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Research Article

Effects of grazing intensity and topography on steppe vegetation and soil properties of Mt. Aragats, Armenia

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Abstract

Steppes are large ecosystems and diverse in plant composition and soils-climatic conditions. Steppes have been used for pastoralism for centuries. Few studies have considered the interactive effects of grazing intensity and topography on steppe productivity, plant composition and soil properties. The study was conducted at no grazed, moderately and free grazed sites of two steppe areas located at 1500-1800 m of the south-east slope of Mt. Aragats. Slope exposition, slope inclination, mean temperature and precipitation for steppe areas were also assessed. Aboveground biomass and plant and soil chemical analysis were measured by the international standard methods, and influencing factors were extracted by RDA. The results showed that the steppe aboveground biomass decreased significantly in line with the grazing intensity increasing (55-70%), irrespective of soil type as was shown by RDA analysis. The vegetation height responds to grazing intensity irrespective of topography and environmental factors. The nitrogen content in plants was mainly affected by grazing and increased in free grazed sites, while it had no effect on phosphorus and potassium content. The grazing intensity, the topography and environmental factors did not affect soil physicochemical properties. Only the litter content was observed to be higher at moderately grazed sites on chernozem like soils. Comparative analysis of the two steppe areas highlighted notable shifts in productivity and key soil properties, primarily driven by grazing pressure rather than environmental conditions. Therefore, effective conservation strategies and site-specific management approaches that take into account the ecological context and ecological resilience are recommended for sustainable pasture management under climate change and anthropogenic pressures.

Keywords: aboveground biomass; grazing; plant nutrients; soil physicochemical properties; steppes

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Introduction

Steppes are a type of rangeland that cover approximately 6% of terrestrial ecosystems (Wesche *et al.*, 2016). Steppes occur on open plains and in regions isolated by surrounding mountains, and they are distributed across various continents, including Eurasia, North America, and South America. These ecosystems differ by

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rainfall levels and plant composition, giving rise to distinct types such as temperate, subtropical, desert, alpine, and forest steppes (Polyakova *et al.,* 2016; Török *et al.*, 2018).

These ecologically important ecosystems are highly sensitive to climate change, environmental variability, and human activities (Chen *et al.*, 2014; Li *et al.*, 2015; Kudrevatykh *et al.*, 2023). They respond to such type of pressures through changes in vegetation structure, alterations in soil characteristics (Reszkowska *et al.*, 2011), and disruptions to nutrient cycling within the soil–plant system. These shifts can impair key hydrological and ecological processes, ultimately reducing the ecosystem's capacity for natural recovery. Without effective management and targeted conservation efforts, such degradation may lead to long-lasting or irreversible ecological and socio-economic consequences (McNew *et al.,* 2023).

Steppes have been used for pastoralism for centuries. The negative impacts of grazing on plant biomass productivity have been well documented in arid ecosystems (Herrero-Jáuregui and Oesterheld, 2018; Bilgili, 2023), montane meadow-steppes (Vernon *et al.,* 2022), and savannas (Melak *et al.,* 2019; Gebremedhn *et al.,* 2023). Grazing can degrade soils by increasing their bulk density (Abdalla *et al.,* 2018), reducing the availability of biogenic elements (Parissi *et al.,* 2014), and accelerating erosion processes (Köbel *et al.,* 2021). However, evidence also highlights potential positive effects of grazing. Studies show that grazing can stimulate the growth of perennial forage species, increase plant height, and enhance biomass productivity (Sanderman *et al.,* 2015). Additionally, animal urine contributes to the mineralization of plant residues and serves as a source of nitrogen, phosphorus, and carbon, enriching soil fertility (Kyriazopoulos *et al.,* 2022; Yang *et* al.*,* 2023). When properly managed, grazing can promote biological and geochemical processes that regulate nutrient cycling in the soil–plant system, thereby supporting plant productivity and overall ecosystem functioning (Deng *et al.,* 2013; Song *et al.,* 2023).

In Armenia, agricultural lands are around one million ha and steppes cover approximately 30% of its total area. They are largely mountainous and exhibit diverse microclimatic conditions. However, grazing in these areas remains largely unregulated, resulting in degradation of many near-settlement pastures manifested as vegetation loss, soil compaction, and erosion. Agriculture remains a critical sector in Armenia's economy, with increasing demand for livestock-based food products. According to the 2021-2026 Government Program of the Republic of Armenia, the livestock sector aims to increase annual meat production by over 50%, milk by 70%, and wool by nearly 100%, relying primarily on natural forage from pastures Despite the importance of sustainable grazing strategy, the effects of different grazing management practices such as fencing, moderately grazing or free grazing on steppes' ecosystems are insufficiently studied. Most research has focused on comparisons between grazed and ungrazed areas, with only a few studies exploring specific indicators such as bareness (Jones *et al.,* 2018; Navasardyan *et al.,* 2024) or species composition (Li *et al.,* 2008). There is limited understanding of how varying grazing intensities affect plant and soil parameters, particularly within heterogeneous landscapes.

This study aimed to investigate the effects of different grazing intensities, including complete grazing exclusion, on plant and soil parameters in steppe ecosystems with varying topographic and ecological features on the southeastern slope of Mt. Aragats, Armenia.

