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Degradation processes and the effectiveness of intensive grazing in foothill pastures of Uzbekistan

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Introduction: Foothill (adry) rangelands of eastern Uzbekistan serve as a key forage resource for regional livestock systems but are increasingly affected by land degradation driven by grazing pressure and environmental variability.

Methods: This study integrates long-term geobotanical survey data (1969–2018) with satellite-derived NDVI time-series analysis (2015–2023) to assess vegetation dynamics in the Akhangaron district. In addition, a field-based experimental comparison between continuous (extensive) and rotational (intensive) grazing systems was conducted to evaluate management impacts on pasture productivity.

Results: The analysis revealed a 46% decline in total pasture biomass and a 20% reduction in forage nutritional value over the 50-year period. Vegetation composition shifted from highly palatable ephemeral species (*Poa bulbosa* L., *Carex pachystylis* J.Gay) toward more grazing-resistant taxa. Seasonal Mann-Kendall trend analysis indicated a weak negative tendency in spring peak NDVI; however, this trend was not statistically significant ($p > 0.05$). Field experiments demonstrated that rotational grazing increased total biomass by approximately 20% and edible biomass by more than 40% compared to continuous grazing, along with improvements in vegetation structure.

Discussion: The findings indicate that long-term pasture degradation is primarily associated with sustained grazing pressure, while short-term improvements under rotational grazing highlight its potential as an adaptive management strategy. The combined use of historical field data and multi-year remote sensing enhances the reliability of pasture monitoring in semi-arid environments.

KEYWORDS

adaptive grazing management, biomass dynamics, foothill pastures, forage quality, NDVI time series, rangeland degradation, rotational grazing, Uzbekistan

1 Introduction

Rangelands in arid and semi-arid regions occupy nearly 40% of the global land surface and constitute a fundamental component of terrestrial food systems, supporting livestock production and rural livelihoods worldwide (Sayre et al., 2017). In Central Asia, rangelands represent the dominant land-use type (Gintzburger et al., 2003), and in Uzbekistan alone they cover more than 21 million hectares, forming the primary forage base for the national livestock sector. However, these ecosystems are increasingly exposed to interacting pressures from climate variability and anthropogenic land-use change, resulting in widespread degradation processes (Mirzabaev et al., 2016; Zandler et al., 2023).

Previous studies in Central Asia have documented vegetation shifts, altered livestock mobility, and uneven pasture utilization following the socio-economic transformation after the collapse of the Soviet Union (Kerven et al., 2011, 2021). Research conducted in the Tien Shan mountains of Kyrgyzstan has demonstrated that grazing pressure, settlement proximity, and climatic oscillations jointly influence vegetation productivity and NDVI dynamics (e.g., Zhumanova et al., 2018; Tomaszewska and Henebry, 2021). Remote sensing analyses have been widely applied to detect vegetation trends (Tucker, 1979; Rouse et al., 1974; Zhumanova et al., 2018), while field-based investigations have assessed biomass decline and changes in plant community composition (Zhumanova et al., 2018; Hoppe et al., 2016). Nevertheless, these studies typically focus either on satellite-based assessments over relatively short time spans or on contemporary field experiments, without integrating long-term historical archival data with modern high-resolution imagery.

In Uzbekistan, particularly in the foothill (adyr) zones of the Western Tian Shan, pastures have historically been subjected to extensive grazing regimes. During the Soviet period, grazing systems were centrally managed and spatially organized, whereas post-Soviet transitions led to fragmented smallholder management and livestock concentration near settlements and water sources (Kerven et al., 2021). Such changes have contributed to localized overgrazing, shifts in species composition, and the replacement of palatable grasses by less desirable or unpalatable species, potentially altering both biomass yield and spectral vegetation signals (Zhumanova et al., 2018).

Despite increasing recognition of degradation patterns, several methodological limitations remain. First, assessments of long-term degradation in Uzbekistan often rely on discontinuous field observations. Second, many remote sensing studies use relatively short NDVI time series, which may be insufficient to detect robust trends in regions influenced by strong interannual climate variability (Zhumanova et al., 2018; De Beurs et al., 2018). Third, few studies explicitly compare satellite-derived vegetation indices with ground-based biomass data to evaluate the reliability of remote sensing as a proxy for forage availability.

To address these gaps, this study integrates long-term historical geobotanical records (1969–2018) with Landsat- and Sentinel-derived NDVI time series (2015–2023) for the foothill pastures of the Akhangaran district, eastern Uzbekistan. By linking archival biomass data with modern satellite observations and field-based grazing experiments, the research provides a multi-decadal perspective on degradation trajectories. Furthermore, the study evaluates whether sustainable intensification—specifically rotational grazing—can improve pasture productivity under semi-arid conditions, consistent with adaptive rangeland management principles (Derner et al., 2022; Teague et al., 2013).

The objectives of this research are therefore to:

- (1) quantify long-term changes in pasture biomass and forage composition over a 50-year period;
- (2) examine recent vegetation dynamics using multi-year NDVI time series and trend analysis; and
- (3) assess the effectiveness of intensive (rotational) versus extensive grazing systems in enhancing pasture productivity under degraded conditions.

2 Materials and methods

2.1 Study area

The study was conducted in the foothill (adyr) zone of the Akhangaran district, Tashkent region, eastern Uzbekistan. The area forms part of the western extension of the Tian Shan mountain system and represents a transitional belt between lowland desert plains and higher mountain pastures. Elevation ranges from approximately 500 to 1,200 m above sea level, creating pronounced slope–aspect gradients that influence soil moisture distribution, vegetation composition, and seasonal productivity.

The climate is strongly continental, with hot, dry summers and relatively cool, moist springs. Mean annual precipitation varies between 300 and 450 mm, with the majority occurring during March–April, which coincides with peak vegetative growth. Snowfall occurs in winter, and in some years snowmelt contributes to early-season soil moisture recharge. Interannual variability in precipitation is high, reflecting broader climatic oscillation patterns affecting Central Asia (Zhumanova et al., 2018; De Beurs et al., 2018).

