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Effects of Grazing and Shrub Management on Species Composition and Soil Properties in Patagonian Grasslands

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Abstract: Historical sheep farming in the Patagonian drylands has led to reduced grass cover, soil erosion, and shrub encroachment, compromising ecosystem function. Effective restoration requires managing shrub cover, bare soil, and patch connectivity through various strategies. This study evaluates rehabilitation interventions in a grass-steppe ecosystem, comparing grazed and ungrazed areas. Over three years, we tested the following: (a) mechanical shrub cutting with biomass redistribution, and (b) enhancing patch connectivity with *Pinus* spp. branch piles, alongside controls, in eighteen 5 m × 5 m plots invaded by *Mulinum spinosum*. Half of the plots were fenced to exclude grazing, resulting in six treatment combinations. We monitored soil properties, vegetation cover, and species composition. The treatments explained twice as much of the variation in community composition as the annual climatic variations (0.26 vs. 0.13). Livestock exclusion increased perennial grass cover more than the grazed plots did (2.14 vs. 1.42 times the initial measure). All treatments reduced the amount of bare soil except the grazed controls. Shrub cutting, especially with grazing, increased the lasting litter coverage by 5–10% and decreased the bare soil equivalently. Organic matter increased except in the non-intervened interpatches (0.95 times). The enclosures with cut shrubs trapped erodible particles, showing a 5% increase. Our study highlights that grazing destabilizes communities, while enclosures stabilize them, with interventions improving soil fertility and mitigating erosion.

Keywords: land degradation; erosion; ecological restoration; organic matter; adaptive management; rangeland

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1. Introduction

Grassland ecosystems, influenced by extensive human activities, face mounting pressure from the global demand for animal products and competition with agriculture [1]. Predominantly located in arid, semi-arid, and sub-humid drylands unsuitable for other uses, these areas experience significant shifts in vegetation and soil due to livestock management [2]. Increased disturbances often result in declines in perennial grass and overall vegetation cover, potentially facilitating shrub encroachment [3]. This process alters landscape heterogeneity by creating patches of vegetation interspersed with bare soil or low-cover areas [4]. Furthermore, shrub encroachment tends to homogenize plant communities, reducing species richness and shifting composition towards non-grazed species at the expense of preferred species (i.e., plants that cattle proportionally consume more of than their abundance in the community) [5]. These changes ultimately affect grassland productivity [6].

In Argentina, shrub encroachment linked to livestock activities is well-documented across diverse regions [7]. Specifically in Patagonia, this process typically reduces livestock productivity by decreasing total cover and palatable species while increasing inedible shrub cover [3,8]. Changes in vegetation cover and composition alter litter inputs to the soil, potentially disrupting soil carbon and nutrient balances [9]. These alterations often coincide with increased rates of water and wind erosion, resulting in pronounced differences in the soil's physical and chemical properties between the vegetated patches and bare soil interpatches [10]. Maintaining soil functionality is critical for successful vegetation rehabilitation efforts, highlighting the need for strategies aimed at enhancing productivity and soil carbon levels [11].

Passive restoration relies on ecosystem resilience, facilitating biota recovery post-disturbance such as through limiting domestic herbivory [12]. Resilience, measured by the system's responsiveness to disturbance removal (elasticity), is crucial for the success of these strategies [13]. Grazing exclusion in the Patagonian rangelands has enhanced vegetation cover and biodiversity, safeguarding seedlings, and bolstering soil organic matter by curbing degradation, despite animals contributing to soil organic matter [14].

In severely degraded Patagonian areas, where significant disturbances cause a shift between shrub and grass dominance [15], regulating grazing alone has proven insufficient for effective recovery [16]. Active restoration often involves intensive actions, such as removing invasive shrubs, with the risk of reducing plant diversity and increasing erosion [17]. Managing rather than eradicating shrub cover is generally preferred [18]. Cut shrub aerial parts can enhance grass productivity by improving water availability and nutrient release, although it may impact the water supply to lower strata species over the long term [19].

In Patagonia, *Pinus ponderosa* Dougl. ex. Laws. plantations often replace grasslands or the steppe-forest ecotone [20], posing challenges in managing forest residues due to their unsuitability for timber and high processing costs [21]. Utilizing these residues for grassland rehabilitation offers a cost-effective alternative by placing branch barriers near vegetation patches to prevent erosion and promote non-shrub species re-establishment in overgrazed areas [22]. This approach enhances productivity and facilitates the establishment of new plants, interrupting the cycle of degradation within a year [23].

This study aims to assess the impact of various rehabilitation interventions on vegetation and soil in a grass-steppe ecosystem encroached on by *Mulinum spinosum* alongside other cushions, comparing the plots subjected to grazing with those where herbivores are excluded. The interventions include the following: (i) mechanically controlling shrub growth and redistributing the extracted biomass into the soil, and (ii) enhancing connectivity between the vegetation patches using *Pinus* branch piles. We hypothesize that implementing mechanical shrub control and branch piles into this degraded grassland will reduce soil erosion through increased litter cover and promote greater coverage of the grassy plants, while reducing shrub cover. Moreover, it is hypothesized that these effects will be more pronounced in plots where interventions are combined with the exclusion of domestic herbivore grazing, compared to those without this exclusion.

