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Controlled intensive grazing, trampling and nutrients supply improve grass cover in degraded grasslands of Tierra del Fuego (Argentina)

Pastoreo intensivo controlado, pisoteo y agregado de nutrientes mejoran la cobertura de gramíneas en los pastizales degradados de Tierra del Fuego (Argentina)

MENDOZA, R.; COLLANTES, M.; ANCHORENA J.

Museo Argentino de Ciencias Naturales "Bernardino Rivadavia" (MACN – CONICET).
Ángel Gallardo 470, C1405DJR. Ciudad Autónoma de Buenos Aires. Argentina.
Rodolfo Mendoza (corresponding author).
rmendoza@macn.gov.ar

Summary

A grazing experiment was conducted in the Magellanic steppe of Tierra del Fuego (Argentina) where degraded grassland had been subjected to extensive grazing for the last 60 years. The objective was to determine whether a series of treatments would effect a transition from that degraded grassland dominated by *Empetrum rubrum* of very poor forage quality into a richer, higher-quality cover. Nitrogen and phosphorus fertilizers and soil compaction by animals or artificial means were applied to restore certain ecological processes characteristic of an optimal grassland state —*e. g.*, raising the soil pH and increasing nutrient availability and grass cover. Soil pH and species diversity increased ($P \leq 0.05$) with intensive grazing, fertilization, or fertilization plus artificial trampling. Increased soil pH was associated with greater grass cover, while extensive grazing resulted in a decreased pH and a cover of prostrate cushion shrubs. After four years, the grass cover was the lowest in extensively grazed areas, but increased ($P \leq 0.05$) in areas where animals were excluded or else grazed intensively with and without fertilizer application. Grass cover in the intensively fertilized areas was more than double (at 67.0 %) that of other locations and was eight times greater than in areas that were extensively grazed (at 8.4 %). These findings contribute to the design of restoration systems for these degraded grasslands.

Keywords: grazing mode, N and P, forage quality

Resumen

Se estudió el efecto del régimen de pastoreo en la estepa magallánica de Tierra del Fuego, donde los pastizales degradados habían sido sometidos a pastoreo extensivo durante los últimos 60 años. El objetivo fue determinar si con una serie de tratamientos se podría realizar una transición desde un pastizal degradado y dominado por arbustos postrados (Empetrum rubrum) de muy mala calidad forrajera, a una cubierta de mejor calidad de forraje. Se utilizaron tratamientos de fertilización con N y P, compactación por animales y compactación por medios artificiales para medir cambios en propiedades del suelo y vegetación. El pH del suelo y la diversidad de especies aumentaron ($P \leq 0.05$) con: pastoreo intensivo, fertilización y la combinación de fertilización más pisoteo artificial. El aumento de pH suelo se correlacionó con una mayor cobertura de gramíneas, mientras que el pastoreo extensivo disminuyó el pH y aumentó la cobertura de arbustos postrados. Después de cuatro años, la cubierta de gramíneas fue la más baja en zonas sometidas a pastoreo extensivo ($P \leq 0,05$), mientras que en zonas donde se excluyeron los animales o bien pastaban intensamente con y sin la aplicación de fertilizantes la cobertura de gramíneas se incrementó. En las áreas intensamente pastoreadas y fertilizadas, las gramíneas cubrieron más del doble del terreno (67,0%) que en otros tratamientos, y fue además ocho veces mayor respecto a las zonas pastoreadas extensivamente (8,4%). Estos resultados contribuyen al diseño de sistemas de restauración de estos pastizales degradados.

Introduction

High-latitude soils are characterized by a slow turnover of nutrients, which limits forage production after defoliation by herbivores (Jefferies *et al*., 1994). On acidic soils from poor parent materials that are dominated by slowly growing plants, mammalian grazing has often altered ecosystem functioning and depressed productivity. That process is triggered by selective grazing, which produces a low-quality litter that retards nutrient cycling even further (Astor *et al*., 1993; Mendoza *et al*., 1995; Brathen *et al*., 2010; Anchorena *et al*., 2011).

The Magellanic steppe of Tierra del Fuego, between 52° and 54° S, is located within a typically cold and semiarid oceanic climate. The dry environment together with coarse parent materials has favored the development of acidic soils, heath communities, and vegetation types characterized by prostrate growth forms, such as *Empetrum rubrum*, that are conservative in nutrient consumption. The heathland soils in Tierra del Fuego are characterized by a low nutrient availability, strong acidity, a low base saturation, and high carbon/nitrogen ratios (Collantes *et al*., 1989).