Vegetation in the adyr zone is characterized by ephemeral–ephemeroïd semi-arid grasslands dominated by early-spring annuals and short-lived perennials. Historically productive species such as *Poa bulbosa* L. and *Carex pachystylis* J.Gay have formed the structural basis of forage production, while increasing grazing pressure has facilitated the expansion of less palatable forbs and xerophytic species. Similar grazing-induced shifts in species composition have been documented in the western Tian Shan region (Zhumanova et al., 2018; Hoppe et al., 2016; Kerven et al., 2021).

Soils are predominantly typical serozems (Calcisols), which are highly vulnerable to erosion when vegetation cover is reduced. The combination of steep slopes, episodic rainfall, and concentrated livestock grazing near settlements and water points increases susceptibility to localized degradation. During the Soviet period, grazing was centrally planned and spatially regulated; however, post-1991 land-use restructuring led to fragmented smallholder management and uneven livestock distribution, often intensifying pressure in easily accessible foothill areas (Kerven et al., 2011, 2021).

The selected study area is therefore representative of degradation dynamics observed in foothill rangelands of eastern Uzbekistan and provides an appropriate case for assessing long-term vegetation change and grazing management impacts.

The spatial distribution of mean annual NDVI for representative years (2015 and 2023) is shown in Figure 1.

2.2. Historical geobotanical data and field surveys (1969–2018)

2.2.1 Revised

Long-term vegetation change was assessed through a retrospective comparative framework integrating archival geobotanical surveys (1969 and 1988) with a modern field survey conducted in 2018. This design allows evaluation of multi-decadal

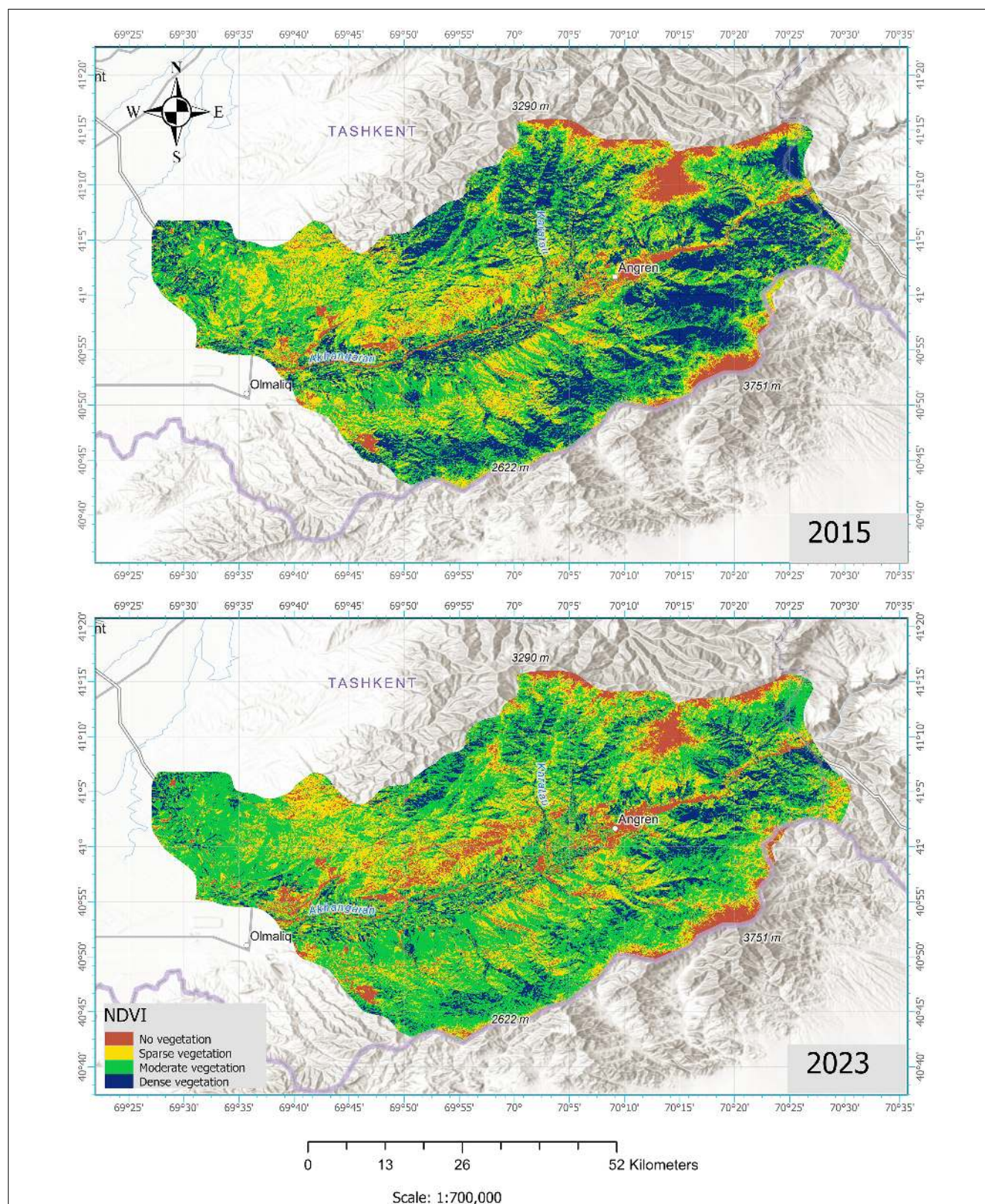


FIGURE 1

Spatial distribution of NDVI-derived vegetation condition in the Akhangaran foothill rangelands (2015 and 2023). Maps show annual mean NDVI values derived from Landsat 7 ETM+, Landsat 8 OLI/TIRS, and Landsat 9 OLI-2 surface reflectance data (30 m spatial resolution). NDVI was calculated as $(NIR - Red)/(NIR + Red)$ following [Tucker \(1979\)](#). Vegetation condition is classified into four categories based on NDVI thresholds: no vegetation ($NDVI < 0.1$), sparse vegetation ($0.1-0.3$), moderate vegetation ($0.3-0.5$), and dense vegetation (>0.5). These classes represent relative vegetation density and photosynthetic activity rather than species composition or forage quality. The comparison between 2015 and 2023 illustrates spatial heterogeneity in vegetation condition, including localized areas of reduced greenness near settlements and water access zones. Elevation contours and hill shade background are included for topographic reference. Coordinate system: WGS84 geographic projection.

changes in biomass production, species composition, and forage quality in foothill rangelands.

