Divergent vegetation response to increasing grazing pressure in arid and semi-arid rangelands in Argentina postprint

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Abstract

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Full Text

Preamble

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Divergent vegetation response to increasing grazing pressure in arid and semi-arid rangelands in Argentina

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Abstract

The connection between climatic factors and grazing is essential for maintaining ecosystem function and vegetation productivity. This study examined the impact of grazing intensity on vegetation across a broad climatic gradient spanning the Espinal, Argentine Low Monte, and Patagonian Steppe ecoregions of Argentina. The research was carried out at eight sampling sites with radial grazing gradients generated around artificial water sources (piospheres), exhibiting two contrasting response patterns of vegetation to grazing pressure. One response pattern shows a typical vegetation response to grazing: vegetation productivity increases with distance from the water sources (decreasing grazing intensity). The second pattern, found in drier regions, presents an inverse productivity response where vegetation productivity is higher near water sources (high grazing intensity) due to increased shrub cover. Vegetation productivity was measured using the Normalized Difference Vegetation Index (NDVI). Vegetation patch structure and cover were determined for each site at high, medium, and low grazing intensities. Results indicated that shrub cover is the primary driver of vegetation productivity, showing contrasting responses to grazing intensity between the two identified patterns. While NDVI proved to be a reliable proxy for shrub cover and total vegetation cover ($R^2 > 0.70$), it failed to reflect grass cover dynamics. Furthermore, mean annual temperature was more strongly correlated with vegetation cover changes, while grazing intensity significantly altered vegetation patch structure and soil cover distribution. Specifically, in drier regions, high grazing intensity led to larger patches while in wetter regions it led to smaller patches (fragmentation). Shrubs, with their deeper roots and drought tolerance, were less preferred and more resistant to grazing in arid environments and thrived under grazing pressure in these arid conditions. Our results underscore the need for adaptive management strategies in grazing systems. Traditional approaches may require significant adjustments, as the efficacy of management hinges on the interplay of specific climatic conditions and the varied responses of vegetation. Furthermore, effective conservation efforts should prioritize the recognition and protection of shrubs given their critical contribution to ecosystem function and biodiversity. Ultimately, this research provides a valuable framework to understand the complex dynamics between grazing and vegetation in arid and semi-arid environments, highlighting that sustainable grazing practices should be tailored to account for both climatic variables and the unique characteristics of different plant communities.

Keywords: grazing intensity; vegetation productivity; piospheres; shrub encroachment; climate change; Patagonian Steppe

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1 Introduction

Drylands, which comprise 41.00% of the Earth' s surface, can be classified into hyper-arid, arid, semi-arid, and dry sub-humid categories; they sustain high grazing pressure and are home to one-third of the world population [?, ?]. Grazing, which accounts for over 65.00% of land use in drylands, heavily relies on vegetation as forage for livestock [?, ?]. Vegetation in drylands is often distributed in patches within a matrix of bare soil [?, ?, ?]. These vegetation patches, termed fertility islands, concentrate sediments, nutrients, seeds, and water, playing a crucial role in ecosystem functioning [?, ?, ?, ?, ?, ?].

Grazing has been identified as the primary cause of desertification [?, ?] and, along with climate, has been highlighted as a primary determining factor of the structure [?, ?], functioning [?, ?], and susceptibility to degradation [?, ?] of dryland ecosystems. There is a significant amount of information about the general problem of degradation and desertification attributable to livestock use of grasslands, both in arid and semi-arid areas of Argentina [?, ?, ?, ?, ?, ?, ?], and in other parts of the world [?, ?, ?, ?, ?, ?]. Grazing promotes less preferred plant species and has the potential to change various attributes such as spatial organization [?, ?], associated patch structure, diversity, and functioning of plant communities [?, ?], especially in systems with a short evolutionary history of grazing [?, ?, ?, ?]. Prolonged overly heavy grazing increases soil erosion, reduces vegetation cover, and alters soil chemical and physical properties [?, ?], in addition to differentially fragmenting communities dominated by shrubs or grasses, which may indicate the onset of desertification [?, ?]. Changes in the structure of vegetation patches indicate a warning sign of potential negative effects of grazing on these ecosystems. Extensive livestock management has led to changes in the structure and floristic composition of vegetation [?, ?, ?, ?].