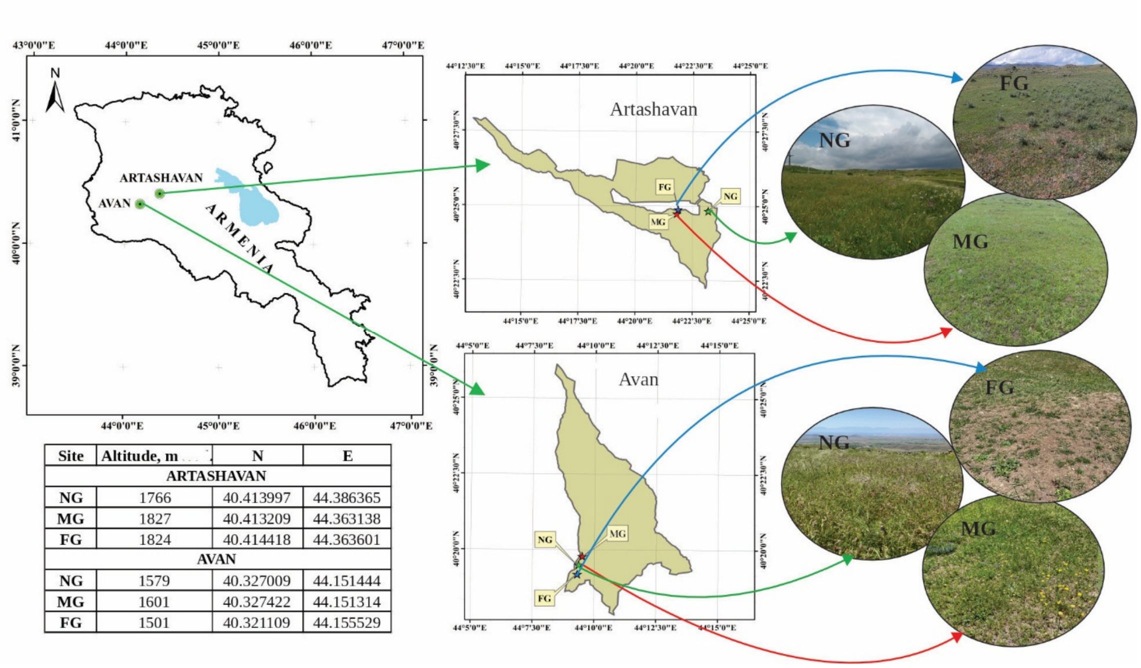
Specifically, the study addressed the following research questions: (1) How does grazing intensity influence plant and soil parameters, as well as the composition of plant functional groups? (2) Does the impact of grazing vary depending on the geographic and climatic conditions of the steppe ecosystems? (3) What are the primary drivers of variability in plant and soil parameters, as well in plant functional group composition, under conditions of complete grazing exclusion?

The results of this study will improve understanding of vegetation and soil dynamics under grazing pressure in diverse steppe environments. These insights will also inform models of future ecosystem trajectories under climate change scenarios and support the development of management recommendations aimed at mitigating and preventing degradation.

Materials and Methods

Description of the study areas and sites

The study was conducted in the mountain steppe zone located on the southeastern slope of Mt. Aragats, Armenia (Figure 1). Two steppe areas were selected for investigation during the period 2022–2024. These areas are situated within the pastures of the Artashavan (ART) and Avan (AVN) rural communities, located in Aragatsotn Marz. Both communities have a long-standing tradition of extensive livestock farming, covering areas of approximately 2,620 to 3,900 ha (80-90% of the total territory), and support around 5,000 heads of large and small ruminants. The primary forage resources used for livestock grazing in these areas include grasses such as *Bromus* Scop., *Festuca* Tourn. ex L., *Agropyron* Gaertn., *Dactylis* L., *Poa* L.; legumes including *Medicago* L., *Trifolium* L., *Onobrychis* Mill., *Vicia* L.; and, occasionally shrubs such as *Rosa* L., *Rubus* L., *Spiraea* L., and *Hippophae* L.



Site	Altitude, m	N	E
ARTASHAVAN			
NG	1766	40.413997	44.386365
MG	1827	40.413209	44.363138
FG	1824	40.414418	44.363601
AVAN			
NG	1579	40.327009	44.151444
MG	1601	40.327422	44.151314
FG	1501	40.321109	44.155529

Figure 1. Location of steppe areas and sites (NG-no grazed, MG-moderately grazed, FG-free grazed) of Avan and Artashavan communities on the southeast slope of Mt. Aragats, Armenia

The ART steppe site lies at elevations of 1700-1850 m and occupies plains and eastern slopes with gradients ranging from 10° to 30°. The predominant soil type is chernozem-like. The AVN site (1500-1600 m) is located on stony chestnut soils, primarily on the southern slopes (15°–30°), with a slight erosion.

The dominant vegetation in both areas consists of mixed grass-forb communities, including: *Aegilops cylindrica* Host., *Agropyrum trichophorum* Richt., *Bromus danthoniae* Trin., *B. fibrosus* E. Hack., *Dactylis glomerata* L., *Festuca sulcata* E. Hack. Rizh., *Hordeum crinitum* Desf., *Poa bulbosa* L., *Stipa pulcherrima* L., *Achillea micrantha* M.B., *Achillea setacea* Waldst. & Kit., *Artemisia austriaca* Jack., *Cynodon dactylon* (L.) Pers., *Eryngium giganteum* L., *Euphorbia gerardiana* Jacq., *E. marschalliana* Boiss., *Gundelia tournefortii* L., *Helichrysum plinthocalyx* Bge., *Nepeta mussinii* Spreng., *Onopordum acanthium* L., *Tanacetum chiliophyllum* (Fisch. & C.A. Mey.), *Pyrethrum myriophyllum* C.A.M., *Thymus kotschyanus* Boiss. et Hohen., and *Xeranthemum squarrosum* Boiss.

Three types of pastures were selected depending on the management of grazing: free grazed (FG), moderately grazed (MG), and no grazed (NG) types. (1) The "free grazed" site is public and the closest to settlements pastures. The FG site was 0.8 ha and 0.4 ha in ART and AVN respectively. The FG sites were used by the whole community livestock from early spring to late autumn. The plant cover comprised 33-40% and Forage utilization percentage (FUP) was 60-80%. The FUP was estimated by the Ocular estimate-by-plot method (Salem and Papachrystou, 2005). The soil horizon was 8.5-13 cm. (2) The "moderately grazed" site is one site far away (approximately 7-8 km) from the settlement. The MG site covered the same area as the FG site. Due to distance, it was grazed less intensively (3-4 months between July and October) and plant cover and composition were non-disturbed (Plant cover = 60-70%, FUP < 50%) and while the soil horizon constituted 13-20 cm. (3) The "no grazed" site comprised approximately 0.35 (AVN) and 0.6 (ART) ha in area. The site is mainly owned by citizens and grazing is absolutely excluded. The vegetation was cut in the period of peak production (mid-July) for steppe aboveground biomass assessment. The soil horizon was 26-27 cm.