2. Materials and Methods

2.1. Study Area

This study was conducted in the Sub-Andean district of Patagonia, Argentina, specifically within the Percy River basin near Esquel city, Chubut province. This district, extending from Subantarctic forests to the Western Sierras and Plateaus steppes [24], spans from 71°30′ and 71° W [25] to 39° to 43° S [26]. Precipitation ranges from 300 mm in the east to 800 mm in the west [24]. The region experiences a concentration of precipitation during winter and a mismatch between wet and growing seasons due to cold temperatures. Transpiration peaks between November and January when temperatures are optimal and sufficient soil water is available [26]. Dominant species show a strong phenological correlation with maximum temperatures [27]. Vegetation types include grassy steppes dominated by the tussocks *Festuca pallescens* (St.-Yves) Parodi and *Pappostipa speciosa* (Trin. & Rupr.) Romasch., shrub-grass steppes with high cover of the native cushion shrub *Mulinum spinosum* (Cav.) Pers. [= *Azorella prolifera* (Cav.) G.M. Plunkett & A.N. Nicolas], and shrublands with *Berberis heterophylla* Juss. ex Poir., *Discaria articulata* (Phil.) Miers, *Schinus patagonicus* (Phil.) I.M. Johnst. ex Cabrera var. Patagonica, and *Colletia hystrix* Clos. Additionally, there are isolated forest patches of *Nothofagus antartica* (G. Forst.) Oerst., *Austrocedrus chilensis* (D. Don) Pic.Serm. & Bizzarri, and *Maytenus boaria* Molina [28] are also present. Overgrazing has led to the expansion of *M. spinosum* and other cushion plants like *Acaena splendens* Hook. & Arn. and *Acaena pinnatifida* Ruiz & Pav. into degraded grasslands [29].

2.2. Study Sites

This study was conducted on the Estancia Río Percy ranch (42°51′ S, 71°23′ W), encompassing 14,000 hectares within the Sub-Andean district [30]. The ranch ranges in elevation from 730 to 1010 m above sea level and receives an average annual precipitation of 650 mm. The landscape features Mollisols with a xeric moisture regime [31]. Sheep farming on the ranch involves extensive grazing across large and heterogeneous paddocks for wool production, with seasonal, continuous grazing in plots designated for either winter or summer grazing annually [32], a practice common in Patagonia [33]. Historical records indicate that sheep farming in Chubut began around 1870, leading to significant ecological impacts due to overgrazing and frequent fires [34]. In 1937, sheep represented 65% of Chubut's livestock with a stocking rate of 0.65 animal units (AU) per hectare [35]. By 2002, the proportion decreased to 37%, and stocking rates were reduced to 0.35 AU/hectare, suggesting diminished forage production capacities [36]. The study location was chosen for its historical ownership dating back to the early 20th century, allowing for a detailed reconstruction of the land use history through interviews with owners and the ranch manager, a rarity at the production unit level [37]. Historically, the area likely consisted of open forests and *F. pallescens* steppes, but anthropogenic activities such as fires, livestock grazing, and wood extraction have significantly altered the vegetation and degraded the soil [29]. Currently, the vegetation includes patches of perennial vegetation interspersed with bare soil and sparse non-shrubby perennial and annual vegetation. The landscape is dominated by the hemispherical canopies of *M. spinosum*, covering large areas across various terrains and slopes, except for valley bottoms and marshy meadows. The land, predominantly used for extensive livestock farming (sheep and cattle), has recently seen afforestation with fast-growing conifers suited to the soil type [38].

2.3. Estimation of Grazing Intensity

We estimated grazing intensity using a combination of animal stocks information from interviews and remote sensing techniques. With the reconstructed data on annual livestock numbers, we calculated animal unit (AU) requirements (4320 kg dry matter per year; [39]) per hectare. We then determined annual NDVI values using Landsat 8 OLI images (30 m pixel) with QGIS. NDVI values were converted to annual net primary production (ANPP) in kg/ha based on the equation by Paruelo et al. [40] for the Patagonian steppe. Finally, we estimated grazing intensity (GI) for each site by calculating the proportion of ANPP required to meet AU needs [41].

2.4. Experimental Design

Six study sites were chosen based on similar landscape characteristics (slope, aspect, and vehicular accessibility). Each site included a 15 m × 5 m area divided into three 5 m × 5 m plots (Figure 1). These plots were randomly assigned to one of three rehabilitation interventions: shrub cut, branch piles, or no intervention. Half of the sites (with 3 plots each) were enclosed with 1.4-meter-high wire mesh fencing to exclude domestic livestock grazing. This created six treatment combinations (in triplicate), involving intervention types with and without grazing: exclusion with shrub cut, exclusion with branch piles, exclusion without intervention, grazing with shrub cut, grazing with branch piles, and grazing without intervention. Shrub cut entailed manual removal of all *M. spinosum* and *A. splendens* shrubs at ground level, followed by biomass chopping and spreading [42]. Branch piles consisted of piles that were 1 m in height and 2 m in width, built from approximately 5 cm diameter branches of *P. ponderosa*, simulating low-diameter forestry pruning residues [43]. We estimated biomass for each pile as 42.9 kg with a leaf/branch ratio of 0.51, following diameter and volume-based equations [44]. The plots were defined in the summer (January) of 2016, and we proceeded with trial treatments in the autumn (April) of 2017. This study lasted for three years, ending in January 2019.