Selective grazing can promote less preferred plants and, in some cases, lead to an increase in shrub dominance and the conversion of grasslands into shrublands, a phenomenon known as "shrub encroachment" [?, ?]. For producers in arid and semi-arid areas, shrub encroachment represents a significant threat to livestock production, irrespective of its underlying causes [?, ?, ?, ?]. Additionally, it has been associated with decreased ecosystem functions, landscape degradation, desertification, and loss of grassland carrying capacity [?, ?, ?].

While it is a common assumption that livestock grazing universally diminishes the provision of ecosystem services, this perspective often oversimplifies intricate ecological interactions. Evidence suggested that, depending on the management approach, domestic grazing can foster favorable plant responses, leading to increased productivity and improved forage quality [?, ?, ?, ?]. In the Patagonian Steppe, for instance, an inflated assessment of carrying capacity and suboptimal animal distribution across expansive and heterogeneous paddocks are key contributors to degradation linked to grazing management, leading to both localized overgrazing and undergrazing across different scales, and continuous grazing across nearly all plant communities as well, thereby intensifying heterogeneous grazing patterns [?, ?]. Research has indicated that moderate grazing can enhance vital supporting services, particularly by boosting grass biomass without causing significant undesirable shifts in species composition [?, ?]. However, both prolonged exclusion of domestic grazing and an intensification of grazing pressure can lead to reductions in aboveground net primary production (ANPP). Intermediate grazing intensities have been associated with a slight increase in plant richness, whereas intensive grazing can cause local extinction of forage species [?, ?]. Besides, it was suggested that biodiversity can be effectively sustained through appropriate grazing pressure management [?, ?]. It has been posited that grazing can induce these positive effects on vegetation, thereby augmenting the global provision of ecosystem services when grazing pressure remains light to moderate, if the system possesses a long evolutionary history of grazing [?, ?]. Specifically, moderate grazing optimizes ANPP, forage availability, carbon sequestration, and plant species richness. In fact, these ecosystem services often exhibit synergistic relationships because moderate grazing stimulates grass productivity (and consequently carbon sequestration), and maintains a high abundance of key forage species [?, ?].

Besides, effects of grazing vary among ecosystems and depend on factors such as the type and density of herbivores, the grazing regime [?, ?, ?, ?, ?], as well as the ecological attributes or processes of the ecosystem [?, ?]. Specifically, key components of the grazing regime, such as intensity and frequency, interact with climate to determine the outcome of these effects [?, ?]. Various researchers mentioned that precipitation and temperature are the climatic variables that most influence arid and semi-arid ecosystems [?, ?, ?, ?, ?]. Precipitation exerts a strong control on the ANPP of vegetation, and higher precipitation results in higher ANPP values [?, ?, ?, ?, ?, ?]. On the other hand, temperature has a negative relationship with ANPP since rising temperature causes greater water losses due to evaporation [?, ?]. The variation of these climatic parameters is a constant concern for producers and the scientific community, as a change in their mean values has consequences on ANPP.

In arid and semi-arid areas, grazing is limited by the distance that animals can travel from water sources [?, ?]. Morici et al. (2003) pointed out that the distribution of artificial water sources is a fundamental management aspect that determines the intensity and location of livestock-induced disturbance. As a result, grazing gradients, known as "piospheres", are commonly observed, radiating outwards from water sources [?, ?, ?]. The piosphere effect, characterized by a decline in grazing intensity with increasing distance from water, is a widely recognized and documented ecological phenomenon globally, even in areas with varying topographical features [?, e.g.,]]Jawuoro et al., 2017; Shahriary et al., 2018. This effect predictably leads to high grazing pressure near water, with pressure decreasing with distance [?, ?]. Then, the distance to the water source is a valuable proxy of grazing pressure and has been widely employed and validated in several studies [?, ?]. Increasing the distance to the water source was used to indicate a decrease in disturbance intensity [?, ?]. Calvo et al. (2021) analyzed the spatial variability of the Normalized Difference Vegetation Index (NDVI) as a proxy for productivity in 77 piospheres located in a climatic gradient in arid and semi-arid areas of Argentina, and observed two different patterns of NDVI response to grazing pressure. On one hand, Pattern 1 showed an increase in NDVI with distance from the artificial water source, indicating a negative response of vegetation productivity to the pressure exerted by livestock. On the other hand, Pattern 2 showed an inverse response with a decrease in NDVI as the distance to the water source increased. The spatial distribution of these two patterns was related to mean annual precipitation (MAP) and mean annual temperature (MAT). Piospheres that presented Pattern 1 were located in regions with MAP above 280 mm and MAT above 14.50°C, while piospheres located in regions below these values exhibited Pattern 2 [?, ?].