Plant inventories made before the introduction of sheep (Dusen, 1905) as well as plant-soil inventories designed to disentangle natural and human controls of/influences on| vegetation (Collantes *et al*., 1989; 1999; Cingolani *et al.,* 1998; Cingolani, 1999) would indicate that the reference state for most acidic ecologic sites—*i. e.,* outwash plains and other geoforms of low nutrient soils—is a mixture of grasses and dwarf-shrubs, referred to as heath-grassland. Nowadays, most of these sites are occupied by *Empetrum* heathlands, while some relatively small sectors support short-grass communities (Cingolani, 1999). The heath would be a final state driven by long-term selective grazing that favored the increased dominance of *Empetrum*, while the short grassland would be a state produced by pulses of high-intensity grazing along with trampling, which would partly destroy *Empetrum* plants and inhibit further colonization (Cingolani, 1999). Soils of the heath state have decreased N cycling compared to the reference state (*i. e.*, heath grassland; Anchorena *et al*., 2001; 2011), and this difference was attributed to the allelopathic effects of *Empetrum* humus, which soil has been shown to inhibit growth and production of grasses (Mendoza *et al*., 1995, Bråthen *et al*., 2010). Experiments on soil fertilization on highly degraded heaths resulted in a pH increase when Ca was incorporated, and an increase in native grasses when fertilized with N and P (Mendoza & Collantes, 1998).

Other alternative consisted of a transition from the heath grassland (reference state) or the *Empetrum* heath (degraded state) into a productive herbaceous state mediated by high-intensity grazing. A similar transition was reported for circumpolar tundra communities under reindeer summer grazing (Olafsson *et al.,* 2001). In the Magellanic region several studies on the characteristics and mechanisms of this transition were undertaken, in search of a possibility for site restoration. The grassland state was found to have soils with a greater bulk density and a lower sand content as well as a higher pH and cation and P concentrations and a lower C/N ratio compared to the soils in the reference and heath states (Cingolani, 1999; Anchorena *et al*., 2001; 2011). N mineralization became increased beneath the grassland and, contrary to the heath states, nitrification dominated over ammonification (Anchorena *et al*., 2011; García *et al*., 2012). The grassland state is characterized by short grasses and some prostrate shrubs. The tussock grass *Festuca gracillima*, very common in the reference state, is totally absent or else occurs only in an open and patchy pattern (Cingolani, 1999).

In fact, the impact of a range of sheep-grazing modes was seen to have determined a series of varyingly degraded grasslands associated with specific levels of soil fertility, vegetation types, and arbuscular mycorrhizae; moreover, the colonization of a dark septate endophyte was present in the roots along with elevated levels of N in the tissues of *Avenella flexuosa*, a palatable soft grass distributed along the degraded grasslands in acidic soils of the Magellanic steppe of Tierra del Fuego (Mendoza *et al*., 2011; García *et al*., 2012). These studies suggested that the transition from heath to grassland would be caused by two drivers under high levels of sheep stocking: trampling and fertilization. Trampling would increase the bulk density of the soil, a variable that would enhance base retention by impeding leaching and might also increase N availability to plants (Bridgham *et al*., 1998). The death of *Empetrum* plants—those being sensitive to trampling (Tybirk *et al*., 2000)—would reduce its recalcitrant litter and the allelopathy effect (Zackrisson & Nilsson, 1992), thus facilitating a germination of grasses.

The other driver would be the input of nutrients by way of feces and urine from the grazers that would change the C/N ratio in humus soil and alter the competitive relationships between species that have different requirements for growth to favor the fast growing plants (Berendse, 1985). A positive feedback is then created between changes in the soil and the increase in graminoids tolerant to high grazing pressures, which grasses produce a decomposable and nutrient-rich litter (Hobbie, 1996).