2.2.2 Historical surveys (1969 and 1988)

Baseline data were obtained from the archival records of the “Uzdaveroi” (formerly Giprozem) Institute, which conducted comprehensive geobotanical expeditions in 1969 and 1988. These surveys applied standardized transect-based vegetation mapping and biomass estimation procedures widely used in Soviet-era rangeland monitoring (Bykov, 1978). Productivity was reported as air-dry aboveground biomass (kg ha^{-1} ; converted from centners to SI units for consistency). Botanical composition was recorded through species dominance and projective cover estimates.

Although the archival datasets represent discrete time points rather than continuous monitoring, such historical records provide rare long-term reference conditions for Central Asian rangelands, where multi-decadal vegetation datasets remain limited (Mirzabaev et al., 2016; Kerven et al., 2021).

2.2.3 Modern field survey (2018)

In 2018, a comprehensive field reassessment was conducted at the same reference coordinates used in the historical surveys to ensure spatial comparability. Vegetation sampling followed the standard mowing method (Bykov, 1978) using 1 m^2 plots with four replications per sampling location ($n = 4$ per site). All aboveground biomass was harvested during peak growing season (April–May), air-dried, and weighed to determine dry biomass (kg ha^{-1}).

In addition to total biomass, species composition and relative abundance were recorded to assess changes in palatability and functional group structure. Particular attention was given to historically dominant forage species such as *Poa bulbosa* L. and *Carex pachystylis* J. Gay, as well as to the expansion of less palatable or ruderal species (Zhumanova et al., 2018; Hoppe et al., 2016). Distinguishing between edible, palatable, and inedible biomass is essential, as vegetation shifts under grazing pressure may alter forage quality without proportionally affecting total biomass (Zhumanova et al., 2018).

2.2.4 Feed unit calculation

Forage nutritional value was calculated in Feed Units (FU), where 1 FU corresponds to the metabolizable energy equivalent of 1 kg of standard oats (approximately 2,500 kcal). Conversion from biomass (kg ha^{-1}) to FU was performed using species-specific forage coefficients derived from regional rangeland evaluation tables applied in Soviet-era geobotanical assessments (Bykov, 1978). These coefficients account for relative digestibility, crude protein content, and palatability of dominant species recorded in each survey year. Species-level FU contributions were weighted by their proportional biomass within each sampling plot.

This approach allows vegetation productivity to be expressed in energetically comparable units directly linked to livestock requirements and carrying capacity estimation, facilitating

quantitative comparison between grazing systems (Derner et al., 2022).

2.2.5 Climatic context

To contextualize vegetation changes, available meteorological records were consulted for the growing seasons of 1969, 1988, and 2018. Given the high interannual variability of precipitation in the Western Tian Shan region (Zhumanova et al., 2018; De Beurs et al., 2018), climatic anomalies were considered as potential co-drivers of biomass fluctuations alongside grazing pressure.

2.2.6 Integration with remote sensing framework

The spatial comparability between historical plots and satellite-derived vegetation metrics follows high-resolution rangeland assessment approaches integrating field data with NDVI-based monitoring (Tomaszewska and Henebry, 2021). This integration enables evaluation of long-term degradation trajectories while accounting for potential discrepancies between ground-based biomass estimates and spectral vegetation indices.

2.3 Remote sensing and NDVI time-series analysis

To complement field-based observations and evaluate recent vegetation dynamics, optical satellite imagery was used to construct a continuous NDVI time series for 2015–2023. The NDVI time series was derived exclusively from Landsat 7 ETM+, Landsat 8 OLI/TIRS, and Landsat 9 OLI-2 surface reflectance products (30 m spatial resolution) to ensure temporal consistency across the study period. Sentinel-2A/B Level-2A imagery (10 m spatial resolution) was used solely for complementary spatial inspection and qualitative comparison of vegetation patterns and was not included in the quantitative NDVI time-series analysis. All Landsat data were processed using surface reflectance products to maintain radiometric consistency prior to temporal aggregation.

2.3.1 NDVI calculation

Vegetation condition was quantified using the Normalized Difference Vegetation Index (NDVI), calculated as:

$$NDVI = \frac{NIR - Red}{NIR + Red}$$

where NIR and Red represent surface reflectance in the near-infrared and red spectral bands, respectively. The formulation follows Tucker (1979), Zhang et al. (2003) which provides the standard peer-reviewed description of the index.

2.3.2 Pre-processing and quality control

Surface reflectance products were used to minimize atmospheric effects. Cloud- and shadow-contaminated pixels were excluded using Quality Assessment (QA) flags provided within Landsat Surface Reflectance and Sentinel-2 Level-2A datasets. Pixels flagged as cloud, cirrus, or cloud shadow were removed prior to compositing.

Monthly mean NDVI values were calculated using cloud-free observations only. For multi-sensor integration, NDVI values were aggregated at monthly intervals and spatially averaged across the study area to ensure temporal continuity and reduce noise associated with individual acquisitions.

2.3.3 Temporal metrics

The following vegetation metrics were derived:

- Monthly mean NDVI (2015–2023)
- Annual mean NDVI
- Spring peak NDVI (April–May composite)
- Coefficient of variation (CV) to quantify interannual variability

Monthly deviations were calculated relative to the 2015–2023 multi-year baseline to detect anomalous vegetation conditions.

2.3.4 Trend analysis

To evaluate monotonic trends in NDVI, the Seasonal Mann–Kendall (SMK) test was applied to monthly NDVI values for the period 2015–2023. The SMK implementation incorporated correction for first-order serial autocorrelation following Hamed (2008), which adjusts the variance of the test statistic to account for temporal dependence between adjacent observations. This correction reduces the risk of inflated significance levels in ecological time series affected by serial correlation (Hirsch et al., 1982; Yue and Wang, 2004; Hamed, 2008).

Trend magnitude was estimated using the Theil–Sen median slope estimator, which provides a robust, non-parametric estimate of change that is resistant to outliers and non-normal distributions. Linear regression lines shown in figures are presented for visualization purposes only; statistical inference is based exclusively on the SMK test and Theil–Sen slope estimates.

Trend analyses were performed separately for:

- Monthly NDVI across the full time series (months treated as seasonal units),
- Annual mean NDVI,
- Spring peak NDVI (April–May composite).