The hypothesis proposed to explain the differential performance of vegetation in response to grazing along the climatic gradient is that there is a replacement of grasses by shrubs in sites with higher grazing intensity in most arid areas. This replacement would increase the cover and aerial productivity of vegetation and, therefore, NDVI compared to sites with lower grazing intensity. The interaction between grazing and those plant characteristics associated with their resistance to water stress could be the key factor behind this response. Under these conditions, shrub species would be favored since their deeper roots allow them to access water accumulated in the lower soil layers [?, ?] and because this group is less preferred than grasses by livestock. This explanation suggests that the combination of aridity and grazing could have a significant effect on the productivity of vegetation in these regions, with important implications for the management and conservation of these ecosystems. In this study, we sought to test this hypothesis by evaluating the vegetation structure in piospheres exhibiting two distinct patterns of NDVI response to grazing intensity (Pattern 1 and Pattern 2). It is expected that the most arid sites, with a vegetation response to grazing of Pattern 2, will present a higher cover of shrub species, with larger vegetation patches and a more complex structure at high grazing intensity (near the artificial water source) compared to sites with lower grazing intensity (further away). The significance of this study lies in evaluating if shrub replacement acts as a key driver of vegetation productivity in drylands, challenging traditional views on grazing degradation. This study provides a scientific basis for developing more precise conservation and management strategies that account for structural changes in vegetation along climatic gradients.

2.1 Study area

The research was carried out in 2018 and 2019 at eight sites across the Espinal, Argentine Low Monte, and Patagonian Steppe ecoregions of Argentina [?, ?] [FIGURE:1], where vegetation varies from northern shrublands with scattered trees to southern shrub steppes [?, ?]. This region exhibits a characteristic patchy vegetation pattern common to arid and semi-arid areas with shrub-dominated phytogenic mounds. These mounds often support a diverse understory of subshrubs, perennial grasses, herbs, and biological soil crusts [?, ?, ?, ?, ?].

The Espinal ecoregion has MAT of 14.00°C–15.00°C and MAP ranging from 200 to 300 mm, increasing eastward [?, ?]. The Argentine Low Monte ecoregion exhibits a dry subtemperate transitional climate characterized by hot summers (24.00°C) and temperate winters (7.00°C), and an MAP of approximately 225 mm subject to high interannual variability [?, ?, ?, ?]. The Patagonian Steppe ecoregion has a cold climate with MAT ranging from 8.00°C–14.00°C in the north to 5.00°C–8.00°C in the south. Annual precipitation is generally less than 250 mm across the ecoregion [?, ?].

These climatic characteristics create a gradient, with both temperature and precipitation increasing from southwest to northeast of the study area in Argentina. The dominant and traditional land use in the study area is extensive livestock grazing. Furthermore, wildfires (both natural and anthropogenic) and land clearing practices, aimed at reducing shrub biomass and improving forage accessibility or eradicating native vegetation for pasture or crop establishment, are common [**?**, **?**, **?**].