The objective of the present study was to acquire information aimed at restoring certain basic ecologic processes and enhancing forage quality in order to approach, and ultimately attain, grassland status within a relatively short period of time through the addition of N and P fertilizers and an exerted artificial soil compaction. The hypothesis underlying the trial was that the addition of nutrients and an increase in soil bulk density, either through animal action or by using artificial means, would restore, at least partially, certain ecologic processes characteristic of the reference state, thus increasing the soil pH as well as the species and life-form diversity, especially through an increase in the grass cover. The conclusions from this trial should contribute to the design of restoration or rehabilitation systems for these

Materials and methods

Study site

The study site was located in the central area of the Magellanic steppe in Tierra del Fuego, near the city of Rio Grande (53º 47' S, 67º 42' W). This region has a temperate oceanic climate, cold and semiarid. The historical average annual rainfall for the period 1957–1988 was 362 mm, the average minimum temperature of the coldest months (June and July) -2.5 °C, and the average peak of the warmer months (December and January) 16.0 °C (Koremblit & Forte Lay, 1991). For collecting data of temperature and rainfall, an automatic weather station (Davis Instruments, USA) was installed at the María Behety ranch (60.000 ha), where the experiment was conducted. The average annual rainfall during the experimental period of four years (2003-2007) was 335 mm and the average rainfall for the four-month growing season (October to January) 99 mm. The minimum mean air temperature for that same period was 1.8 °C, the mean maximum 15.4 °C, and the mean median 8.3 °C; while the mean soil temperature (5-10 cm) was 8.2 °C.

We selected a large paddock in a sheep estancia that for nearly 60 years has received continuous low-intensity grazing with pulses of high stocking at the beginning of summer for 15–20 days. After approximately 1960 these pulses were suspended and the paddock was grazed by a traditional continuous extensive regime. Within the large paddock, a homogeneous area in topography, soil characteristics, and vegetation of approximately 5 hectares was fenced and supplied with drinking water for sheep. The site selected was a slightly undulated outwash plain of a Cryumbrept soil with 24% clay, 30% silt, and 46% sand (Anchorena *et al*., 2001). The soil was acidic and deficient in N and P for plant growth (Mendoza & Collantes, 1998). The main chemical soil properties are shown in Table 1.

Table1: Soil properties of the study site before installation of the experiment (Mendoza and Collantes 1998).

Horizon	Depth (cm)	pH (1:2.5w)	EC (dS/m)	C (%)	N (%)	C:N	P (mg/kg)	CEC (cmol/kg)	Base sat. (%)
Ao	4	4,9	0,17	16,3	0,68	24	9,4	29,2	48
A	11	4,7	0,31	7,5	0,51	14,7	0,6	27,8	17
A	20	4,7	0,15	3,75	0,24	15,6	0,5	19,8	10
C	> 20	5,1	0,14	0,5	0,03	16,7	0,3	11,8	33

The plant community at the beginning of the experiment was characterized as an *Empetrum* heathland (Cingolani, 1999) with high relative frequency of *Empetrum rubrum* (48%) and other dwarf cushion or evergreen cushion shrubs—*e. g.*, *Bolax gummifera*, *Azorella lycopodioides*, and *Baccharis magellanica*. The total evergreen-cushion-shrub frequency was 80%. Grasses were poorly represented (8%); with the most abundant being *Avenella flexuosa*, *Festuca gracillima*, *Festuca magellanica*, and *Poa spiciforme.* Forbs and herbs were scarce (4%). Lichens, *Pseudocyphellaria freycinetii,* and *Protousnea* sp. were also present. Bare soil occupied 10% of the area.

Experimental design

Within the paddock of 5 hectares, grazed during the experimental period at a stocking rate of 30-40 animals (Corriedale) per hectare for 3 weeks every year in early summer (December), permanent plots of 10-m length by 1-m width were placed and spaced no less than 40 m from each other. The animals were capons with an initial average of 60.8 kg per animal and after 3 weeks of grazing the paddock the average was 56.7 kg per animal.

The plots were randomly placed in December 2003 and 5 grazing treatments (5 plots per treatment) were randomly assigned:

1. *Intensive grazing* (IG): Five plots not fertilized were placed in December of the year of the establishment of the experiment (2003, one year before sampling and measurements began) along which 5 plots of 10 m x 1 m were placed.
2. *Intensive grazing with fertilization* (IGF): Five plots were similarly placed and fertilized with urea (46-0-0) and triple superphosphate (0-46-0) in December 2003, the year of the establishment at a rate of 100 kg.ha^{-1}.
3. *Intensive grazing with fertilization and artificial trampling* (IGFT): Another five plots were placed the 3rd year (2006) to measure the effect of fertilization plus an application of artificial trampling a year after. A manual mechanical compactor was used to simulate sheep trampling. The compactor, weighing 1.75 kg with an impact surface of 12.6 cm^2 (Fig. 1), was dropped freely and perpendicular to the ground from a height of 1 m above the ground. The pressure at the point of impact was about 0.06 MPa. In each plot 100 impacts were applied in the central 0.5 m over the 10-m length of the plot (5 m^2). The distribution of the impacts was at a rate of 10 per 0.5 m^2. The plots were fertilized as mentioned in Treatment 3.
4. *Traditional extensive grazing* (EG): In addition and adjacent to the 5 hectares of the fenced paddock, a further treatment was added in the year of the establishment of the experiment (December 2003). Five plots of 10 m x 1 m were similarly established but placed in an area outside the fenced paddock. This area was part of the same paddock that has been subjected to the traditional continuous extensive grazing regime for approximately the last 60 years. This grazing mode was used as a control treatment.
5. *Exclosure* (EX): Adjacent to the fenced paddock, other 5 plots of 10 m x 1 m were placed in an area of approximately 40 x 40 m. The area was fenced in the year of the establishment (December 2003), and grazing was excluded throughout the experimental period.

The experimental design could be taken as false replication trial because within a broad homogeneous paddock all treatments were set, instead of having many paddocks of similar management as repetitions are chosen. Because of the geomorphology, altitude, slope and soil characteristics; it is impossible to find repeated situations in the area. However, analyzing the studied variables separately year per year could be sufficient to justify the results, especially the effect of the different grazing treatments on grasses cover.

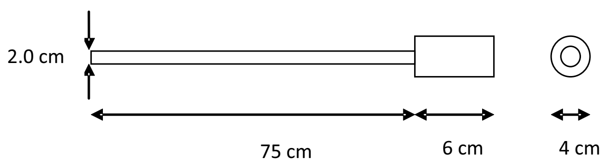
Vegetation and soil measurements

Changes in vegetation and soil measurements were recorded the year after the experiment was established and consecutively during 4 years (2004-2007). In each of the permanent 25 plots corresponding to the 5 grazing treatments that were replicated 5-fold, the species cover was measured by the point-quadrant method (Levy & Madden, 1933) in 100 points separated by 10 cm along the central 10-m line of each plot. In addition, bare soil, litter, and standing death vegetation were measured. The floristic similarities among treatments as measured by the Sorensen index ranged from 66 to 80% when the experiment was established one year before sampling. This degree of similarity is about the maximum that can be expected for replicate stands (Mueller-Dombois & Ellemberg, 1974). The cover of grasses was also estimated in the areas representing the EG and IG in the year of the establishment of the experiment. This measurement allowed us to identify the dominant plant life-forms present before the experiment was begun. Soil samples from the A horizon (0–15 cm) were collected to measure pH and the electrical conductivity (EC) at the end of the experiment in year 4 (Jackson, 1964).

Soil-penetration resistance (SPR) was estimated in the year of the establishment (2003) and again at the end of the experiment in the EG and IG treatments. Additionally to EG and IG measurements at the end of the experiment, SPR was measured in a paddock subjected to a historical intensive grazing (HIG) over approximately the last 60 years. This paddock is used every year as concentration area for 2–3 weeks in the early summer for the sheep on the way to shearing. Even though this information did not qualify as a treatment, the data would permit us to infer the effect of the different grazing modes from the overall data collected from our experiment. The SPR, an estimate of soil compaction, was measured with a penetrometer (Cosacov SACI & F) having a circular point of 1/10 square inch. Between 20 and 30 records were taken alongside the permanent plots. The operator penetrated the soil for a distance of at least 5 cm and then read the graduated driving shaft. The reading (kg) was divided by the needle cross sectional area (cm^2) and then converted to units of resistance (kN/m^2= kPa = 0.001 MPa) by multiplying by the factor 98.07 (Bradford, 1986).

The sampling for measuring soil pH (1:2.5 water) and species richness and diversity was started one year after the treatments were placed and thereafter was made for all four years at the rate of one per year—except for IGFT, installed in the 3rd year and thus only sampled once in the fourth, when the EC of the soil was

Figure 1. Diagram of the artificial compactor (1.75 kg) used to simulate the sheep trampling.



also measured. The soil pH and EC were analyzed in a pooled sample from 10 subsamples taken of topsoil from each treatment. All measurements on the soil and vegetation were made in late spring (December).