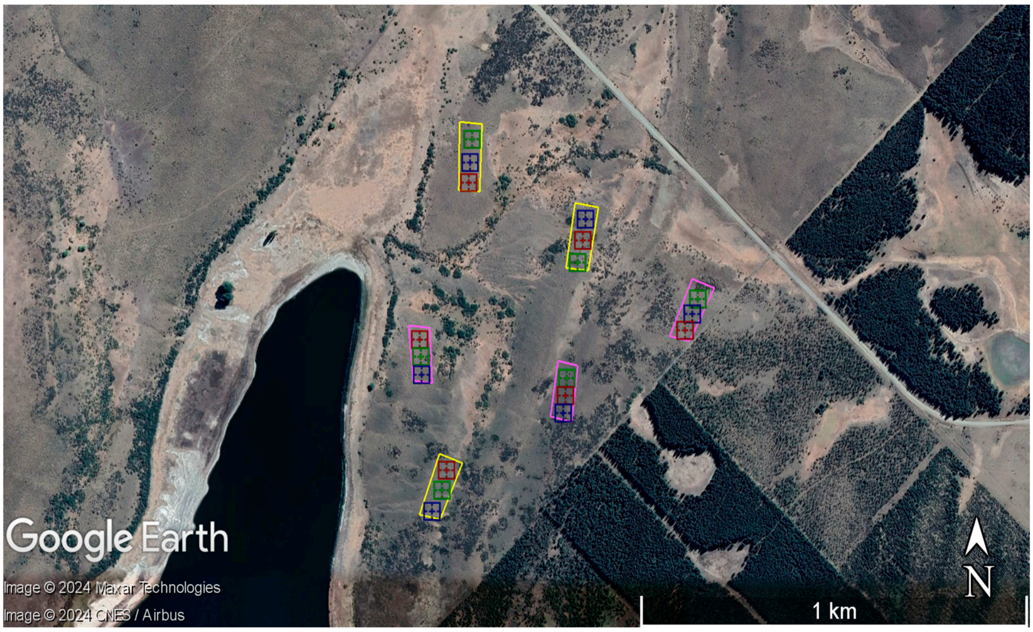

Figure 1. Study site locations and experimental design. The map shows the six study sites. Rectangles indicate grazing exposure (yellow) or exclusion (pink), and squares within them indicate the intervention applied to each plot: shrub cut (blue), branch piles (red), or control (no intervention) (green).

2.5. Vegetation Monitoring

Monitoring employed transects and the point intercept method, spaced 20 cm apart [45]. In the summer of 2016/2017, two 7 m perpendicular transects were established across each plot, extending between opposite vertices. Initial vegetation measurements were conducted prior to the autumn 2017 interventions, which included shrub cut and branch piles. Fieldwork coincided with the peak growth season for these grasslands [26]. Transects were revisited annually until summer 2019. We measured cover categories by dividing the intercepted points of each category (e.g., species, life form, litter, bare soil) by the total points sampled along transects. Annual precipitation, livestock load, and grazing intensity during the study period are detailed in Table 1.

Table 1. Annual data on precipitation (PPT in mm), animal stocking rate (AU/ha), and grazing intensity (GI, proportion of cattle forage to total pasture production) at the study site during the assay period.

	2019	**2018**	**2017**	**2016**
PPT (mm)	588.6	595.2	613.5	383.3
Stock (AU/ha)	0.13	0.00	0.13	0.13
GI	0.61	0.00	0.15	0.77

2.6. Soil Sampling and Analysis

In each of the 18 square plots, soil samples were collected in 2016 from the superficial soil layer (0–5 cm) beneath *M. spinosum* patches and adjacent bare interpatch areas to assess sediment redistribution in erosion-prone soils [46]. Sampling locations were marked using GPS (eTrex 22x, Garmin Ltd., Olathe, KS, USA) and pegs. Additional samples were collected at the end of the 2019/2020 summer to evaluate soil changes over the study period. Laboratory analyses included a determination of organic matter content (TDHM-G muffle furnace, Tecnodalvo SRL, Santa Fe, Argentina) [47], erodible fraction (Zonytest LR2006 digital vibrating equipment, Rey & Ronzoni SRL, Buenos Aires, Argentina) [48], and particle size distribution using laser diffraction (Mastersizer 3000, Malvern Panalytical Ltd., Malvern, UK) [49].

2.7. Statistical Analysis

The Principal Response Curves (PRCs) method [50] assessed changes in community composition over time relative to a control (E_control). Species frequencies were log-transformed [51]. Multivariate regression was applied to the sample × taxon matrix, with treatment and treatment × time as explanatory variables and time as a covariate [52]. The PRC plots show compositional changes relative to the control over time, with the y-axis representing treatment effects via unitless canonical coefficients (cdt), which indicate magnitude and direction of treatment effects on community structure [53]. The PRC graph highlights annual taxonomic changes, focusing on species with weights >0.5 [53]. Significance was determined using Monte Carlo permutations, and the analysis used the *vegan* package in *R* software (version 2023.12.1 Build 402).