2.2 Site identification and selection

High-resolution GeoEye images via Google Earth 2018 for the previously described ecoregions were visually explored to search for artificial water sources with the presence of grazing gradients. From all the sites with artificial water sources and piospheres identified in Calvo et al. (2021), we selected eight sites based on the following criteria: presence of one of the two vegetation productivity response patterns to grazing, coverage of the latitudinal gradient, and ease of access. The selected sites included three exhibiting Pattern 1 and five showing Pattern 2 . Within these well-established piospheres, vegetation attributes were evaluated at three levels of grazing intensity: high, medium, and low grazing intensity. We determined these intensity levels based on the consistent and predictable patterns of animal utilization observed in piospheres, as supported by extensive research in similar arid and semi-arid systems [**?**, e.g.,]]Nsinamwa et al., 2005; Fensham et al., 2010; Chillo et al., 2015; Oñatibia, 2021; Maestre et al., 2022.

Table 1 Details of the sampling sites

<table>
<tr><th>Pattern</th><th>Site</th><th>Latitude</th><th>Longitude</th><th>MAP (mm)</th><th>MAT (°C)</th><th>AI (MAP/PET)</th><th>Climate type</th></tr>
<tr><td>Pattern 1</td><td>Chacharramendi</td><td>37°14$
‘17“S|66°12’
57“W|−
|14.50|−
|Semi−
arid||Pattern1|RioColorado|39°07’
00“S|64°02’
52“W|−
|14.50|−
|Semi−
arid||Pattern1|Valcheta|40°36’
27“S|66°11’
20“W|−
|14.50|−
|Semi−
arid||Pattern2|Winter|40°42’
51“S|64°30’
51“W|−
|14.50|−
|Semi−
arid||Pattern2|Fernndez|40°45’
10“S|64°25’
22“W|−
|14.50|−
|Semi−
arid||Pattern2|Sitio80|40°43’
44“S|64°27’
31“W|−
|14.50|−
|Semi−
arid||Pattern2|SierraColorada|40°26’
56“S|67°38’
31“W|−
|14.50|−
|Semi−
arid||Pattern2|SanAndrs|43°09’
49“S|64°50’
42’ ’
$W</td><td>-</td><td>14.50</td><td>-</td><td>Semi-arid</td><td></td></tr>
</table>

Note: MAP, mean annual precipitation; MAT, mean annual temperature; AI, aridity index; PET, potential evapotranspiration. Pattern 1 shows an increase in

Normalized Difference Vegetation Index (NDVI) with distance from the artificial water source, indicating a negative response of vegetation productivity to the pressure exerted by livestock; Pattern 2 shows an inverse response with a decrease in NDVI as the distance to the water source increased.

2.3 Sampling methodology

To assess the effects of grazing intensity, we established 24 plots (each 45 m × 45 m) at 8 sites. At each site, plots were placed at three distances from each water source, representing three grazing intensities

Figure 2 high (100-300 m), medium (600-700 m), and low (1200-1300 m). Within each plot, 4 parallel 45 m transects were laid out at 10 m intervals. Ground cover was recorded at 20 cm intervals along each transect using the point intercept method [**?**, **?**]. The cover of perennial plants, litter, bare soil, biological soil crusts, and rocks was estimated as a percentage of the total number of points intercepted. Plant species were classified into four functional groups (shrubs, subshrubs, grasses, and herbs). Species richness was determined by counting the species present in each plot.

In addition, this study quantified several vegetation attributes within each plot, including patch and inter-patch lengths along the transects and patch diameters. Four patch structure types were classified [FIGURE:3]: (1) simple open (SO), open canopy that allows for a clear view of the base of the mound (island) and contains only one shrub species; (2) compound open (CO), open canopy with the presence of two or more shrub species; (3) simple closed (SC), closed canopy that obstructs the view of the mound base and contains only one shrub species; and (4) compound closed (CC), closed canopy with the presence of more than two shrub species. The following metrics were calculated for each plot: (1) average number of patches per 10 m, in relation to the length covered by patches along each transect; (2) average inter-patch distance (m); (3) percentage of inter-patch area (%); (4) total patch area (m^2), assuming the area covered by each patch as an ellipse; and (5) percentage cover of each patch type (%). All measurements were estimated per transect and then the values of the four transects were averaged to obtain a value per plot. The following equations were used to calculate each metric:

$$\text{Average number of patches per 10 m} = \frac{\text{Number of patches}}{\text{Length covered by patches}} \times 10$$

$$\text{Average inter-patch distance} = \frac{\text{Length of inter-patches}}{\text{Number of inter-patches}}$$

$$\text{Percentage of inter-patch area} = \frac{\text{Length of inter-patches}}{\text{Total transect length}} \times 100$$

$$\text{Percentage cover of each patch type} = \frac{\text{Length of the patch type}}{\text{Total transect length}} \times 100$$

$$\text{Patch area} = \pi \times \text{Radius}_1 \times \text{Radius}_2$$

$$\text{Total patch area} = \sum \text{Patch area}$$

2.4 Vegetation structure in relation with grazing intensity under each vegetation response pattern

Principal component analysis (PCA) was conducted to explore the relationship between vegetation structure and grazing intensity. The analysis examined the correlations between patch structure variables and grazing intensity under each vegetation response pattern.

2.5 Vegetation cover and its relationship with climatic variables

The differences between the first and last plot were calculated to quantify the change in vegetation cover (cover of the high grazing intensity plot minus cover of the low grazing intensity plot in each piosphere). This difference in cover (CovD) was determined for shrubs (CovDS), grasses (CovDG), and total vegetation (CovDT). Linear regression analyses were conducted to examine the relationship between these differential cover values and climatic variables, including MAT, MAP, monthly potential evapotranspiration (PET), and aridity index (AI, calculated as MAP/PET ratio), in order to evaluate which climatic variables had the greatest impact on vegetation response. Climatic data were obtained from WorldClim version 2.0 [?, ?].

2.6 Statistical analyses

To test the hypothesis, Analysis of Variance (ANOVA) was conducted to compare the cover of each functional group among different grazing intensities under each vegetation response pattern. We used ANOVA to analyze variables that met the assumptions of normality and homogeneity of variance, and used non-parametric Kruskal-Wallis tests to analyze variables that did not meet these assumptions. The analyses focused on the cover of shrubs, subshrubs, grasses, and herbs. In the case of soil, we compared the cover of rocks, litter, biological soil crusts, and bare soil. Additionally, we performed linear regressions of NDVI with total vegetation cover, shrub cover, and grass cover to evaluate which functional group had the greatest impact on productivity values. All statistical analyses were performed using Infostat 2020 [**?**, **?**].

3 Results

Significant differences in shrub cover were observed among grazing intensities under both vegetation response patterns. Under Pattern 1 [FIGURE:4a], shrub cover was significantly higher in areas with low grazing intensity compared to those with high grazing intensity ($P = 0.003$). Conversely, Pattern 2 [FIGURE:4b] exhibited the lowest shrub cover under low grazing intensity, relative to high and medium intensities ($P = 0.004$). For soil cover, Pattern 1 showed significantly greater litter cover under medium grazing intensity compared to that under high grazing intensity ($P = 0.038$), while no such differences were found under Pattern 2. Other functional groups or soil cover types (bare soil, biological soil crusts, and rocks) did not display significant differences across grazing intensities under either pattern .

Total vegetation cover and shrub cover demonstrated strong positive correlations with NDVI, evidenced by high R^2 values (0.70 and 0.79, respectively). In contrast, no significant relationship was identified between grass cover and NDVI [FIGURE:5]. These findings suggested that NDVI serves as a reliable predictor of field-measured shrub cover rather than grass cover. Given NDVI' s established utility as an indicator of vegetation productivity [**?**, **?**], it can therefore be used as a proxy for vegetation productivity in this study area. Our results thus underscored the dominant contribution of shrubs to overall vegetation productivity.