2.3.5 Field–satellite correspondence (2018)

To assess the degree of agreement between spectral vegetation signals and ground-based productivity estimates, peak NDVI

values from 2018 were compared with field-measured total biomass and vegetation cover collected during the same growing season. This analysis evaluates correspondence rather than formal validation, recognizing that NDVI represents total green biomass and does not distinguish between palatable and grazing-resistant species (Zhumanova et al., 2018; Pettorelli et al., 2005).

2.4 Experimental design for grazing intensity

To evaluate the effectiveness of alternative grazing strategies under degraded foothill conditions, a controlled comparative field experiment was established during the 2018 growing season. The experimental design contrasted continuous extensive grazing with managed rotational grazing, following adaptive rangeland management principles (Derner et al., 2022; Teague et al., 2013).

2.4.1 Grazing systems

Two grazing treatments were implemented:

(1) Extensive grazing (control):

This treatment reflected the prevailing local management practice characterized by continuous, season-long grazing without regulated stocking density or scheduled rest periods. Mixed livestock herds consisting primarily of sheep (*Ovis aries* L.) and goats (*Capra hircus* L.), with occasional cattle (*Bos taurus* L.), grazed freely across unfenced pasture areas. Grazing pressure was spatially uneven, particularly concentrated near watering points.

(2) Intensive (rotational) grazing:

In the managed treatment, livestock were rotated among fenced paddocks with defined grazing and rest cycles. Each paddock was grazed for a short duration followed by a 25–30 day rest period to allow vegetation recovery. Paddock size and stocking density were determined based on calculated forage availability and Feed Unit (FU) requirements per livestock unit. This design aimed to synchronize animal demand with seasonal forage production.

2.4.2 Experimental layout and sampling

Control and rotational paddocks were selected within comparable slope positions, soil types (typical serozems), and elevation ranges to minimize terrain-induced variability. Each treatment included replicated sampling plots ($n \geq 4$ per paddock). At peak biomass, vegetation was harvested from 1 m² quadrats to quantify:

- Total aboveground biomass (kg ha^{−1})

- Edible biomass fraction (kg ha^{-1})
- Vegetation height (cm)
- Species composition and relative cover

Residual biomass at the end of the grazing season was used as an indicator of ecosystem recovery capacity. Special attention was given to key forage species such as *Poa bulbosa* L. (a perennial grass with high early-season palatability) and *Carex pachystylis* J.Gay (a sedge species contributing to spring forage), whose regeneration rates were monitored across treatments.

2.4.3 Evaluation metrics

Treatment effectiveness was evaluated using mean residual biomass, edible biomass proportion, regeneration rate of dominant forage species, and vegetation height. Differences between grazing systems were tested using independent-samples *t*-tests ($p < 0.05$). For proportional data (edible biomass/total biomass), comparisons were performed using appropriate tests for proportions. Error metrics are reported as standard error (SE) with corresponding sample sizes (n).

2.4.4 Methodological considerations

Because vegetation greenness measured by NDVI does not directly distinguish between palatable and unpalatable species, field-based species composition and biomass partitioning were incorporated to assess functional forage quality. This combined approach reduces the risk of overestimating ecosystem recovery based solely on spectral vegetation indices (Zhumanova et al., 2018; Pettrelli et al., 2005).

2.5 Statistical Analysis

All statistical analyses were conducted using standard statistical software. Descriptive statistics are presented as mean $\pm$ standard error (SE), and sample sizes (n) are explicitly reported for each comparison.

2.5.1 Biomass and forage quality comparisons

Differences in total aboveground biomass among the three benchmark years (1969, 1988, and 2018) were evaluated using one-way analysis of variance (ANOVA). Prior to analysis, assumptions of normality and homogeneity of variance were tested using the Shapiro–Wilk and Levene tests, respectively. Where ANOVA indicated significant differences ($p < 0.05$), Tukey's HSD *post-hoc* comparisons were performed to identify pairwise contrasts.

For the grazing experiment (extensive vs. rotational systems), differences in:

- total biomass (t ha^{-1}),
- edible biomass (t ha^{-1}),

- vegetation height (cm),
- and vegetation cover (%)

were tested using independent-samples *t*-tests when assumptions were met. Where variance homogeneity was violated, Welch's correction was applied.

Because edible biomass proportion (edible biomass/total biomass) represents a bounded ratio variable (0–1), differences between grazing systems were evaluated using independent-samples *t*-tests after arcsine square-root transformation to stabilize variance. Back-transformed means are presented for interpretation.

2.5.2 NDVI time-series analysis

Monotonic trends in NDVI (2015–2023) were evaluated using the Seasonal Mann–Kendall (SMK) test following the seasonal framework described by Hirsch et al. (1982) and applied to NDVI data by De Beurs and Henebry (2004). Calendar months were treated as independent seasonal strata (i.e., all January values were compared across years, all February values across years, etc.) to account for phenological variability. The test statistic was aggregated across months to evaluate the overall monotonic trend. Serial dependence between adjacent months was assessed using lag-1 autocorrelation, and variance correction was applied following Hamed (2008). Analyses were implemented in Python using the pymannkendall package with a seasonal period of 12 months.

Trend magnitude was estimated using the Theil–Sen median slope estimator, which provides a robust non-parametric measure resistant to extreme values.

Trend analyses were performed for:

- Monthly NDVI (months treated as seasons),
- Annual mean NDVI,
- Spring peak NDVI (April–May composite).

Linear regression lines shown in figures are provided for visualization only; statistical significance is based exclusively on the SMK test.

2.5.3 Field–NDVI correspondence analysis

To assess correspondence between spectral greenness and ground-based productivity, peak-season NDVI values for 2018 were correlated with field-measured total biomass and vegetation cover using Pearson correlation analysis. Correlation coefficients (r), 95% confidence intervals, and associated p -values were calculated.

2.5.4 Significance threshold

For all statistical tests, statistical significance was accepted at $p < 0.05$.

3 Results

3.1 Long-term geobotanical degradation trends (1969–2018)

The retrospective analysis of archival and modern geobotanical surveys indicates substantial structural changes in foothill pastures of the Akhangaran district over the past five decades. Although observations are limited to three benchmark years (1969, 1988, and 2018), the magnitude and consistency of shifts in biomass and species composition suggest a long-term degradation trajectory rather than short-term fluctuation. Long-term geobotanical monitoring in the foothill (adyr) rangelands of the Akhangaron district reveals a significant decline in ecosystem productivity over the 50-year period. Compared to the 1969 baseline, pasture biomass and forage value decreased substantially by 2018, accompanied by shifts in species composition (Table 1). This reduction is primarily attributed to combined anthropogenic pressures and changing climatic conditions.