We analyzed annual frequencies of key species from the PRC analysis and assessed species by life form and grassland degradation indicators (grasses, shrubs, litter, bare soil, total vegetation cover). The interventions' progressive effects were evaluated through intra-annual comparisons across all treatments data. Short- to medium-term impacts, which include changes observed between 2016 and 2019, were assessed based on the proportional change between these two years. Assumptions of normality and homoscedasticity were checked; the ANOVA or Friedman test was used as appropriate, with Fisher's LSD test for ANOVA. Statistical analyses were performed with *InfoStat* software (version 2020).

We used Ecological Trajectory Analysis (ETA) to assess temporal changes in community composition across treatments. ETA is a robust method that visualizes and quantifies the direction, magnitude, and rate of changes in multivariate space [54]. It utilizes principal coordinates analysis (PCoA) on a Bray–Curtis distance matrix to compare species abundance over time [55]. The analysis was conducted using the *ecotraj* package in *R* software (version 2023.12.1 Build 402).

Proportional soil changes were computed across treatments, representing the ratio of soil conditions in the first year relative to those in the last year, and statistical comparisons assessed differences relative to the control and within treatments over time. Normality and homoscedasticity were checked; the ANOVA or the Friedman test was used accordingly, with Fisher's LSD test for ANOVA. Analyses were performed with *InfoStat* (version 2020) and graphs were created using the *ggplot2* package in *R* software (version 2023.12.1 Build 402).

3. Results

3.1. Vegetation Response to Interventions and Grazing

Vegetation monitoring consistently identified *M. spinosum* and *Poa ligularis* Nees ex Steud. var. ligularis as the dominant species across all years and sites, alongside perennial grasses preferred by livestock (*P. ligularis*, *F. pallescens*, *Bromus setifolius* J. Presl var. setifolius, *Hordeum comosum* J. Presl), and shrubs (*M. spinosum*, *A. splendens*, *Senecio filaginoides* DC. var. filaginoides). The PERMANOVA analysis indicated significant differences in species composition between years and treatments (see Table A1 in Appendix A).

The Principal Response Curve analysis (Figure 2) demonstrated that the "treatment" variable explained twice as much of the variation as the "year" variable. Monte Carlo permutation tests confirmed a significant shift in community composition among the treatments over time (F = 5.6937, $p = 0.002$). In 2017, the sites undergoing cut interventions showed distinct community changes compared to the controls, primarily driven by the most frequent species, excluding *C. hystrix*. The grazed plots with active cattle exhibited contrasting community shifts. By 2018, cessation of grazing in the unclosed plots led to reduced treatment effects due to ranch management decisions, aligning more closely with the controls than in 2017. By 2019, cut interventions maintained minimal shrub coverage (significant in the enclosures).

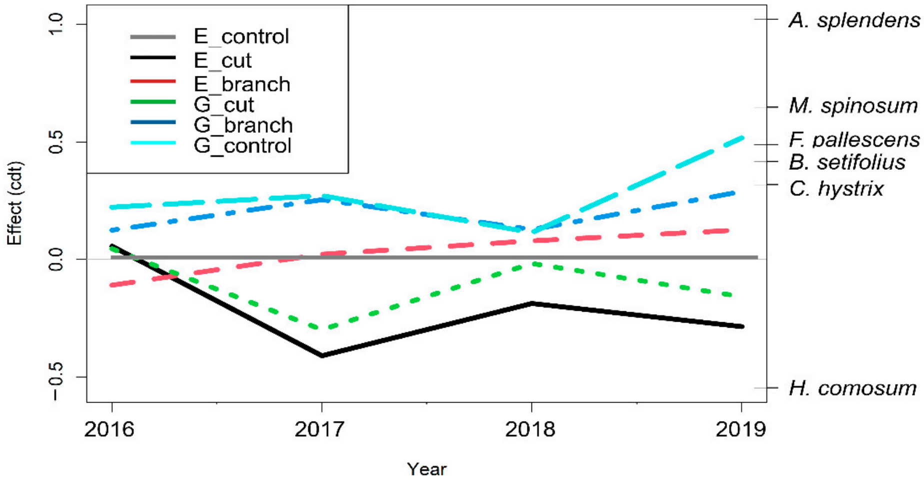

Figure 2. Principal Response Curves (PRCs) showing annual changes in total vegetation composition relative to the reference treatment E_control (gray horizontal line, effect = 0.0). Only species with weights > |0.5| are shown. Variance explained: Time (0.13), Treatment (0.26), and Unconstrained variables (0.61). Positive values on the Y-axis (above the reference treatment) indicate increased species importance compared to the effect = 0 line, while negative values (below the reference treatment) indicate decreased species importance.

Intra-annual comparisons from 2016 onwards (Figure 3) revealed the distinct effects of the interventions on vegetation dynamics and soil cover. By 2017, approximately nine months post-intervention, shrub cutting notably reduced shrub cover while increasing litter accumulation. These same plots exhibited the lowest levels of bare soil coverage, contrasting sharply with the control plots (grazed or not), which had the highest bare soil percentages. The cutting treatment resulted in reduced total vegetation cover, whereas grazed control plots without intervention maintained the highest overall vegetation cover for the year. In 2018, with all plots temporarily released from grazing due to the ranch manager's decision, the persistence of vegetative residues in the cut and enclosed plots led to the highest litter coverage, whereas the grazed control plots, despite the cessation of grazing, recorded the lowest litter accumulation. By 2019, the enclosure plots with the cutting treatment exhibited the highest litter values, followed by the grazed plots with the same intervention, while the remaining grazed plots (branching and control) showed the lowest litter values. During the final sampling, shrub cutting, and enclosed treatments still had the lowest vegetation coverage of all plots; whereas branched plots (both grazed and enclosed) and grazed control plots exhibited the highest vegetation coverage. From 2016 to 2019, the proportional increase in grass cover was significantly greater in the enclosed plots compared to the grazed plots (Table 2).