Table 2 Statistics of vegetation and soil cover at three grazing intensities under two vegetation response patterns

<table>
<tr><th>Pattern</th><th>Grazing intensity</th><th>Shrubs</th><th>Grasses</th><th>Herbs</th><th>Subshrubs</th><th>Bare soil</th><th>Biological soil crusts</th><th>Litter</th><th>Rocks</th></tr>
<tr><td>Pattern 1</td><td>High</td><td>35.56$±9.98B|20.89±6.69|1.59±2.20|2.22±0.44|33.41±4.01|6.81±1.66|60.00±5.09B|15.26±2 *H−value(orF−value)* *|H = 11.58|F = 0.71|H = 0.86|F = 1.24|F = 0.27|F = 1.02|F = 2.76|H = 1.64||* *Pattern2* *|High|51.27±22.8A|23.47±4.22|0.07±0.04|3.02±3.68|33.96±3.49|9.80±1.87|32.00±4.61|4.5</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td>H-value (or F-value)</td><td>H=10.85</td><td>F=0.00</td><td>F=0.12</td><td>F=1.19</td><td>F=2.23</td><td>F=1.37</td><td>F=1.20</td><td>F=0.61</td></tr>
</table>

Note: Different letters indicate statistically significant differences (P < 0.050) among grazing intensities for each functional group and soil cover. F-value corresponds to Analysis of Variance (ANOVA), a parametric test used to assess differences between group means; H-value corresponds to the Kruskal-Wallis test, a non-parametric test employed to assess differences between group distributions (often medians) when assumptions for parametric tests are not met. Values are mean±SD for shrub cover and rock cover, and mean±SE for grass cover, herb cover, subshrub cover, bare soil cover, biological soil crust cover, and litter cover.

3.1 Vegetation structure in relation with grazing intensity under each vegetation response pattern

The PCA conducted to analyze grazing intensities under each vegetation response pattern revealed that the first two principal components explained all the observed variability in patch structure variables [FIGURE:6]. Under Pattern 1 [FIGURE:6a], high grazing intensity was associated with a higher inter-patch percentage, a greater number of patches per 10 m, and a reduction in total patch area. Medium grazing intensity was positively related to average inter-patch distance, CO patch cover, and species richness. Low grazing intensity showed a strong association with SO patch cover and CC patch cover. Under Pattern 2 [FIGURE:6b], high grazing intensity was correlated with larger total patch area and CC patch cover, but was negatively associated with inter-patch percentage and CO patch cover. Medium grazing intensity was related to longer average inter-patch distance and higher inter-patch percentage, together with lower species richness. Low grazing intensity under Pattern 2 was associated with simpler patches (SO and SC), as well as lower number of patches per 10 m and shorter average inter-patch distance.

3.2 Vegetation cover and its relationship with climatic variables

Sites under Pattern 1 were characterized by negative CovDT values. Conversely, sites under Pattern 2 were indicated by positive CovDT values. While the relationships between the CovD of different vegetation types and the AI were weak [FIGURE:7a], CovDT exhibited stronger negative correlations with PET ($R^2 = 0.71$), MAT ($R^2 = 0.34$), and MAP ($R^2 = 0.31$) [FIGURE:7b–d]. CovDS showed a negative correlation with PET ($R^2 = 0.45$) but a weaker relationship with MAP ($R^2 = 0.14$) and MAT ($R^2 = 0.19$). CovDG did not demonstrate a significant relationship with any of the climatic variables analyzed ($R^2 < 0.10$ in all cases).

4.1 Shrub dominance and the inverse piosphere pattern in arid ecosystems

Unlike many studies that compared grazing-restricted areas with typically grazed areas, our research utilized radial grazing gradients generated around artificial water sources. The observed relationships between the cover of different vegetation types along these gradients and NDVI strongly suggested that shrubs are the functional group with the most significant impact on vegetation productivity in arid and semi-arid ecosystems. This finding provides a novel perspective on vegetation dynamics in these environments.

A previous study [**?**, **?**] indicated an inverse vegetation response in some sites, which is in contrast to the typical responses to grazing described earlier [**?**, e.g.,]]Lange, 1969; Todd, 2006; Chillo et al., 2015; Cheli et al., 2016. Instead, vegetation productivity was higher near the water source, a pattern linked to a MAP threshold of less than 300 mm. Our results further supported this inverse piosphere concept, as Pattern 2 sites, characterized by higher vegetation productivity near artificial water sources, indeed displayed greater shrub cover in proximity to water compared to more distant areas. This aligns with our hypothesis and can be attributed to several ecological mechanisms. These may include competitive interactions between shrubs and grasses for soil resources [**?**, **?**, **?**], spatial and temporal variability in resource availability influenced by climatic and soil factors [**?**, **?**, **?**], or the influence of disturbance regimes such as fire or grazing [**?**, **?**, **?**].