3.1.1 Biomass dynamics

Total aboveground biomass declined from $6.0 \pm 0.4 \text{ t ha}^{-1}$ (mean $\pm$ SE; $n = 4$) in 1969 to $4.8 \pm 0.5 \text{ t ha}^{-1}$ in 1988 and further to $3.2 \pm 0.3 \text{ t ha}^{-1}$ in 2018. Compared to the 1969 baseline, biomass decreased by approximately 46.7% by 2018. One-way ANOVA indicated statistically significant differences among survey years ($p < 0.05$).

While climatic variability may partly explain interannual productivity differences, available meteorological records indicate no extreme drought anomaly uniquely characterizing 2018 relative to historical variability. Therefore, the magnitude of biomass decline likely reflects cumulative grazing pressure combined with episodic climatic stress (Mirzabaev et al., 2016; Kerven et al., 2021).

3.1.2 Forage quality and palatability shifts

Beyond total biomass reduction, substantial qualitative changes were observed in plant community composition. In 1969, the pasture was dominated by high-value ephemeral and ephemeroid species such as *Poa bulbosa* L. and *Carex pachystylis* J.Gay, which are characterized by high early-season palatability and digestibility. By 1988, mixed dominance included species such as *Taeniatherum crinitum* (L.) Nevski, indicating transitional degradation.

By 2018, dominance had shifted toward genera such as *Cousinia*, *Centaurea*, and *Bromus*, which include species often considered grazing-resistant or less palatable under intensive grazing regimes (Zhumanova et al., 2018; Hoppe et al., 2016). It is important to distinguish between “inedible” and “unpalatable”: certain species may be physiologically edible but avoided by livestock due to structural defenses or reduced nutritive value. Such compositional changes alter forage accessibility and livestock intake efficiency without necessarily producing proportional changes in total biomass (Zhumanova et al., 2018; Tomaszewska et al., 2020; De Beurs et al., 2018).

3.1.3 Feed unit decline

The nutritional value of the pasture, expressed in Feed Units (FU ha^{-1}), decreased by approximately 20% between 1969 and 2018. This decline reflects not only reduced biomass but also the transition from palatable perennial grasses and sedges to lower-quality forbs. Consequently, maintaining equivalent livestock numbers under current conditions would require expansion of grazing area or increased stocking pressure on remaining productive patches.

3.2 Vegetation dynamics and NDVI time-series (2015–2023)

To provide an independent assessment of ground-based degradation trends, we extended the NDVI analysis to cover the full 2015–2023 period using Landsat 7/8/9 (30 m) and Sentinel-2 (10 m) imagery. Extending the time series improves robustness in detecting interannual variability and climatic oscillation effects, which are pronounced in Central Asia (Zhumanova et al., 2018; Tomaszewska et al., 2020). Seasonal NDVI dynamics are presented in Figure 2.

3.2.1 Trend detection

Seasonal Mann–Kendall analysis across all months (2015–2023) indicated no statistically significant monotonic trend in annual mean NDVI ($p = 0.78$). The Theil–Sen slope for the full monthly time series was close to zero (-2.9×10^{-5} NDVI units yr^{-1}), suggesting overall stability of mean vegetation greenness during the study period.

For spring peak NDVI (April–May composite), the Theil–Sen slope was negative (-2.42×10^{-3} NDVI units yr^{-1}); however, this trend was not statistically significant ($p = 0.92$). Although the upper envelope of spring NDVI values showed a slight downward tendency, the observed variability falls within the range of interannual climatic fluctuations.

3.2.2 Spring peak dynamics

Peak NDVI values, typically occurring in April–May and associated with ephemeral vegetation flush, exhibited interannual variability with a weak negative tendency over the 2015–2023 period. Given that ephemeral grasses (*Poa bulbosa* L.) dominate early-season forage production, fluctuations in peak NDVI may influence palatable biomass availability; however, the absence of statistical significance suggests that short-term climatic variability likely contributes substantially to these dynamics.