Data analysis
The effect of the five treatments on the floristic composition of the vegetation was analyzed by a detrented correspondence analysis (DCA) that included 85 measurements of 34 plant species —that is, 20 plots (EG, IG, EX, IGF) x 4 years plus 5 plots x 1 year (IGFT)— constituting a total of 85 lines of 100 measurements (8.500 points). DCA analysis is an eigenvector-ordination technique based in correspondence analysis (Kent and Coker, 1992). The DCA is geared to ecologic-data sets, and the terminology is based on sample units and species. DCA was devised in order to attempt to solve the two problems of correspondence analysis: the so-called "arc effect" and the compression of points at the ends of the first axis. Pearson's Correlation Analysis was calculated to determine the relationship of plant species to the DCA axes.

Species diversity was calculated from the species cover of each permanent plot on each date by means of the Simpson index: (D = $1-\Sigma(p_i*p_i)$), where p_i is proportion of individuals belonging to species i (PCORD 5.0; McCune & Grace, 2002).

The effect of the various treatments on SPR, EC, soil pH, grass cover, and species richness and diversity variables was analyzed separately for each sampling date (year) by one-way ANOVA (Statgraphic 5.0). The data were transformed to normalize the mean distribution when necessary. The Tukey test was used to compare the effects of treatments on the variables for each year separately at a significance level of $P \leq 0.05$.

In addition of the one-way ANOVA analysis separately year per year, a temporal split-plot analysis was used to analyze the changes in grasses cover affected by the four grazing treatments (IG, IGF, EG, and EX). The grazing treatments were used as main plot and each of the four years were used as subplot. The IGFT treatment was excluded from this analysis because the data were collected only for the fourth at the end of the experiment. This design permits the analysis of data from an experiment in which several observations of the same variable (total cover of grasses) were recorded on each of the experimental units over time (Rowell & Walters, 1978). The results were considered

Results

Soil acidity
The first change in pH occurred during year 2 of the experiment, and there in the fertilized plots of the IGF treatment. This result was repeated during the third year (Table 2). In the fourth year, the soil pH was the lowest in the EG treatment, which value differed from the EX and from the IGFT. The EC of the soil suspension was higher in all treatments including the EX, than in EG treatment. Moreover, the EC was higher in the IGFT than either in the EX or the IG treatment (Table 2). We also found a positive correlation between the values of grass cover and the values of soil pH and EC for the overall data set of the different grazing modes measured in soil on the last year of the experiment.

Soil-penetration resistance
The SPR in the first year of the experiment was 0.64 ± 0.15 MPa and 0.71 ± 0.04 MPa for the EG and IG treatments, respectively. After four years, the SPR was again similar between EG (0.65 ± 0.01 MPa) and IG (0.78 ± 0.04 MPa), but quite different from the historical intensive grazing (1.67 ± 0.24 MPa), measured in the paddock adjacent to the experimental site used as a concentration area of sheep for 2–3 weeks in early summer on the way to shearing (*cf.* Materials and Methods).

Floristic composition
When the experiment was started one year before the first sampling, the cover of grasses was similar between the areas representing the EG (10.8 ± 1.7%), the IG (16.8 ± 2.9%), and the EX (9.7 ± 1.2%). This measurement assured us that the cover of grasses was similar when the experiment began and that the differences, if any, could be ascribed to the grazing treatments.

The diagram of the vegetation-sampling points (centroids) of the DCA analysis (Fig. 2a) shows a clear grouping of treatments along axis I (23.5% of the variance). The treatments involving fertilization (IGF and IFGT) approached the origin, where soft grasses were concentrated, and correlated negatively with this axis (Fig. 2a-2b, Table 3). The EG points were ordinate at the positive end of axis I, where prostrate shrubs such as *B. magellanica* and *E. rubrum* predominated. The points sampled in the EX and in the IG groups occupied the central sector of axis I, where the acidophilous dwarf shrubs (*B. gummifera*, *A. lycopodioides*) and certain grasses are mixed together as a group.

Axis II (8.9% of the variance) separated the points sampled in the EX that occupied the top positive sector from the other treatments (Fig. 2a). The most prevalent acidophilous dwarf shrubs (*B. gummifera, A. lycopodioides*) together with the dominant tussock grass (*F. gracillima*) were positively correlated with this axis, while other grasses (*Agrostis* spp, *F. magellanica, P. spiciforme, A. flexuosa, T. spicatum*) were negatively correlated (Table 3).