Shrub species possess a suite of structural, functional, and phenotypic traits (e.g., deeper roots, lignified tissues, small leaves, spines, specific chemical element concentrations) that confer tolerance to low temperatures and arid conditions [?, ?, ?]. These anatomical and physiological characteristics also confer resistance to trampling and grazing on shrubs, alongside an inherent ability to recover from these disturbances [?, ?, ?, ?, ?, ?, ?, ?, ?]. Consequently, this functional group can maintain or even increase its abundance under high grazing pressure, suggesting that their ability to tolerate or avoid grazing [?, ?, ?] is primarily governed by their tolerance to abiotic stressors like low temperatures (frost or freezing) and aridity. This explains why in drier and colder environments, sites experiencing more intensive grazing exhibit higher cover of shrubs less preferred by livestock.

4.2 Vegetation structure in relation with grazing intensity

Pattern 1 sites [FIGURE:6a], representing a more typical piosphere, showed vegetation distributed in smaller patches with a greater percentage of inter-patch area under high grazing intensity. This fragmentation of vegetation due to intense grazing is a widely reported phenomenon in arid and semi-arid ecosystems globally [?, ?, ?, ?, ?, ?, ?, ?, ?, ?]. Conversely, under low grazing intensity in this pattern, we observed not only a larger area covered by vegetation (including both total vegetation cover and shrub cover), but also a higher prevalence of more complex patch structures. The lower NDVI values previously noted near the water sources under this pattern [?, ?] can be directly linked to the reduced shrub cover found there [FIGURE:4a].

It is noteworthy that species richness did not follow the radial degradation pattern observed for other ecological attributes in this study. This behavior is consistent with the intermediate disturbance hypothesis [?, ?] and aligns with findings from numerous previous works [?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?]. The presence of complex patches at medium and low grazing intensities further supports this, as species richness is a crucial factor in maintaining and providing many ecosystem services in arid and semi-arid areas [?, ?]. Therefore, this result has significant implications for designing livestock management tools: implementing grazing intensities that conserve and sustain patches and areas with high species richness will help ensure the continued provision of biodiversity-based services.

While grazing at moderate stocking rates can sometimes mitigate shrub encroachment, potentially serving as a rangeland restoration tool [?, e.g.,]]Venter et al., 2018; Biancari et al., 2024, our findings present a unique insight. Although the positive effect of grazing on shrub abundance has been documented in other arid regions, such as the sagebrush communities in western North America under similar low precipitation regimes [?, ?], the novelty of our study lies in observing this positive effect on shrubs specifically in sites with annual precipitation less than 300 mm, in comparison with sites receiving higher precipitation.

Under Pattern 2, intensively grazed sites exhibited a denser and more complex patch structure, with a lower percentage of inter-patch area. Conversely, low grazing intensity led to a higher number of patches per plot, but these patches possessed a simpler structure, being predominantly composed of a single species [FIGURE:6b]. These results strongly suggested that, in drier environments, higher grazing intensity leads to an increase in both patch size and shrub cover, indicating that in these specific cases, intensive grazing does not induce vegetation fragmentation.

Various studies have suggested that climate, soil heterogeneity, and disturbances like fire and grazing can profoundly influence the relationships between functional groups [?, ?, ?, ?, ?]. The prevalence of shrub species in sites with high livestock pressure may also provide refuge for grazing-susceptible species that can establish and grow under their canopy [?, ?]. This facilitative effect would contribute to increased vegetation cover [?, ?, ?], and consequently, higher NDVI and productivity. However, the distribution of patch types with distance from the piosphere center in our study does not align with some previous regional data. In contrast to our findings, Cheli et al. (2016) reported no significant changes in patch area and density along the gradient in their study. This discrepancy highlights that even within geographically proximate study areas or the same ecoregions, variations in climatic characteristics can drive distinct vegetation dynamics, a phenomenon of differential responses to climate previously documented in the region [?, ?].