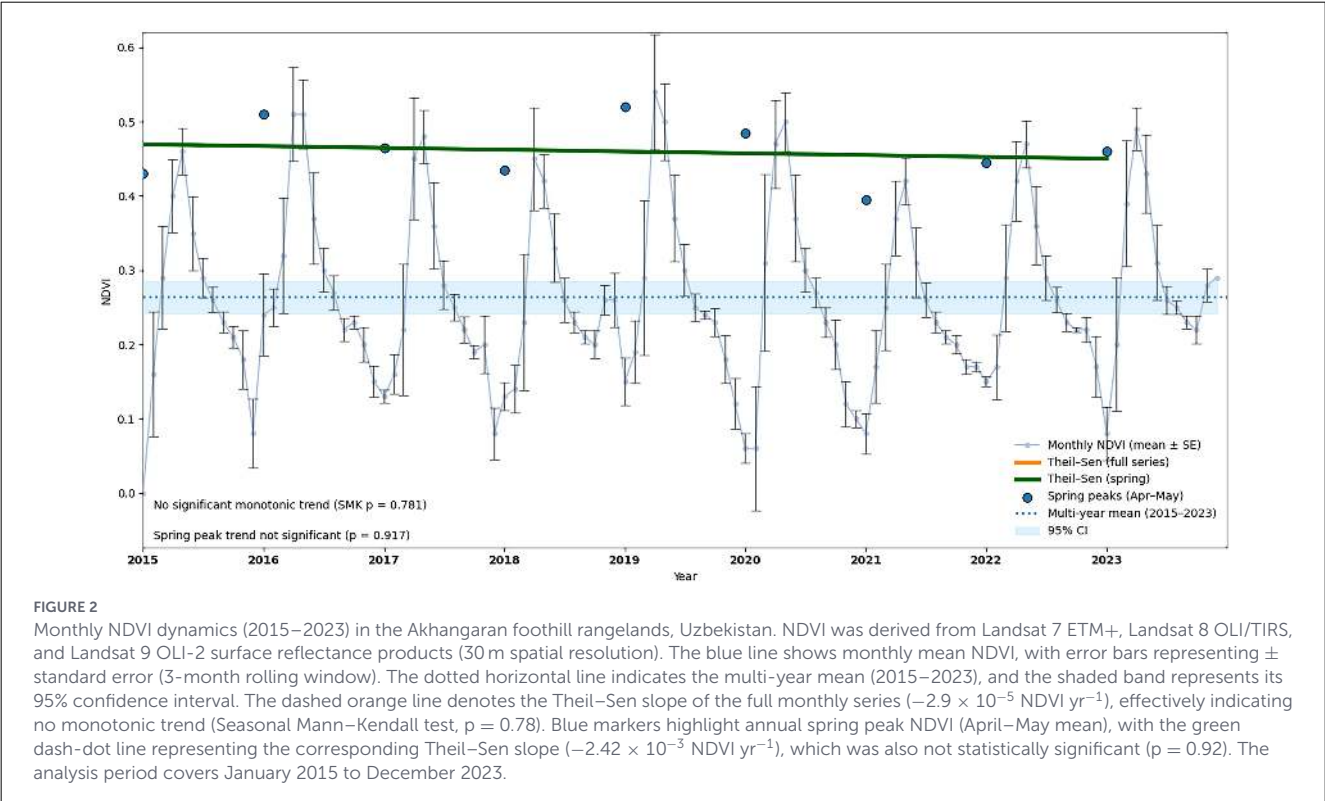
3.2.3 Seasonal recovery capacity

However, post-2020 years exhibited several months with NDVI values below the multi-year mean. While this pattern may reflect reduced soil moisture retention or grazing pressure, the lack

TABLE 1 Long-term changes in pasture biomass, forage value, and dominant species composition (1969–2018).

Year	Total biomass (t ha ⁻¹)	Feed units (FU ha ⁻¹)	Dominant species (Ecological group)	Relative change in total biomass (%)
1969 (Baseline)	6.0 ± 0.4 (n = 4)	4.5	<i>Poa bulbosa</i> L.; <i>Carex pachystylis</i> J.Gay (Ephemerals/Ephemerooids)	—
1988	4.8 ± 0.5 (n = 4)	3.9	<i>Poa bulbosa</i> L.; <i>Taeniatherum crinitum</i> (L.) Nevski (Transitional mixed community)	−20.0
2018 (Modern)	3.2 ± 0.3 (n = 4)	3.6	<i>Cousinia</i> spp.; <i>Centaurea</i> spp.; <i>Bromus</i> spp. (Grazing-resistant forbs)	−46.7

Values represent mean ± standard error (SE); n = 4 per survey year. Aboveground biomass is expressed in metric tons per hectare (t ha⁻¹). Feed Units (FU ha⁻¹) were calculated using species-specific forage coefficients derived from regional rangeland evaluation tables (Bykov, 1978). Relative change (%) was calculated against the 1969 baseline. Differences among years were tested using one-way ANOVA (p < 0.05).



of a significant monotonic trend indicates that these deviations represent episodic variability rather than a consistent directional decline (Tomaszewska et al., 2020; Kerven et al., 2021).

3.2.4 NDVI–Field Correspondence (2018 overlap)

To assess correspondence between satellite-derived NDVI and field-based measurements, peak NDVI values for 2018 were compared with field-measured total biomass from the 2018 survey. The temporal coincidence between relatively low NDVI maxima and the documented long-term biomass decline suggests consistency between spectral greenness patterns and ground observations. However, NDVI reflects total photosynthetically active biomass and does not distinguish between palatable and unpalatable species; therefore, remote sensing results should be

interpreted alongside species composition data (Zhumanova et al., 2018; Pettorelli et al., 2005).

3.3 Comparative effectiveness of grazing systems

The rotational (intensive) grazing system significantly improved pasture structural and productivity indicators compared to the continuous (extensive) grazing system.

3.3.1 Experimental design clarification

Control plots were selected in immediately adjacent areas with comparable slope, soil type (typical serozem), and initial

vegetation composition to minimize confounding terrain effects. Each treatment was replicated four times ($n = 4$ per system). Error values reported represent standard error (SE).

3.3.2 Biomass response

Total aboveground biomass under extensive grazing averaged $3.20 \pm 0.25 \text{ t ha}^{-1}$, whereas intensively managed paddocks produced $3.85 \pm 0.28 \text{ t ha}^{-1}$, corresponding to a 20.3% increase.

Edible biomass showed an even greater response: $2.10 \pm 0.18 \text{ t ha}^{-1}$ under continuous grazing vs. $2.95 \pm 0.22 \text{ t ha}^{-1}$ under rotational management (+40.5%). This indicates that the benefit of rotational grazing is not merely increased total biomass, but a disproportionately larger increase in palatable forage.

The proportion of edible biomass relative to total biomass was calculated for each plot and compared between grazing systems. Rotational grazing exhibited a significantly higher edible biomass ratio (mean $\pm$ SE: 0.77 ± 0.04) than continuous grazing (0.66 ± 0.05 ; independent-samples t -test, $p < 0.05$). Ninety-five percent confidence intervals did not overlap, indicating a statistically meaningful difference in forage quality composition between management systems.

3.3.3 Vegetation structure

Vegetation cover increased from 45% to 50% under continuous grazing to 60%–65% under rotational grazing. Mean plant height increased from 12.5 to 18.2 cm (+45.6%).

These structural improvements are consistent with reduced trampling intensity and enhanced regrowth during the 25–30 day rest period. Periodic defoliation followed by recovery is known to stimulate tillering and carbohydrate reserve accumulation in perennial grasses (Derner et al., 2022; Teague et al., 2013).

3.3.4 Soil surface condition

Qualitative field assessment indicated that continuously grazed plots exhibited higher surface compaction and reduced litter cover, whereas rotational paddocks maintained moderate compaction levels. Reduced compaction likely enhances infiltration and root penetration, indirectly supporting biomass accumulation.

Soil surface condition was assessed using a categorical field-based evaluation of surface hardness, visible trampling intensity, and litter cover. Plots were classified as highly compacted or moderately compacted based on repeated field observations during peak grazing season.

Although the magnitude of improvement is clear, it is important to note that the experiment was conducted during a single growing season (2023). Therefore, results demonstrate short-term recovery potential rather than long-term ecosystem restoration. Future multi-year monitoring would be required to confirm persistence of these gains.