Climate

According to the Köppen-Geiger climate classification, the region has a cold semi-arid climate (Bsk). The vegetation period spans from March through July. The mean annual rainfall over the 2017-2021 period (Figure 2) was 362 mm, with the high amount in March-May (Center of Hydrometeorology and Monitoring of the Ministry of Environment of RA). The mean temperature ranges in winter from +0.5 to - 4.3 °C and in summer from +15.0 to -27.7 °C, with maximum and minimum values in July and January, respectively. The climatic data obtained from the closest weather stations (10-15 km) show that the mean monthly temperature within 2022-2024 was the highest for AVN area, while the precipitation was highest for ART area. The highest temperature (9.7 °C) and the highest precipitation (829 mm) were registered in 2024 for the sites of AVN and ART, respectively and the lowest ones in 2022 were recorded for the sites of ART and AVN (6.8 °C and 416 mm). Compared with the indicators of long-term average precipitation and temperature, the study years were relatively wet and hot years.

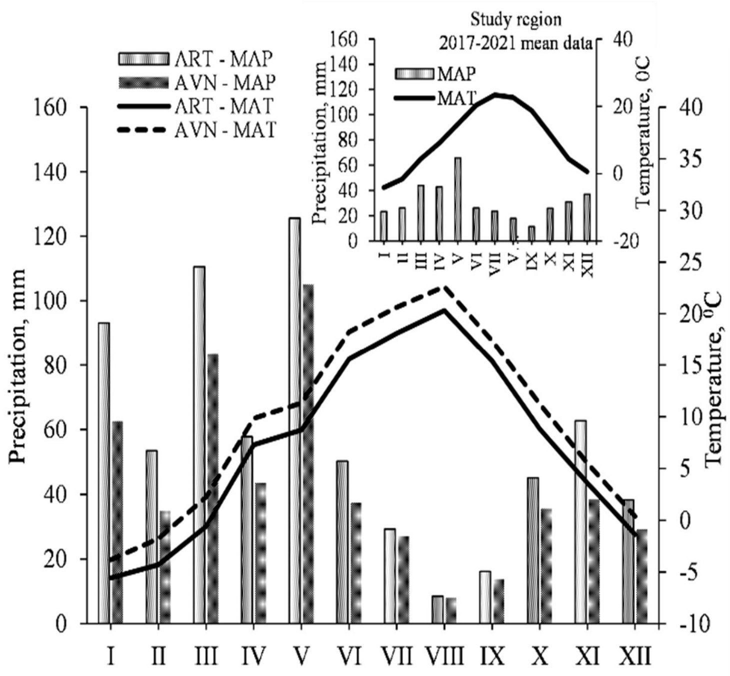


Figure 2. Mean annual precipitation (MAP, mm) and mean annual temperature (MAT, °C) during the period 2022–2024 in the Artashavan (ART) and Avan (AVN) study areas.

Plant and soil sampling design

The sampling of vegetation was conducted at the end of the growing season of 2022, 2023, and 2024 in the FG, MG and NG sites of two steppe areas. The 40 m length transect method was used across every site with two replications (i.e. 2 transects per site). The aboveground biomass (AGB) was obtained using a standard harvesting method with twenty quadrants (25 cm × 25 cm) within each site located at least 4 m apart on two transects. Three plant functional groups (grasses, legumes, and forbs) were identified from each quadrat. The AGB samples (i.e. functional groups samples) were separately oven-dried at 65 °C for 48 h and weighed. The floristic composition was measured as a percentage of the biomass retrieved from grasses, legumes and forbs. The difference among AGB of no grazed, moderately and free grazed sites was used to calculate FUP. The vegetation height was measured using a ruler, and the plant cover was determined by the Braun Blanquet method in each (25 cm x 25 cm) quarters. Three soil samples from each transect were collected using quadrats (20 cm x 20 cm). Thus, a total of 36 samples (3 replicates × 2 communities × 3 sites) were obtained for performing the soil parameters measurement. Soil samples were purged of plant residues, roots, stones, and others. Afterwards, the soil samples were air-dried, ground, crushed, sieved through a 1mm diameter sieve (ISO 11464). The fraction smaller than 1 mm was analysed in order to evaluate the following physicochemical parameters: the bulk density (ISO 11272:2017), the sandy content (ISO 3340:1976), pH (ISO 10390:2005), the litter content (FAO, 2019), the total nitrogen (ISO 11261), the total phosphorus (Truog and Meyer 1929; ISO 11263), the total potassium (ISO 7485), and $CaCO_3$ (ISO 5796:2000).

Statistical procedures

All statistical analyses were conducted by IBM SPSS Statistics 20. The two-way ANOVA was employed in order to detect the effect of steppe areas (AVN vs ART areas) and grazing intensity (NG, MG, FG sites) on vegetation productivity, height and macronutrients content, soil physical and chemical parameters, and floristic composition. The difference between mean values at the significant level of $P < 0.05$ was evaluated by Tukey's Studentized Range (HSD) test. The Redundancy analysis (RDA) (Legendre and Legendre, 2012) was conducted to show the crossed effect of topography of areas and grazing intensity on the following: 1) the vegetation aboveground biomass, height and macronutrients content; 2) the soil physical and chemical parameters, 3) the floristic composition. The grazing intensity was included in the RDA analysis as Dummy variables.