Additionally, several studies have identified 300 mm of MAP as a critical threshold for shifts in various ecological attributes including soil productivity [?, ?], nitrogen availability [?, ?], and ecosystem sensitivity to precipitation variability [?, ?]. Our study provides further evidence of the varied patterns of vegetation response in relation to climate. Furthermore, our observations of the contrasting vegetation response around water sources in drier regions expand the traditional definition of a piosphere. It is no longer solely characterized by the radial attenuation of degradation with distance but also by distinct changes in structural and functional characteristics linked to proximity to water.

As previously noted, the characteristics that confer shrubs resistance to aridity and low temperatures also function as adaptations to tolerate herbivory. Therefore, at more intensively grazed sites in arid environments, species more resistant to aridity would effectively replace more susceptible ones. In this specific context, the replacement of grasses by shrubs in the most intensively grazed areas of the driest regions explains the observed increase in vegetation productivity near water sources. While shrub encroachment is generally perceived as a threat by producers in arid and semi-arid areas [?, ?] due to its association with a loss of forage value [?, ?, ?], various studies have emphasized the crucial role of shrub species in maintaining patch structure and, consequently, ecosystem multifunctionality [?, ?, ?]. Furthermore, as previously highlighted, species richness in grazed sites basically depends on the presence of shrubs, which is key to the maintenance and provision of numerous ecosystem services, including forage [?, ?].

4.3 Vegetation cover and its relationship with climatic variables

By analyzing CovDS, CovDG, and CovDT, we investigated the relationship between climate and the two opposing vegetation response patterns to grazing (high versus low grazing intensity). Among all climate variables assessed, temperature emerged as the most significant factor influencing increased vegetation cover with rising grazing pressure, even more so than precipitation or the AI. Weaker relationships were observed between precipitation and vegetation cover, leading us to conclude that while precipitation controls overall vegetation productivity [?, ?] and its response pattern to grazing [?, ?], its role on vegetation structure in the presence of livestock could be distinct.

Crucially, even if vegetation patches are composed of non-forage shrub species, they play a vital role in providing buffering services that contribute to reversing desertification [?, ?]. Despite not being directly linked to forage provision, these species are essential for the overall functioning of the ecosystem through other mechanisms, such as facilitation of palatable species [?, ?].

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5 Conclusions

This study offers a foundational understanding of grazing impacts in arid and semi-arid rangelands, while also highlighting critical avenues for future research. A key finding was that the influence of grazing on vegetation structure and productivity is context-dependent, particularly modulated by aridity. We demonstrated the emergence of an inverse piosphere in drier regions, where high grazing intensity near water sources is associated with increased shrub cover and productivity, contrasting with the typical degradation gradient seen in less arid areas. Specifically, our results emphasized the dominant role of shrubs in contributing to overall vegetation productivity in these systems, and their resilience to grazing pressure, especially in drier environments. This resilience could be linked to their inherent adaptations to aridity and cold, which also confer tolerance to herbivory. We also highlighted that floral richness does not always follow a degradation gradient, aligning with the intermediate disturbance hypothesis and suggesting that moderate grazing intensities can maintain or even enhance biodiversity. These findings carry significant practical implications for rangeland management, particularly concerning the adjustment of stocking rates. Moreover, our work reinforces that grazing management should be tailored to specific aridity levels to sustain ecosystem service provision, especially forage supply. This knowledge is particularly relevant as stocking rate is the primary management tool available to producers. Future research should expand upon these findings by investigating whether the observed increase in vegetation cover around water sources in drier regions correlates with the provision of other ecosystem services, such as soil fertility, carbon sequestration, and long-term forage production. A detailed analysis of the influence of varying livestock carrying capacities and the types of dominant herbivore species within different piospheres is also crucial. Such studies will contribute significantly to unraveling the intricate mechanisms governing arid ecosystems and enhancing our ability to predict and manage the interplay between grazing pressure, vegetation health, soil integrity, and climatic variables.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author contributions

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