Moreover, while NDVI trends (Section 3.2) suggest broader landscape-scale decline, the experimental results demonstrate that

management intervention can partially offset degradation at the paddock scale.

4 Discussion

4.1 Anthropogenic drivers of long-term degradation

The long-term decline in biomass (−46%) and feed value (−20%) documented between 1969 and 2018 indicates substantial structural transformation of foothill pasture ecosystems in eastern Uzbekistan. Although climatic variability contributes to interannual productivity fluctuations, the magnitude and compositional nature of the observed changes suggest that grazing pressure has been the dominant driver of degradation.

Recent regional analyses across the Tian Shan and broader Central Asian rangelands indicate that post-Soviet land-use restructuring significantly altered livestock mobility patterns (Robinson, 2016; Kerven et al., 2011, 2021). During the Soviet period, rotational transhumance systems redistributed grazing pressure seasonally, allowing partial recovery of lower-elevation pastures. In contrast, post-1991 fragmentation of collective farms led to reduced herd mobility and concentration of livestock near settlements and water points, producing spatially uneven grazing intensity.

This pattern is consistent with the well-documented “piosphere effect,” whereby vegetation degradation radiates outward from livestock concentration zones due to repeated selective defoliation and trampling (Briske et al., 2008; Teague et al., 2013). In the Akhangaran foothills, the decline of highly palatable ephemeral species such as *Poa bulbosa* L. and *Carex pachystylis* J.Gay and their replacement by grazing-resistant forbs (e.g., *Cousinia* spp., *Centaurea* spp.) reflect this process.

Importantly, species replacement has implications not only for biomass quantity but also for forage quality. NDVI trends (2015–2023) indicate a weak negative tendency in spring peak values; however, this trend was not statistically significant. While ephemeral grasses dominate early-season productivity, observed NDVI fluctuations likely reflect a combination of grazing pressure and interannual climatic variability. However, NDVI integrates total green biomass and does not differentiate between palatable and unpalatable species (Zhumanova et al., 2018; Pettorelli et al., 2005). Therefore, shifts toward structurally green but nutritionally inferior vegetation may partially mask functional degradation in remote sensing signals.

Climatic influences must also be considered. Central Asia exhibits pronounced interannual variability driven by large-scale atmospheric oscillations affecting precipitation and snowmelt dynamics (Zhumanova et al., 2018; Tomaszewska et al., 2020; De Beurs et al., 2018). While no extreme anomaly uniquely explains the 2018 biomass reduction, cumulative grazing pressure likely reduced vegetation resilience, making the system more sensitive to episodic drought.

Thus, degradation in the foothill adyr zone appears to result from an interaction between reduced livestock mobility, localized overgrazing, and climatic variability. The convergence

of archival geobotanical data and recent NDVI patterns supports the interpretation that long-term anthropogenic pressure has contributed substantially to degradation, although climatic variability remains an important interacting factor.

4.1.1 Interpretation and limitations

Although the dataset includes only three temporal benchmarks, the magnitude of change in both biomass and species composition supports the conclusion of progressive degradation in the foothill adyr zone. However, given the discontinuous nature of archival data, these findings are interpreted as indicative of long-term structural change rather than evidence of linear annual decline. Additional remote sensing analysis (Section 3.2) provides complementary temporal context for recent vegetation dynamics.

4.2 Synergy between ground data and remote sensing

A central contribution of this study lies in the integration of archival geobotanical surveys (1969–2018) with extended NDVI time-series analysis (2015–2023). This combined approach allows interpretation of vegetation dynamics across both decadal and interannual scales, thereby addressing limitations of discontinuous field data.

4.2.1 NDVI against field data (2018 overlap)

To evaluate the reliability of NDVI as a proxy for vegetation productivity, peak growing-season NDVI values for 2018 were compared with ground-measured total biomass and edible biomass recorded during the 2018 field survey. The correspondence between reduced peak NDVI and documented 46% biomass decline supports the use of NDVI as an indicator of overall vegetation productivity in foothill adyr systems. However, NDVI reflects total photosynthetically active biomass and does not discriminate between palatable and grazing-resistant species (Zhumanova et al., 2018; Pettorelli et al., 2005; Huang et al., 2021). Therefore, remote sensing must be interpreted alongside species composition data to avoid overestimating functional forage availability.

4.2.2 Spring peak dynamics and forage accumulation

In ephemeral–ephemeroid ecosystems, the April–May period represents the primary annual accumulation of forage biomass. The observed interannual variability in spring NDVI peaks (2015–2023), evaluated using the Seasonal Mann–Kendall test, did not indicate a statistically significant monotonic decline but suggests variability in early-season vegetation vigor. Because ephemeral grasses such as *Poa bulbosa* L. dominate spring production, declining peak NDVI values likely reflect reduced productivity of palatable forage species rather than only phenological variability.

4.2.3 Climate variability and snowmelt context

Central Asian rangelands are strongly influenced by interannual precipitation variability and snowmelt dynamics (Zhumanova et al., 2018; Tomaszewska et al., 2020). In foothill zones of the Western Tian Shan, snow accumulation during winter contributes to early spring soil moisture. Variability in winter precipitation may therefore influence peak NDVI magnitude independently of grazing pressure. However, the repeated occurrence of lower-than-average spring peaks in several post-2020 years suggests potential interaction between grazing intensity and climatic variability. Instead, cumulative grazing pressure may reduce vegetation resilience, making the system more sensitive to episodic drought.

4.2.4 Spatial degradation patterns

Field observations indicated intensified degradation near settlements and water sources, consistent with the “piosphere” pattern of grazing concentration (Briske et al., 2008). Similar spatial heterogeneity in grazing intensity has been documented in mountain rangelands using high-resolution remote sensing (Tomaszewska and Henebry, 2021). While the present study did not incorporate a full DEM-based terrain correction, the consistency between field observations and NDVI anomalies suggests that grazing intensity gradients contribute substantially to vegetation decline.

4.2.5 Implications for monitoring

The integration of ground-based surveys with medium- and high-resolution satellite data demonstrates the potential for operational pasture monitoring in Uzbekistan. NDVI-based monitoring can provide near-real-time assessment of vegetation status, enabling adaptive livestock movement strategies aligned with forage availability (Derner et al., 2022). However, effective application requires coupling spectral indicators with periodic field validation to account for compositional shifts and palatability changes.