Results

The floristic composition of the steppes did not differ significantly in terms of the grass cover between the ART and AVN areas (Table 1). However, legumes were significantly more abundant ($p \leq 0.05$) in no grazed (NG) and moderately grazed (MG) sites of ART, while forbs were significantly more abundant ($p \leq 0.05$) in the same grazing intensity sites of AVN. The grazing intensity had a significant effect on legumes in both areas and on forbs specifically in ART. No significant differences in the grass cover were observed between NG and MG sites in either area. In both steppes, the lowest proportions of the grasses and legumes were recorded at the free grazed (FG) site, while the lowest forbs cover was found at NG sites.

Significant differences ($p \leq 0.05$) were detected between areas for aboveground biomass (AGB), vegetation nitrogen (VTN) and phosphorus (VTP) contents, as well as soil nitrogen (STN), potassium (STK), Ca ($CaCO_3$), litter (SL), sandy (SS) and pH. On the other hand, the vegetation height (VH) and vegetation potassium (VTK) were not significantly affected. Besides, a significant effect of grazing intensity was recorded for AGB, vegetation height (VH) and VTN content, as well as soil phosphorus (STP), STK, Ca, SS, bulk density (BD). The significant ($p \leq 0.05$) interaction between area and grazing intensity was obtained for VH, VTN and SL content (Table 2) indicating different effects of grazing intensity in the two study areas.

Table 1. Vegetation characteristics of no grazed (NG), moderately grazed (MG) and free grazed (FG) sites at Artashavan (ART) and Avan (AVN) steppes

Area/ Grazing Intensity	Plant cover (%)	Floristic composition (%)*			FUP**
		Grass	Legume	Forbs	
ART					
NG	94	40^{Aa}	32^{Aa}	$28^{A a}$	0
MG	69	33^{Aa}	20^{Ab}	47^{Ab}	50
FG	40	22^{Ab}	5^{Ac}	73^{Ac}	67
AVN					
NG	88	43^{Aa}	16^{Ba}	41^{Ba}	0
MG	61	38^{Aa}	6^{Bb}	55^{Ba}	58
FG	33	19^{Ab}	4^{Ac}	77^{Ab}	74

*Mean followed by the same lowercase letter in the row within area do not differ by the Tukey test at the 5% probability. Mean followed by the same uppercase in the row within different grazed sites of two steppe areas do not differ by the Tukey test at the 5% probability.

**FUP-Forage utilization percentage

Table 2. The probability of two-factors ANOVA (area and grazing intensity) on vegetation and soil parameters (AGB-aboveground ground biomass, VH-vegetation height, VTN-vegetation total nitrogen, VTP-vegetation total phosphorus, VTK-vegetation total potassium, STN-soil total nitrogen, STP-soil total phosphorus, STK- soil total potassium, SS-sandy, BD-bulk density, pH, SL-litter, Ca-$CaCO_3$)

Source of variation	Area	Grazing Intensity	Area/ Grazing Intensity
AGB	*	*	NS
VH	NS	*	*
VTN	*	*	*
VTP	*	NS	NS
VTK	NS	NS	NS
STN	*	NS	NS
STP	NS	*	NS
STK	*	*	NS
Ca	*	*	NS
SL	*	NS	*
S	*	*	NS
BD	NS	*	NS
pH	*	NS	NS

Notice: *significant (F Test at ($p \leq 0.05$)); NS $p > 0.05$

As far as the vegetation parameters concern, the AGB of steppes across all grazing intensities was significantly higher ($p \leq 0.05$) at ART area than that at AVN (Figure 3).

Moreover, the VTN was significantly higher at ART area and VTP at AVN area respectively (1.2 times). The AGB significantly decreased ($p \leq 0.05$) from NG to MG and to FG sites from 258 to 120 and to 75 g.m-^{2} in both areas (Table 3, Figure 3). Similarly, VH significantly decreased ($p \leq 0.05$) from NG to FG. The higher (38 cm) and the lower (6 cm) VH was recorded at NG and FG of the AVN area respectively (Table 3).

The VTN content of NG (across ART and AVN areas) was significantly lower (1.1 and 1.2 times) than that of the MG and FG sites. However, the VTN was significantly higher at the FG site compared to the MG site in AVN, while the VTN did not significantly differ between the FG and MG sites in ART (Table 3).

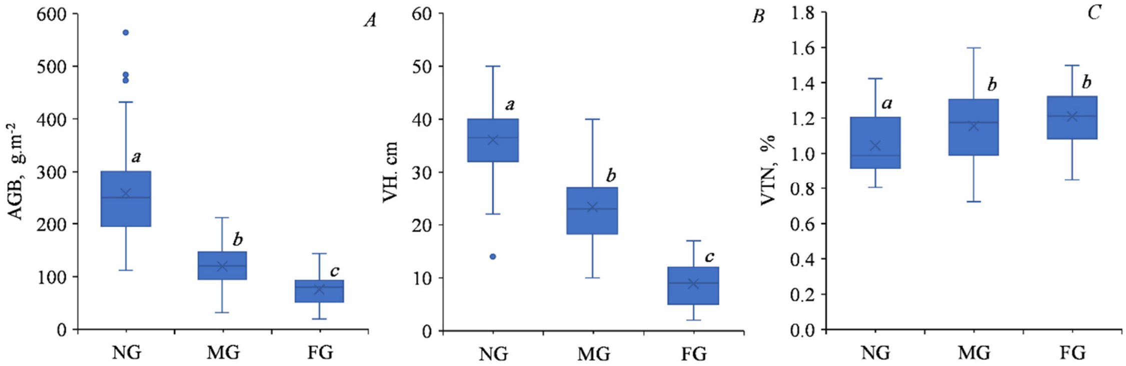


Figure 3. Productivity (AGB-aboveground biomass, $g.m^{-2}$-A), vegetation height (VH, cm-B) and total nitrogen (VTN, %-C) content in vegetation samples at no grazed (NG), moderately grazed (MG) and free grazed (FG) sites of steppes

Table 3. The area and grazing intensity interaction effect on vegetation parameters of Artashavan (ART) and Avan (AVN) steppe areas (AGB-aboveground biomass, $g.m^{-2}$, VH-vegetation height, cm, VTN-vegetation total nitrogen, %, VTP-vegetation total phosphorus, %, VTK- vegetation total potassium, %)