The diagram of the plant species in the DCA analysis separated the three different life-forms studied (Fig. 2b), whereas the soft and short grasses were segregated to the negative sector of the axis I. The prostrate and cushion shrubs were displaced to the positive sector of this axis and *F. gracillima* of tussock life-form to the top right quadrant of the diagram.

Grass cover
The grass cover was greater in the IGF one year after fertilization (Table 4) and was again greater compared all others in the second year, while the cover was likewise greater in IG than in the EG at that time. In the third year, the grass cover in the EX also differed from that found in the EG, that cover being the lowest of all treatments. In the fourth year, the grass cover in the IGFT treatment more than doubled the others, and it was eight times greater than the cover observed in the EG. In addition, the EX, IG, and IGF treatments had similar grass covers three to four times greater than that of the EG (Table 4).

The statistical analysis was consistent with the results of the analyses performed separately for each year of the experiment and indicated a strong effect ($P \leq 0.000$) of the grazing mode on the grass cover (Table 5). Moreover, the differences between grazing modes remained similar with time, indicating that no further effect occurred over the 4-year period ($P \geq 0.05$). Over time, however, an interaction ($P \leq 0.000$) between grazing modes and the years became evident (Table 5). Figure 3 shows the graphical results of the split-plot analysis. The mean value of grass cover for each grazing mode over the four years differed among the four grazing treatments (with IGFT not being included in the analysis). The ascending order was EG < EX < IG

Table 2. Soil pH of the A horizon (0-15 cm) of the grazing treatments analyzed separately year per year and for the four years of the experimental period, and electrical conductivity (EC) of the soil at the 4th year of the experimental period.

Grazing mode	Year 1	Year 2	Year 3	Year 4	
	pH	**pH**	**pH**	**pH** [1]	**EC**
Extensive (EG)	4.65 a	4.84 a	5.20 a	4.95 a	0.17 a
Intensive (IG)	4.81 a	4.95 a	5.23 a	5.28 ab	0.20 b
Exclosure (EX)	4.95 a	5.02 a	5.21 a	5.37 b	0.20 b
Intensive-fertilized (IGF)	4.84 a	5.41 b	5.45 b	5.23 ab	0.21 bc
Intensive-fertilized-trampled (IGFT)				5.38 b	0.23 c

Figure 2. The plot in figure 2a shows the ordination for the first two axes of the DCA analysis of the grass cover for the different treatments (grazing modes) corresponding to the four years of the experiment. The points represent the centroids for each grazing mode (EG, extensive; IG, intensive; EX, exclosure; IGF, intensive-fertilized; and IGFT), intensive-fertilized-trampled) and the corresponding year as identified by the adjacent number. The plot in figure 2b shows the output of the DCA analysis for the most representative species (prostrate-cushion shrubs, soft grasses, and tussock grass) segregated to the different quadrants of the diagram associated with the various grazing modes.

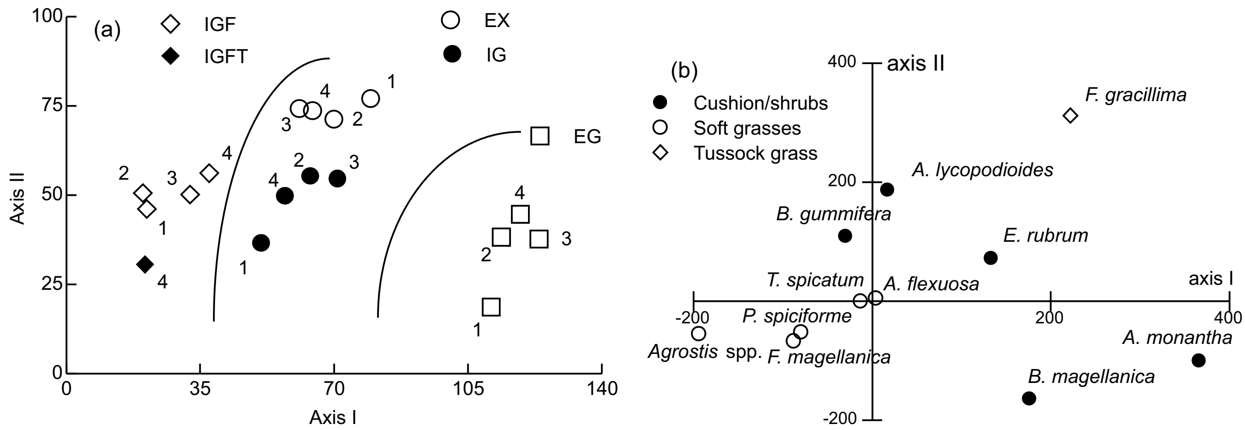


Table 3. Pearson correlation coefficient (R) and the *P*-value for the relationship between axes I and II of the DCA analysis and the cover of the plant species at the different grazing modes (EG, IG, EX, IGF, IGFT) and after 4 years of the experiment.

