ISSN 3079-9449 (Onlaýn)

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VOL.4, ISSUE 7

2026

ESASLANDYRYJYSY – TÜRKMEN MILLI DÜNÝÄ DILLERI INSTITUTY · PASTURE ECOLOGY · LAND DEGRADATION · REMOTE SENSING

UDC 631.45:574.4(575.4)

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.

ACKNOWLEDGEMENTS

The authors express sincere gratitude to the pastoral communities of the Ahal province for their time, generosity, and willingness to share traditional ecological knowledge. Field survey logistics were supported by the Institute of Deserts, Flora and Fauna of the Academy of Sciences of Turkmenistan. Laboratory analyses were conducted at the Soil Science Laboratory of the Turkmen Agricultural University. The study received financial support from the Academy of Sciences of Turkmenistan research grant programme (Grant #AoS-2022-0047) and supplementary funding from the UNCCD Science-Policy Interface Central Asia Land Degradation Assessment Initiative. The authors declare no conflicts of interest. Data and materials supporting the findings are available from the corresponding author upon reasonable request.

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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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Submitted: 14 January 2026 | Revised: 10 March 2026 | Accepted: 18 March 2026 | Published: 1 June 2026