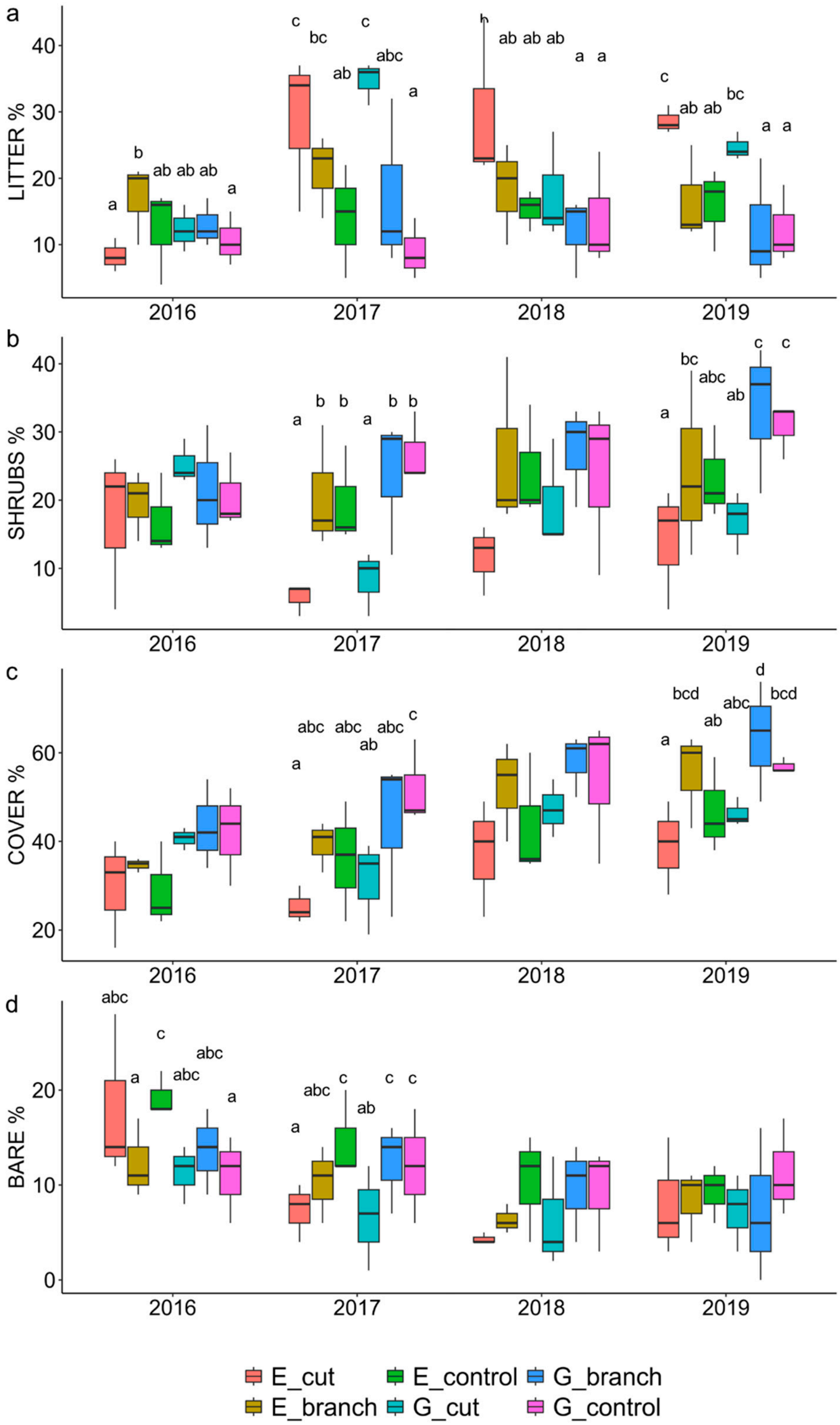

Figure 3. Box-plots showing the median (central horizontal line), quartiles Q1 and Q3 (lower and upper limits of the box), and the outlier-free range (vertical bars) for the percentages of (**a**) litter cover, (**b**) shrub cover, (**c**) total vegetation cover, and (**d**) bare soil, categorized by treatment and sampling year. Different letters indicate statistically significant differences ($p < 0.05$) based on pairwise mean comparison tests among treatments within the same sampling year.

Table 2. Proportional change in grass cover from 2016 to 2019 for grazed and enclosed conditions, irrespective of specific interventions. Values represent the proportional change in grass cover over the period. Different letters indicate statistically significant differences ($p < 0.05$) between conditions.