Plant species	Axis I		Axis II	
	R	*P*- value	R	*P*- value
Soft Grasses				
Poa spiciformis	-0.318	0.0030 **	-0.048	0.6636 ns
Festuca magellanica	-0.756	0.0000 ***	-0.306	0.0044 **
Trisetum spicatum	-0.697	0.0000 ***	-0.079	0.4701 ns
Agrostis spp	-0.489	0.0000 ***	-0.255	0.0183 *
Avenella flexuosa	-0.625	0.0000 ***	-0.048	0.6635 ns
Tussock grass				
Festuca gracillima	0.297	0.0058 **	0.394	0.0002 ***
Prostrate-Cushion shrubs				
Empetrum rubrum	0.127	0.2472 ns	0.597	0.0000 ***
Bolax gummifera	-0.760	0.0000 ***	0.354	0.0009 ***
Azorella lycopodioides	-0.431	0.0000 ***	0.717	0.0000 ***
Azorella monantha	0.558	0.0000 ***	-0.412	0.0000 ***
Baccharis magellanica	0.234	0.0226 **	-0.587	0.0000 ***

*= *P ?* 0.05; ** = *P* ? 0.01; *** = *P ?* 0.001; ns = no significant.

< IGF (Fig. 3a). In a comparison of the mean values for each year with respect to the four grazing treatments together, the grass cover was not affected among the years (Fig. 3b). The interaction between grazing modes and years indicated in Table 5 is clearly shown here (Fig. 3c). Whereas the grass cover decreased from years 1 through 4 in EG and IGF, the cover increased over time in the EX and did not change during the four years in IG treatment (IGFT was not analyzed.).

Richness and diversity
Species richness among the treatments did not vary during the experiment, except for the IGFT, where a greater richness occurred during the year after its installation than was seen with the EG over the four years (Table 6). The diversity was greater with both intensive-grazing treatments (IG and IGF) a year after starting the experiment and furthermore was greater with all grazing modes compared to EG during the third and fourth years.

Figure 3. Graphical results of the split-plot analysis to explain the changes in grass cover affected by the different grazing treatments (main plot) over time (subplot). The cover of grasses affected by the five grazing treatments is plotted over the four years together (3a), for the four grazing treatments for each individual year (3b), and a multiple comparison (grazing x year) of the grasses cover affected by all the grazing treatments (3c). Different letters above the columns indicate significant differences by the Tukey test at a level of $P \leq 0.05$. The data were logarithm-transformed for this analysis and then plotted as original data. The bars show the standard error of the mean. The IGFT treatment was not included in the analysis and represents only year 4.