Parameters	**Area/Grazing Intensity**					
	ART			**AVN**		
	NG	***MG***	***FG***	***NG***	***MG***	***FG***
AGB	266^{a}	134^{b}	87^{c}	250^{a}	106^{d}	64^{f}
VH	34^{a}	23^{b}	12^{c}	38^{d}	24^{eb}	6^{f}
VTN	1.14^{a}	1.3^{b}	1.24^{b}	0.95^{c}	1.01^{d}	1.17^{a}
VTP	0.82^{a}	0.92^{b}	0.89^{ab}	1.08^{c}	1.01^{bc}	1.06^{c}
VTK	1.18^{a}	1.16^{a}	0.95^{b}	1.12^{a}	1.28^{a}	1.29^{a}

Notice: Mean followed by the same lowercase letter in the row do not differ by the Tukey test at the 5% probability.

The first and second axes (F1, F2) of ordination diagram of RDA1 (Figure 4) explain 91.1% ($p < 0.0001$) and 5.36% ($p < 0.0001$) of total variations of AGB, VH, VTN, VTP, VTK by topography and environmental conditions and grazing management.

The plant cover was the explanatory variables that best correlated with axes F1, while MAT, the aspect and the slope best correlated with axes F2. The AGB and VH are best correlated with the plant cover at the no grazed site. Besides, the VH were positively related to MAP and the AGB with altitude. All data (three-year replications) of no grazed sites at ART and AVN areas were involved in the formulation of axes F1. As for the VTN it was related to free grazed sites, while VTP and VTK were positively correlated with MAT, the aspect and FUP and the moderately grazed site.

The grazing intensity and topography of areas, the climate and the state of sites explained variations in functional groups composition (RDA 2, Figure 5). The FUP, the MAT and the aspect were significant for axes F1 and MAP, and the altitude for F2. F1 variables explained the 81.39% of variations and the 10.9% of axis F2 ($F=51$, $p < 0.0001$). Legumes and grasses are best correlated with axis F1 and the forbs with axis F2. The legumes spread at no-grazed sites and its percentage went up with the increase of altitudinal and temperature gradients.

The grasses positively correlated with moderately grazed site and the MAT, negatively correlated with the MAP and slope angle and slope exposition. The spread of forbs best correlated with FUP at free grazed sites.

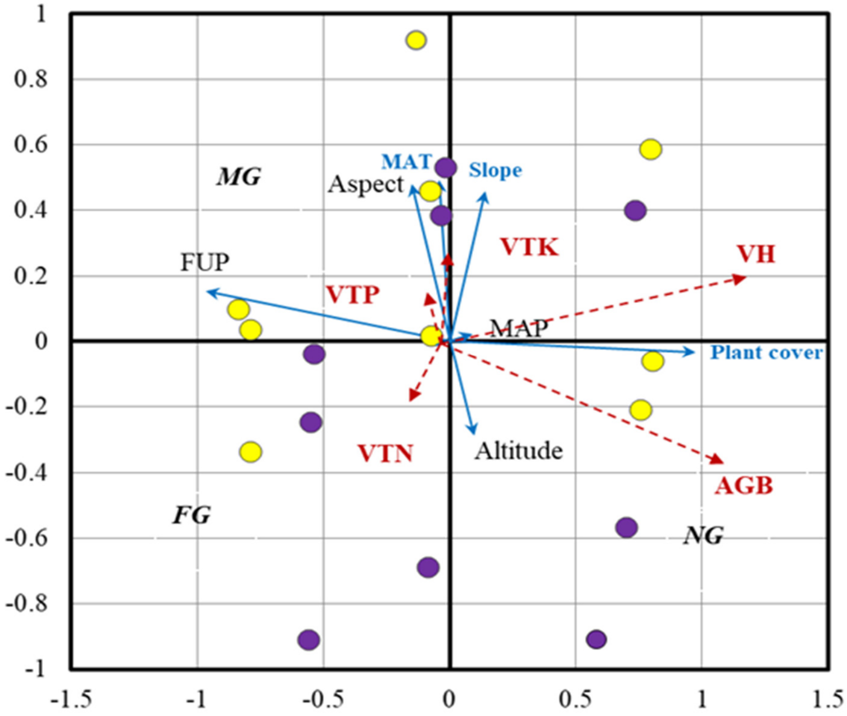


Figure 4. RDA1 diagram of vegetation aboveground biomass (AGB, g.m^{-2}), vegetation height (VH, cm), vegetation total nitrogen (VTN, %), vegetation total phosphorus (VTP, %), vegetation total potassium (VTK, %) and topography, environment and grazing intensity

Areas are represented by purple (Artashavan) and yellow (Avan) points

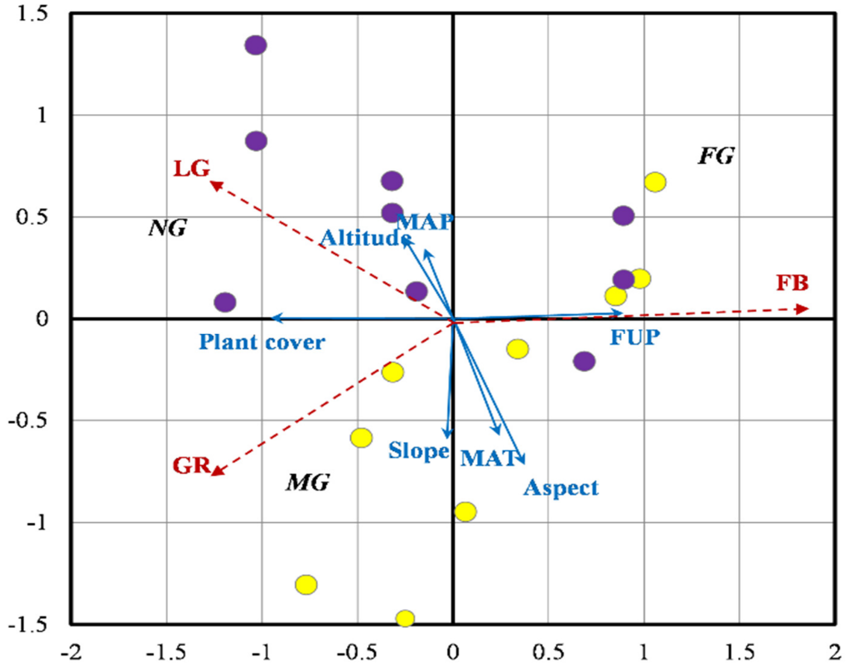


Figure 5. RDA2 diagram of floristic composition (GR-grasses, %, LG- legumes, %, FB-forbs, %) and topography, environment and grazing intensity