Condition	Mean	n	s.e	
Grazed	1.42	9	0.22	a
Enclosed	2.14	9	0.22	b

Shrub cut interventions (E_cut followed by G_cut) showed the longest ecological trajectories (Figure 4), with grazed sites (G_branch piles and G_control) exhibiting longer trajectories than enclosed sites (E_branch piles and E_control). Among the grazed treatments, G_control displayed the most significant directional change, particularly from 2017 to 2018. The enclosures without cut (E_branch piles and E_control) showed minimal directional change. Convergence testing indicated a trend towards similarity between the enclosed and grazed control plots by 2018, with a return to a state resembling that of 2017 by 2019. E_branch piles demonstrated the greatest trajectory stability, while G_cut sites were the most unstable.

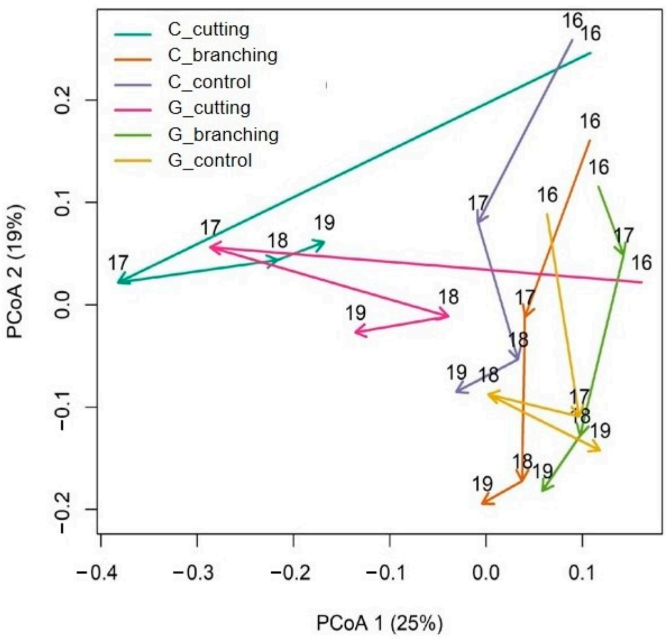

Figure 4. Graphical depiction of ecological trajectories illustrating community states during grassland rehabilitation treatments. Treatments include enclosure (E) or grazing (G) combined with interventions: shrub removal (cut), piles with pruning residues (branch), or no intervention (control). Each trajectory segment connects points from consecutive samplings, labeled with the last two digits of the sampling year (16, 17, 18, 19). Community coordinates are depicted in the first two dimensions of the PCoA matrix.

3.2. Changes in Soil Properties Due to Interventions and Grazing

We observed proportional soil changes in physical properties between the initial year (pre-intervention) and the final year (after 4 years). Clay content decreased in the interpatches of the control plots (Figure 5a), especially those under an enclosure, and increased in all the interventions. The erodible soil fraction (Figure 5b) generally decreased across all treatments over time, with patches of the enclosed plots with shrub cut demonstrating the sole significant increase.