4.2.6 Methodological limitations

While NDVI provides a consistent proxy for vegetation greenness and density, it does not directly distinguish between palatable and unpalatable species. Therefore, remote sensing results were interpreted in conjunction with species composition data from field surveys to avoid over-attribution of spectral changes to grazing effects alone.

4.3. Effectiveness of intensive grazing as a restoration strategy

The controlled field experiment indicates that rotational (intensive) grazing enhanced short-term pasture productivity

TABLE 2 Comparative effectiveness of grazing management systems on pasture indicators (2023 field experiment, Akhangaran district).

Indicator	Extensive grazing (Control) (n=4)	Intensive grazing (Rotational) (n=4)	Improvement (%)
Total biomass (t ha ⁻¹)	3.20 ± 0.25	3.85 ± 0.28	+20.3
Edible biomass (t ha ⁻¹)	2.10 ± 0.18	2.95 ± 0.22	+40.5
Vegetation cover (%)	45–50	60–65	+15 points
Mean plant height (cm)	12.5 ± 1.3	18.2 ± 1.6	+45.6
Soil surface condition	Highly compacted	Moderately compacted	—

Values represent mean ± standard error (SE); n = 4 replicate plots per treatment. Edible biomass refers to aboveground biomass of species classified as palatable to small ruminants (*Ovis aries* L., *Capra hircus* L.) based on regional forage evaluation standards (Bykov, 1978). Differences between grazing systems were tested using independent-samples *t*-tests ($p < 0.05$). The rotational treatment incorporated 25–30 day rest periods between grazing events.

relative to continuous grazing under degraded foothill conditions. Rotational paddocks produced approximately 20% higher total biomass and more than 40% greater edible biomass compared to extensively grazed control plots (Table 2). These differences were statistically significant and consistent across replicated sampling units ($n = 4$ per treatment).

Importantly, the benefit of rotational grazing was not limited to total biomass accumulation. The disproportionate increase in edible biomass suggests that rest periods enhanced recovery of palatable ephemeral and ephemeroïd species such as *Poa bulbosa* L. and *Carex pachystylis* J.Gay. This observation is consistent with ecological theory indicating that repeated defoliation without recovery reduces carbohydrate reserves, root biomass, and plant persistence (Teague et al., 2013; Derner et al., 2022; Derner and Augustine, 2016).

The 25–30 day rest period implemented in this study allowed plants to partially restore photosynthetic tissue and root energy reserves, thereby improving regrowth capacity. Reduced trampling intensity and lower soil surface compaction in rotational paddocks likely contributed to improved infiltration and microhabitat conditions.

However, caution is warranted in interpreting these findings as evidence of full ecosystem restoration. The experiment was conducted during a single growing season, and long-term vegetation trajectory under sustained rotational management remains to be evaluated. Furthermore, NDVI analysis (Section 3.2) indicates broader landscape-scale variability driven by both grazing intensity and climatic oscillations. Therefore, rotational grazing should be viewed as a management strategy that enhances short-term resilience rather than a guaranteed reversal of long-term ecosystem degradation.

At the socio-economic level, these findings challenge the perception that intensive grazing management necessarily reduces

herd size or imposes prohibitive labor costs. Instead, rotational grazing may represent a form of ecological intensification—improving forage productivity per unit area while maintaining livestock numbers—an approach increasingly advocated for sustainable food systems in drylands (Mirzabaev et al., 2016).

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5 Conclusion

This study provides a multi-decadal assessment of vegetation change in foothill (adyr) pastures of eastern Uzbekistan by integrating archival (1969, 1988) and recent (2018) geobotanical surveys with satellite-derived NDVI time-series analysis (2015–2023). The combined evidence supports three principal conclusions.

First, substantial structural changes have occurred in foothill pasture ecosystems over the past five decades. The 46% decline in total biomass and 20% reduction in feed value between 1969 and 2018 indicate long-term degradation, accompanied by compositional shifts from highly palatable ephemeral grasses such as *Poa bulbosa* L. and *Carex pachystylis* J.Gay toward more grazing-resistant or less palatable species. While climatic variability contributes to interannual fluctuations, the magnitude and persistence of these changes suggest that altered grazing management and reduced livestock mobility have played a central role.

Second, the integration of field-based biomass data with extended NDVI time series (2015–2023) demonstrates the value of combining ground observations with remote sensing in data-scarce dryland systems. Seasonal Mann–Kendall analysis revealed declining spring peak NDVI values, consistent with reduced early-season vegetation vigor. However, NDVI reflects total greenness rather than forage quality; therefore, remote sensing should complement, rather than replace, periodic field validation.

Third, the experimental comparison of grazing systems indicates that rotational (intensive) management can enhance short-term pasture recovery under degraded conditions. Rotational paddocks showed significantly higher total and edible biomass relative to continuously grazed controls, suggesting improved vegetation resilience when rest periods are incorporated. Nevertheless, these findings represent short-term responses, and long-term sustainability under rotational management requires further monitoring.

From a policy perspective, improving pasture management efficiency may be as important as regulating livestock numbers. Adaptive grazing systems supported by satellite-based vegetation monitoring could provide a scalable framework for sustainable livestock production in foothill drylands. Future research should aim to disentangle climatic variability effects from anthropogenic drivers and to evaluate multi-year ecosystem responses to rotational grazing.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

RT: Conceptualization, Data curation, Investigation, Methodology, Writing – review & editing. KK: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. RS: Data curation, Investigation, Validation, Writing – review & editing. BI: Data curation, Investigation, Writing – review & editing. OD: Investigation, Resources, Writing – review & editing. SI: Conceptualization, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing. HT: Data curation, Formal analysis, Validation, Writing – review & editing. MT: Data curation, Visualization, Writing – review & editing. KT: Investigation, Software, Validation, Writing – review & editing. SS: Data curation, Investigation, Writing – review & editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was used in the creation of this manuscript. Generative AI was used to assist with language editing, structural refinement, and clarity of the manuscript. The author(s) take full responsibility for the content, data interpretation, and conclusions presented in this work. The use of generative AI did not influence the study design, data collection, data analysis, or scientific conclusions.

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