Areas are represented by purple (Artashavan) and yellow (Avan) points

Regarding soil physicochemical parameters, significant differences $p < 0.05$) between areas were observed for the content of STN, STK, Ca, SS, SL and pH (Figure 6). The STP and BD contents did not change at the ART and AVN areas and consisted of 0.38-0.41% and 0.98-1.02 $g.m^{-3}$. The content of STN (1.5 times), STK (1.3 times), litter (1.4 times) and sandy (1.1 times) was significantly higher at ART area while the soil pH (1.3 times) and Ca (1.7 times) were higher at AVN area (Figure 6).

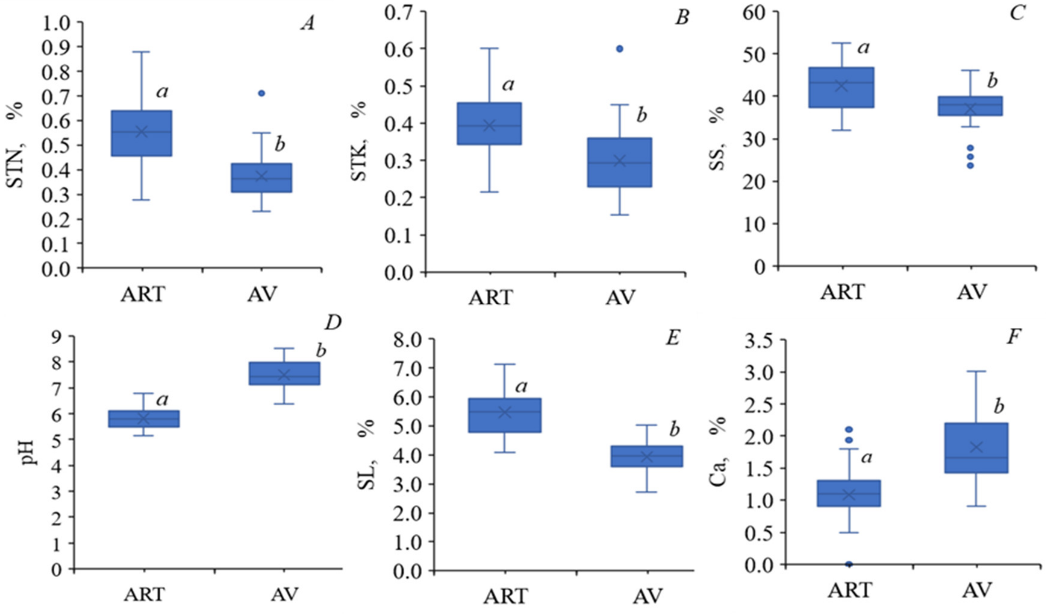


Figure 6. Total nitrogen (STN, %-A), total potassium (STK, %-B), sandy (SS, %-C), pH (D), litter (SL, %-E) and $CaCO_3$ (Ca, %-F) content in soils at ART (Artashavan) and AVN (Avan) areas of steppes

The effect of grazing intensity was similar in the two areas for all soil parameters except SL (Table 2). Particularly, STP, STK, Ca and BD in soils were significantly lower at the NG compared to MG and FG sites (Figure 7, Table 4). Inversely, SS was higher at the NG than in MG and FG sites. Finally, the effect of grazing on SL content was differentiated between the two areas. The higher SL content was recorded at the MG of ART while the lower at the MG of AVN area (Table 4).

Table 4. The area and grazing intensity effect on soil parameters of ART (Artashavan) and Avan (AVN) steppe areas (STN-total nitrogen, %, STP-total phosphorus, %, STK-total potassium, %, SS-sandy, %, BD-bulk density, $g.m^{-3}$, pH, SL-litter, %, Ca-$CaCO_3$, %)

Parameters	**AREA/GRAZING INTENSITY**					
	ART			**AVN**		
	NG	*MG*	*FG*	*NG*	*MG*	*FG*
STN	0.55a	0.54a	0.58a	0.34b	0.34b	0.43c
STP	0.34a	0.45b	0.46b	0.33ac	0.39ad	0.43b
STK	0.35a	0.38a	0.45b	0.25c	0.32a	0.32a
SS	44.7a	42.8ab	39.7b	39.7bc	38.1bc	33.3d
BD	0.86a	1.06b	1.14c	0.81d	1.02b	1.12bc
pH	5.73b	6.04a	5.67b	7.42c	7.51c	7.57c
SL	5.45b	5.82a	5.15ab	4.06c	3.73d	4.03cd
Ca	0.88a	1.23b	1.13ab	1.62c	1.79cb	2.08d

Notice: Mean followed by the same lowercase letter in the row do not differ by the Tukey test at the 5% probability.