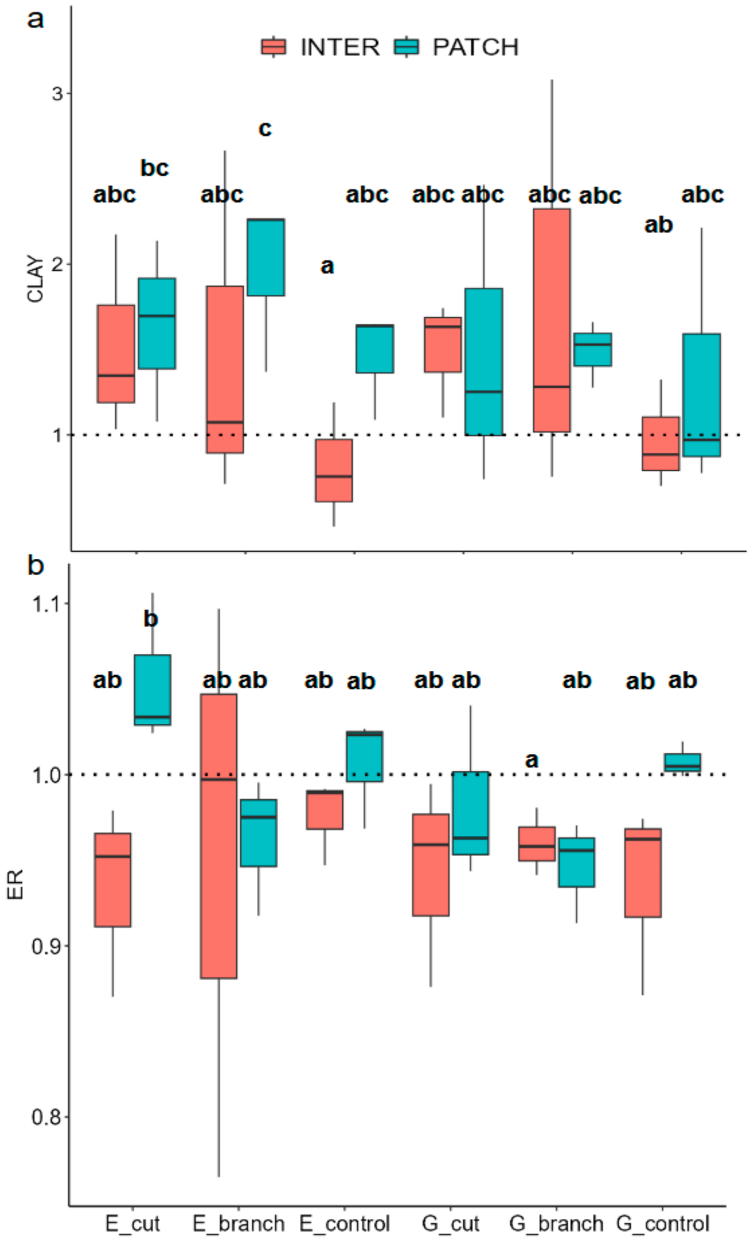

Figure 5. Box-plots displaying proportional changes in soil properties from 2016 to 2019, comparing vegetation patches (PATCH) and bare interpatch areas (INTER). Soil properties examined are (**a**) clay content (CLAY), and (**b**) the erodible fraction is less than 840 µm (ER). Treatment codes are the following: cut for shrub cut, branch for branch piles, E_ is for enclosed, and G_ is for grazed. The dotted line at Y = 1 represents no change. Values above the line indicate increases, while values below indicate decreases Bold letters above the bars denote mean comparisons across all conditions (patches and interpatches), with different letters indicating statistically significant differences ($p < 0.05$).

Regarding the proportional changes in soil chemical properties between the first and last year of sampling within patches and interpatches, excluding the analysis of livestock use, we observed that the total organic matter decreased proportionally only in the interpatches of the control plots (Table 3). In contrast, almost all other situations showed significant proportional increases.

Table 3. Changes in soil total organic matter (OM) proportions by 2019 (end of trial) relative to 2016 (initial sampling) across cut, branch piles, and control interventions, stratified by vegetation patches (PATCH) and bare interpatches (INTER). Values above 1 indicate an OM increase from initial levels, while those below indicate a decrease. Letters denote significant differences ($p < 0.05$) based on the Friedman mean comparison test.

Intervention	2016	2019	Mean	
control_INTER	4.20	3.99	0.95	a
cut_INTER	3.81	4.42	1.16	a b
cut_PATCH	4.01	5.09	1.27	b
branch_PATCH	3.66	5.16	1.41	b
control_PATCH	3.50	5.18	1.48	b
branch_INTER	3.08	4.32	1.40	b

4. Discussion

The increase in soil coverage is likely a response to precipitation fluctuations typical in grasslands [26]. However, persistent bare soil in the control grazed plots suggests that interventions, including exclusion, contributed to reducing the bare soil. The reduction of bare soil within 3 years indicates faster grassland recovery compared to the longer periods reported previously in Patagonia and other pastoral areas [46]. This reduction typically improves system functionality [56].

Our trials demonstrated that grazing reduces litter cover, expands bare soil patches, and promotes shrub growth, while reducing total vegetation cover, as reported in diverse ecosystems [57]. This effect negatively impacts forage provision and soil erosion control in the *Festuca*-dominated Sub-Andean steppes [58]. The sustained rise of the dominant shrub species suggests a continued decline in forage availability and soil protection, which explains the decrease in livestock loads reported in our study region [59].

In our study, under average precipitation conditions, fenced plots exhibited significant increases in grass coverage. These grasses, primarily grazed in winter, benefited from reduced herbivory during autumn and winter, which promoted vegetative growth and potentially enhanced forage provision. Managing resting paddocks during these seasons could protect preferred species from excessive defoliation and help restore degraded pastures without prolonged enclosure [33]. While similar long-term effects have been documented [46], our trial observed substantial increases in grass coverage within just three years of enclosure, highlighting the system's resilience and ability to restore functions after disturbance removal [13]. Additionally, potentially facilitative interactions from branches and shrub debris promoted grass cover. Canopy-dense plants, such as cushion species like *M. spinosum*, act as effective nurse plants, aiding in forage species recruitment [60]. Our study suggests that grasses may benefit from biotic facilitation through shrub litter, resulting in increased coverage [61]

The stabilizing effect of shrubs in grasslands [62] may be compromised if shrub cover drops below critical levels [63]. Cutting shrubs at the root collar maintains their regrowth capacity, temporarily reducing their competitive ability while preserving grassland stability and resilience in the assessed term [12]. Although further testing under diverse conditions is needed, our study suggests that this approach holds promise for enhancing grassland productivity under specific environmental conditions. Generating shrub litter through cutting and protecting it from grazing [64] mitigates the soil erosion risk due to its recalcitrance [65], while effectively reducing the resprouting shrub cover. Despite shrubs regaining coverage in the grazed plots over time, the effect of shrub cutting remained discernible until this study's conclusion. Maintaining reduced shrub cover in the long term may require complementary strategies [66]. In areas dominated by similar species, repeated cut interventions after significant shrub recovery may reduce their competitive advantage, diminishing their dominance in both fenced and grazed plots. Combining shrub cutting with subsequent grazing extends control over the shrub cover [67]. Our findings indicate that animal activity enhances litter incorporation into the soil, suggesting targeted livestock grazing strategies to suppress shrub cover and promote non-woody forage plants [68]. The choice between maintaining persistent litter cover or integrating it into the soil should consider soil fragility and erosion susceptibility.

