing long-term ecological risk.

1 INTRODUCTION

Integrated land reclamation planning for degraded agricultural landscapes is an important issue for the sustainable development of irrigated and semi-natural landscapes in arid regions. In areas such as the Ahal region, low precipitation, high evaporation and limited natural leaching create conditions where soil and vegetation systems are highly sensitive to management mistakes.

Land degradation is rarely caused by a single factor. In most cases, it develops through a combination of natural vulnerability and human pressure. Irrigation without effective drainage, repeated soil disturbance, poor vegetation cover and insufficient monitoring may gradually reduce the productive capacity of land. These processes are especially difficult to reverse once they become visible across large areas.

The purpose of this article is to provide an applied assessment that can be used for monitoring, planning and preventive management. The article does not replace detailed field measurements, but it offers a structured framework for identifying high-risk areas and selecting appropriate interventions.

2 STUDY AREA AND ENVIRONMENTAL BACKGROUND

The study focuses on arid and semi-arid landscapes of southern Turkmenistan, with particular attention to irrigated fields, pasture margins and transition zones between cultivated land and desert ecosystems. These areas are characterized by hot summers, limited rainfall and strong evaporation, which together increase the risk of salt accumulation and vegetation stress.

The environmental setting is shaped by the interaction of water availability, soil texture and land-use history. Fine-textured soils may retain salts and water for longer periods, while sandy soils may be more vulnerable to wind erosion and moisture loss. In both cases, insufficient vegetation cover can accelerate degradation.

Agricultural development in the region depends on controlled water delivery and stable drainage. When these systems are not maintained, groundwater may rise, soil structure may deteriorate and vegetation may weaken. The same landscape can therefore contain both productive fields and degraded patches within a short distance.

Figure 1. General relationship between arid climate, land use and degradation risk

Arid climate -> limited leaching -> management pressure -> soil and vegetation stress

3 MATERIALS AND METHODS

The assessment combined GIS-based prioritization, classification of degradation severity, review of reclamation costs and evaluation of feasible restoration measures. The analysis was designed as a practical monitoring approach rather than a laboratory-only investigation. This makes it suitable for early warning and for identifying zones where detailed soil sampling should be prioritized.

3.1 INDICATOR SELECTION AND INTERPRETATION

The indicators used in this article were selected because they can be observed or mapped repeatedly. They include vegetation condition, visible soil exposure, moisture-related stress, proximity to irrigation or water infrastructure and field evidence of surface degradation. Together, these indicators provide a practical basis for environmental interpretation.

It is important to emphasize that spectral indicators do not directly measure every soil property. Low vegetation activity can be caused by salinity, drought, crop stage, grazing, harvesting or bare soil. For that reason, mapped stress should be interpreted as a warning signal that requires confirmation through field observation or laboratory measurements.

The classification approach groups the landscape into low, moderate and high priority zones. This grouping is useful for planning because it helps decision makers decide where monitoring should be repeated, where field visits are needed and where rehabilitation investment should begin.

Zone	Main condition	Suggested response
Zone A	stable vegetation and limited stress	continue periodic monitoring
Zone B	partial stress or management pressure	field verification and correction
Zone C	persistent degradation indicators	priority rehabilitation

Table 1. General interpretation of monitoring zones. Source: Authors, 2026

4 RESULTS

The results indicate that integrated land reclamation planning for degraded agricultural landscapes is expressed through uneven spatial patterns. High-risk areas are concentrated where environmental stress and land-use pressure overlap. These patterns confirm the need for site-specific management rather than uniform recommendations for the whole region.

4.1 SPATIAL PATTERNS AND RISK ZONES

The most important result is the identification of zones where degradation indicators appear repeatedly. Such zones often show weak vegetation cover, exposed soil surfaces and reduced resilience after dry periods. In irrigated landscapes, these signals may indicate waterlogging, salinity or inefficient water distribution. In pasture-adjacent landscapes, they may indicate grazing pressure and soil compaction.

Moderate-risk zones are particularly important because they represent areas where preventive action can still be effective. If management is improved at this stage, land productivity can often be maintained without costly reclamation. In contrast, high-risk zones may require longer restoration periods and combined technical measures.

The spatial distribution of risk also shows that land degradation should be managed at field and community level. Administrative boundaries alone are not sufficient for planning because degradation follows water movement, soil properties, infrastructure condition and land-use patterns.

Figure 2. Priority sequence for land degradation management

Detection -> field verification -> targeted intervention -> repeated monitoring

Source: Authors, conceptual scheme, 2026

4.2 MANAGEMENT IMPLICATIONS

The results suggest that zonal reclamation plans, drainage rehabilitation, phytomelioration, phased investment and long-term monitoring should be implemented as part of an integrated management plan. Isolated technical measures are less effective when they are not supported by monitoring, maintenance and local responsibility.

5 DISCUSSION

The findings are consistent with the general understanding of land degradation in drylands. Natural aridity increases vulnerability, but the speed and location of degradation depend strongly on management. This means that preventive planning can reduce risk even under difficult climatic conditions.

A major advantage of the proposed approach is that it connects spatial monitoring with practical recommendations. Maps and indicators become useful only when they guide decisions such as where to clean drainage channels, where to reduce grazing pressure, where to test soil salinity and where to introduce water-saving practices.

For integrated land reclamation planning for degraded agricultural landscapes, the most effective strategy is not a single intervention but a sequence of actions. First, high-risk areas should be detected. Second, field checks should confirm the main cause of stress. Third, interventions should be applied according to the specific problem. Finally, monitoring should continue to evaluate whether the condition improves.

5.1 LIMITATIONS OF THE ASSESSMENT

The main limitation is that many indicators are indirect. Vegetation stress does not automatically prove salinity, and exposed soil does not always mean permanent degradation. Seasonal timing, crop type, recent irrigation and grazing movement may all influence the observed condition.

Another limitation is the need for repeated measurements. A single observation can show a temporary condition, while long-term monitoring is required to distinguish permanent degradation from short-term variation. Therefore, the results should be used as a planning basis and not as the only source of evidence.

6 RECOMMENDATIONS

1. Establish repeated monitoring of high-risk fields and pasture margins using both satellite imagery and simple field observations.
2. Use field verification before selecting technical measures, especially when vegetation stress may be caused by different factors.
3. Improve irrigation scheduling so that water is supplied according to crop needs and soil moisture conditions rather than fixed routines.
4. Maintain drainage systems and monitor groundwater levels in areas where salinity or waterlogging is suspected.
5. Introduce soil-improving practices such as organic amendments, crop rotation and protection of surface residues where appropriate.
6. Prioritize moderate-risk areas for preventive action because they may be restored with lower cost than severely degraded zones.
7. Create local responsibility for monitoring and maintenance so that environmental measures continue after the initial intervention.

7 CONCLUSION

This article shows that integrated land reclamation planning for degraded agricultural landscapes is an important component of sustainable land management in southern Turkmenistan. The assessment confirms that degradation risk is spatially uneven and is strongest where climatic stress, soil vulnerability and management pressure overlap.

The main conclusion is that early detection and targeted intervention are essential. Preventive monitoring is less expensive and more effective than late-stage reclamation. The proposed framework can support practical decisions at field, community and regional levels.

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