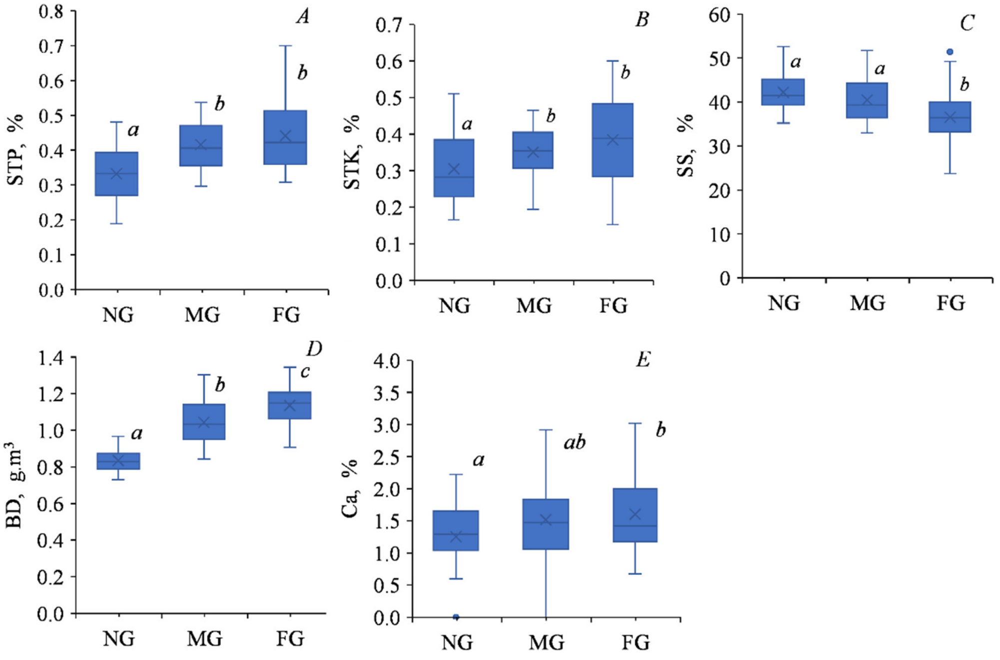


Figure 7. Total phosphorus (STP, %-A), total potassium (STK, %-B), sandy (SS, %-C), bulk density (BD, g.m^{-3}-D), $CaCO_3$ (Ca, %-E) content in soils at no grazed (NG), moderately grazed (MG) and free grazed (FG) sites of steppes

Grazing management, topography and environmental conditions explain the 92.3% of the total variability for soil physicochemical properties (F=8.9, $p < 0.0001$, Figure 8).

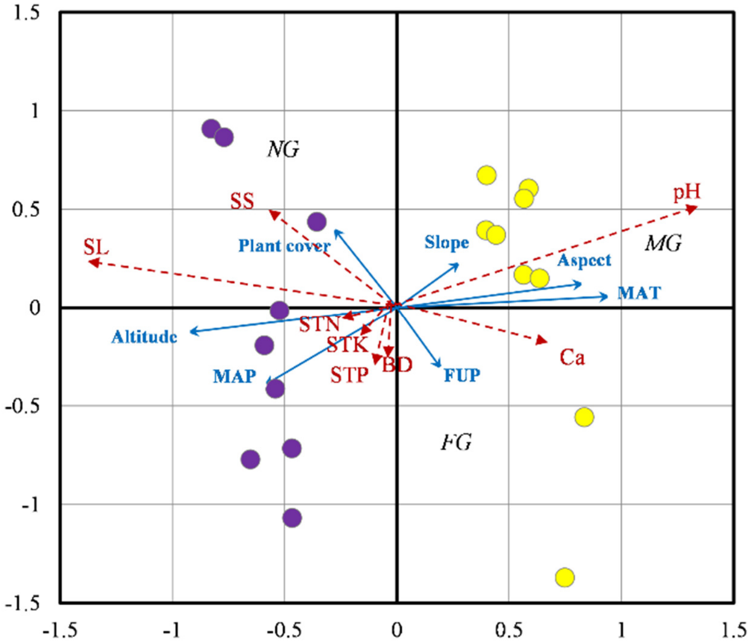


Figure 8. RDA3 diagram of soil parameters (STN-total nitrogen, %, STP-total phosphorus, %, STK-total potassium, %, SS-sandy, %, BD-bulk density, g.m^{-3}, pH, SL-litter, %, Ca-$CaCO_3$, %) and topography, environment and grazing intensity. Areas are represented by purple (Artashavan) and yellow (Avan) points

The slope angle and exposition, the MAP with grazing intensity and FUP best correlated with F1 axis and explained the 81.39% of variations in soil properties. Only the plant cover percentage, the altitude and MAP explain the 10.9% of variations of soil properties. All observations of the AVN area participated in the construction of axis F1, and observations of ART with F2 regarding the NG, MG and NG sites. pH and Ca best correlated with F1 axes at the MG and FG sites of AVN area. The STN, STK, STP, SL and SS of soils are best correlated with the NG site and ART area

Discussion

Effects of grazing, topography, and environment on vegetation characteristics

Livestock grazing is a primary land use in mountain steppe ecosystems, and its impact on vegetation structure and nutrients content is shaped by both management intensity and site-specific environmental factors. Our results demonstrate that the grazing significantly reduced the aboveground biomass and vegetation height, while increasing forage nitrogen concentration. These effects were further modulated by climatic and topographic conditions. The ART steppe area, located on the east-facing slopes at higher elevation (~1800 m) received more precipitation and experienced lower temperatures compared to the AVN area (~1600 m), which was situated on the south-facing slopes. These environmental differences resulted in taller vegetation and greater biomass in ART, along with higher nitrogen concentrations in the plant tissue. In contrast, the AVN area exhibited lower biomass but slightly elevated phosphorus content. Such variations reflect well-documented influences of elevation, slope aspect, and climate on plant productivity and nutrient composition in steppe ecosystems (Wu *et al.,* 2014; Wang *et al.,* 2019).

The grazing-induced reductions in AGB and VH observed in this study are consistent with findings from other semi-arid and arid rangelands. In Inner Mongolia and the Tibetan Plateau, intensive grazing has been shown to reduce plant cover, height, and productivity (Zhou *et al.,* 2019; Munkhzul *et al.,* 2021). Notably, the observed increase in forage N content under grazing may result from a higher proportion of young, fast-growing tissues or an increased presence of nitrogen-fixing species, as suggested by Xu *et al.* (2018). Indeed, the percentage of the legumes was higher in the ART area under all grazing intensities.