The grazed plots reversed their trajectory within a year of cessation, underscoring the system's elasticity which is crucial for resilience [4] and highlighting the significant impacts of livestock on grasslands. Resistance, the ability to maintain stability amid disturbances, was compromised as the grazed plots exhibited substantial community shifts due to livestock interactions, indicating instability. Elasticity and stability are critical attributes for maintaining negative feedback mechanisms and preventing the ecosystem from reaching degradation thresholds [13]. The grassland recovery signs after grazing cessation highlight the rapid responsiveness of this system to well-planned management, while enclosures stabilize the interventions by removing grazing pressures, enhancing the intervention's effectiveness.

Livestock management was the primary factor influencing changes in the soil variables and secondary interventions. The enclosed areas effectively trapped erodible particles, while the grazed plots exhibited losses indicative of active erosion, highlighting soil vulnerability. Soil erosion in the region typically involves selective sand removal, a phenomenon observed in other parts of Patagonia [69]. Freeze–thaw cycles, particularly in bare interpatch spaces, further increase erosion susceptibility, making Patagonia one of the most erosion-affected regions in the country [70]. Our trial observed the initial signs of soil erosion mitigation, with grazing exclusion transforming the plots into sediment and resource-trapping sites. Cut interventions effectively controlled wind erosion, increasing the fraction of erodible material (<840 μm) within the enclosures. Vegetation cover, both live and dead, played a crucial role in trapping soil particles displaced from bare soil areas. Thus, enclosure combined with shrub cutting (and to a lesser extent, branch barriers) created zones of accumulated eroded material, enhancing the soil and air quality [71]. These early-stage effects underscore the urgent need for soil erosion management and highlight the potential of simple, low-input techniques for effective mitigation.

After three years of treatment and a return to normal precipitation levels following a prolonged drought, organic matter and clay increased in all treatment scenarios except for the interpatch spaces of the control plots. The clay fraction interacts with organic matter to develop stable microaggregates, enhancing the interaction capacity of smaller soil particles [72], which is crucial for soil nitrogen content [73]. Grazing exacerbates bare soil and reduces litter content, leading to soil desiccation caused by livestock, which destabilizes organic matter in microaggregates, resulting in erosion [74]. The interpatch areas in our study showed ongoing soil degradation due to historical and current disturbances, unlike the vegetated patches [59]. Grazing negatively impacts the soil carbon balance by decreasing inputs and increasing outputs, which contributes to the observed organic matter losses in the interpatch areas of the control plots.

The cut intervention protected the soil from erosion and increased the amount of organic matter in the shrub patches compared to the grazed controls, although it decreased in the enclosed soils. Unlike other long-term grazing exclusion studies in Patagonia [64], our trial did not show significant increases in soil organic matter with the pasture enclosure, suggesting that soil recovery in these water-limited systems may require more time [4]. Livestock exclusion can reduce organic matter input by decreasing the plant material and altering the decomposer activity through trampling and digestion [75]. Moderate grazing improves soil quality by increasing above-ground and root biomass and promoting higher-quality litter [76]. However, prolonged herbivore exclusion might decrease forage productivity and soil carbon incorporation due to reduced nutrient cycling [77]. Our results advocate for sectorized interventions utilizing accessible resources to enhance soil organic matter, as cut interventions partially reversed grassland degradation. While our trial revealed subtle changes, prolonged monitoring could uncover more pronounced effects.

Our findings suggest that grassland rehabilitation and improvements in forage supply can occur within shorter timeframes than typically observed [46,58], emphasizing the potential of combining local resources and moderate enclosure periods to mitigate erosion and enhance grassland conditions.

5. Conclusions

Our study highlights the significant early benefits of strategic livestock management interventions in the Patagonian grasslands, shortly after implementation. Over a three-year period, all treatments effectively reduced bare soil coverage compared to the continuously grazed plots, indicating immediate improvements in soil stability and erosion control. Livestock exclusion consistently promoted an increase in perennial grass coverage, underscoring its role in enhancing vegetation resilience against grazing pressure and promoting ecosystem recovery. Furthermore, interventions such as shrub cut within enclosures demonstrated rapid effects on litter coverage increase and the suppression of shrub re-establishment. Combining grazing with these interventions optimized mulch incorporation into the soil, further enhancing soil fertility and erosion resistance within the study period.

However, to validate the long-term sustainability of these interventions, continued monitoring of similar environmental and geographical settings is essential. Our findings suggest that adaptive management approaches integrating localized interventions and livestock impact monitoring offer promising strategies for restoring degraded grasslands under water-limited conditions. These conclusions emphasize the need for broader geographical and environmental validation to ensure the applicability and robustness of these strategies across diverse grassland ecosystems. Continued research will be crucial in refining these management practices and assessing their scalability and effectiveness in mitigating degradation and promoting sustainable land use practices globally.

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Appendix A

Table A1. PERMANOVA analysis results testing differences in composition between years, between treatments, and the interaction of both predictors. Significance codes: 0 '***'.

	gl	Sum of Squares	Mean Squares	F. model	R^2	Pr(>F)	
treatment	5	0.68	0.14	2.17	0.13	0.001	***
YEAR	1	0.58	0.58	9.35	0.11	0.000	***
treatment:YEAR	5	0.14	0.03	0.45	0.03	0.998	
Residuals	60	3.75	0.06	0.73			
Total	71	5.16	1				

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