Our findings align with numerous studies highlighting the positive effects of grazing exclusion on rangeland restoration. For instance, grazing exclusion in arid and alpine steppes of China has proven to increase plant biomass, enhance soil moisture, and improve organic carbon and nutrient content over the period of 6-11 years (Hou *et al.,* 2024). Similarly, grazing exclusion in Central Asian and Iranian rangelands resulted in recovery of vegetation cover and improved soil properties (Dastgheyb *et al.,* 2021; Nasiyev *et al.,* 2022). However, the effectiveness of grazing exclusion is site dependent. Areas with favourable climatic conditions and higher soil fertility, such as ART, may respond more rapidly to reduced grazing pressure. In contrast, areas like AVN, with lower water availability and greater exposure, may require more conservative grazing strategies or longer rest periods to achieve recovery.

Effect of grazing intensity, topography and environment on the composition of plant functional groups

Grazing intensity, along with environmental conditions and soil types, also shaped the composition of plant functional groups in the study areas. The steppe ecosystems, developed on chestnut and chernozem-like soils, were dominated by grasses and forbs, with significant site-based variation in legume abundance. Redundancy analysis (RDA) revealed that different grazing strategies influenced plant groups differently: free grazed site was positively associated with forbs, no grazed with legumes, and moderately grazed sites with grasses. Grazing intensity had a particularly strong impact on legumes: intensive grazing led to reduced legume cover, whereas grasses appeared relatively resistant to changes in grazing intensity. Forbs remained largely stable across the management regimes. Lan *et al.* (2023) found that grazing enclosures significantly increased the grass biomass, while legume and forb biomass remained unchanged. Similarly, long-term fencing studies in Qinghai-

Tibetan meadow grasslands (Xixi *et al.,* 2019) reported an increase in the cover of all three functional groups (grasses, legumes, and forbs), highlighting the role of grazing exclusion in facilitating vegetative recovery and functional diversity. Our findings suggest that in semi-arid steppes, legumes and grasses are more sensitive to grazing pressure, while forbs are relatively resilient. The differential response of functional groups may reflect differences in palatability, root systems, and nutrient acquisition strategies, which influence competitive dynamics under grazing stress.

Effects of grazing intensity, topography, and environment on soil physicochemical properties

This study highlights the significant role of both topography and grazing intensity in shaping soil physicochemical properties in mountain steppe ecosystems. Grazing notably influenced key parameters such as the content of total phosphorus, potassium, calcium, and bulk density, with observed site-specific differences. For instance, nitrogen increased under free grazed conditions in the drier AVN area, likely due to nutrient return via livestock excreta, whereas in ART, nitrogen levels remained stable across treatments.

Phosphorus and calcium increased consistently with grazing intensity in both areas, suggesting enhanced nutrient input from dung and urine, in line with findings from Lan *et al.* (2023) and Sun *et al.* (2023). Potassium showed a more variable pattern: it increased significantly with grazing in ART but remained relatively unchanged in AVN. These results partially support Yang *et al.* (2023), who reported lower K levels under heavy grazing and no difference between no- and moderately grazed sites.

The bulk density increased under higher grazing pressure at both areas, consistent with previous studies (Fasinmirin, 2015; Zhang *et al.*, 2017; Lai and Kumar, 2020), reflecting soil compaction due to trampling. The sand content declined with grazing intensity, possibly due to erosion or changes in particle sorting as a less commonly reported but ecologically relevant effect. In contrast, soil pH remained relatively stable across treatments, aligning with meta-analyses by Abdalla *et al.* (2018) and Contosta *et al.* (2021), which found pH to be largely unaffected by grazing.

The litter content, an important indicator of soil fertility and productivity, was significantly affected by grazing and steppe area conditions. In ART, the litter peaked under moderately grazing, while in AVN it declined under both MG and FG. These site-specific patterns reflect interactions between grazing pressure, primary productivity, and climatic conditions. Our findings align with Abdalla *et al.* (2018), who has noted that litter responses to grazing vary with climate and it typically increases in warm, moist environments and decreases in colder, drier regions. Overall, these results emphasize that grazing impacts on soil properties are context-dependent, varying with site conditions, soil type, and climate. Effective rangeland management must therefore account for local environmental gradients to sustain soil health and ecosystem productivity.

Conclusions

This study highlights the complex interplay between grazing intensity, topography, and environmental conditions in shaping vegetation characteristics, soil properties, and plant functional group composition in mountain steppe ecosystems. The gazing consistently reduced aboveground biomass and vegetation height, while increasing forage nitrogen content, with effects varying across sites due to differences in elevation, slope aspect, and climatic factors. Soil nutrients, particularly phosphorus, potassium, and calcium, also responded to grazing, with marked variations between soil types and grazing regimes. Additionally, grazing pressure influenced plant functional group distribution, with grasses showing greater sensitivity than legumes and forbs. These findings underscore the importance of site-specific management approaches that account for environmental context and ecological resilience. Long-term monitoring and enhanced soil-vegetation analyses are recommended to better understand ecosystem responses to grazing under changing climatic conditions and to inform sustainable rangeland management practices.

Author's Contributions

Conceptualization: M.N. and E.M.A.; Data curation: M.N. and T.S.; Formal analysis: M.N. and T.S.; Funding acquisition: M.N.; Investigation: M.N., T.S. and H.D.; Methodology: M.N. and E.M.A.; Project administration: M.N.; Resources: M.N. and T.S.; Software: M.N., T.S. and H.D.; Supervision: E.M.A.; Validation: M.N., T.S. and E.M.A.; Visualization: M.N., T.S. and H.D.; Writing - original draft: M.N. and T.S.; Writing - review and editing: M.N. and E.M.A.

All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare that there are no conflicts of interest related to this article.

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