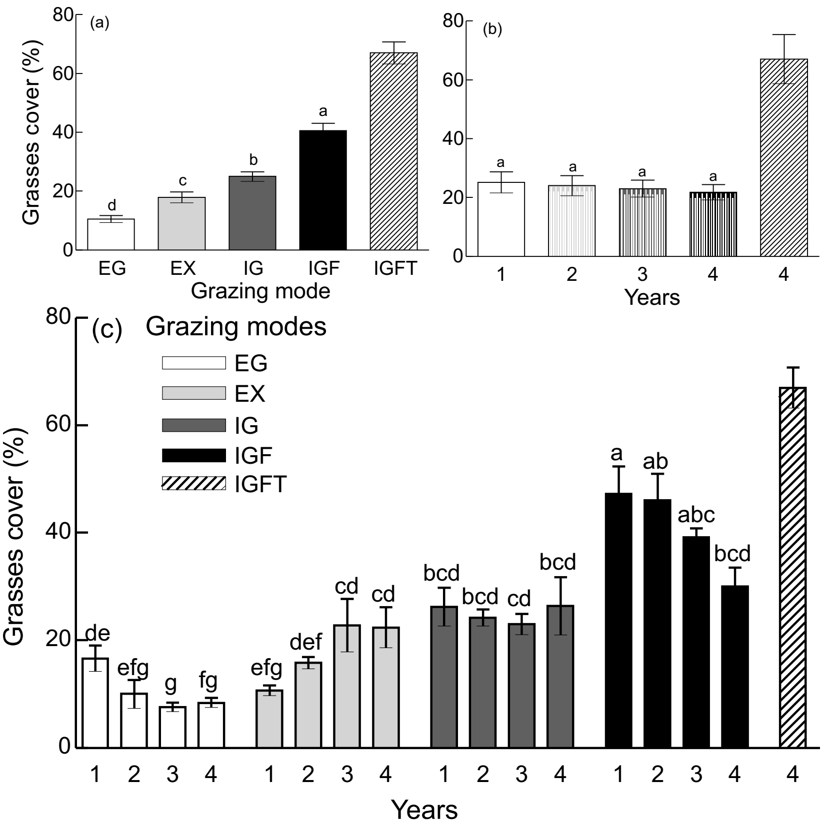


Table 4. Grasses cover (%) affected by the grazing treatment analyzed separately year per year and during the 4 years of the experimental period.

Grazing mode	Year 1	Year 2 [(1)]	Year 3 [(2)]	Year 4
Extensive (EG)	16.6 a	10.0 a	7.6 a	8.44 a
Intensive (IG)	24.2 a	24.4 b	23.0 b	20.5 b
Exclosure (EX)	10.7 a	15.8 ab	20.8 ab	22.4 b
Intensive-fertilized (IGF)	47.2 b	46.0 c	39.2 c	30.0 b
Intensive-fertilized-trampled (IGFT)	-	-		67.0 c

[1]Log transformed data. [2] Sqrt transformed data. Different letters for each year indicate a difference at a *P* ? 0.05 according to the Tukey test.

Table 5. Results of the split-plot analysis to explain the changes in grass cover (%) affected by the different grazing treatments (EG, IG, EX, IGF) used main plot with time (years) used as subplot.

Source of variation	D of F	Sum squares	Mean squares	F value	*P* value
Replicates (Rept.)	4	0,1793	0,0448	----	----
Grazing mode (GrM)	3	4,1205	1,3735	77,7	0
Error Rept x GrM	12	0,2121	0,0177	----	----
Year (time)g	3	0,0303	0,0101	0,65	0,587
GrM x Year	9	0,7904	0,0878	5,66	0
Error Rept x GrM x Year	48	0,7453	0,0155	----	----
Total	79	6,0779	----	----	----

[1] Logarithm transformed data.

Table 6. Species richness (SR) and diversity (DV) with respect to each grazing treatment (EG, IG, EX, IGF, IGFT) analyzed separately year per year during the 4 years of the experimental period.

Grazing mode	Year 1		Year 2		Year 3		Year 4	
	SR	DV	SR	DV[2]	SR	DV	SR	DV
Extensive (EG)	13.0 a	0.68 a	11.6 a	0.49 a	10.2 a	0.48 a	10.4 a	0.53 a
Intensive (IG)	15.4 a	0.78 b	15.6 a	0.71 ab	12.8 a	0.71 bc	14.0 ab	0.73 bc
Exclosure (EX)	13.6 a	0.68 a	13.2 a	0.67 a	12.0 a	0.69 b	11.2 ab	0.69 b
Int-fert (IGF)	15.0 a	0.82 b	15.0 a	0.82 b	13.8 a	0.79 c	13.2 ab	0.75 bc
Int-fert-tramp (IGFT)	-	-	-	-	-	-	15.4 b	0.80 c

[1] Abbreviations of grazing modes are indicated in table 2 and 3. Different letters for each year indicate a difference at a P ? 0.05 by the Tukey test. 2 Kruskal-Wallis test.

Discussion

This study demonstrated that adding nutrients and increasing soil compaction, either by way of animal action or through artificial means increased soil pH and enhanced the cover of grasses in degraded grasslands from the Tierra del Fuego. The results suggested that these grasslands could be rehabilitated for sheep production.

The addition of nutrients to arctic vegetation was seen to favor graminoids growth (Jonasson, 1992, Chapin *et al*., 1995, Chapin & Shaver, 1996). In those communities fertilization was found have similar effects to those of herbivory suggesting that the increase in grasses via herbivory may be a response to a larger nutrient pool resulting from urine and fecal deposition (McKendrick *et al*., 1980; Pastor *et al*., 1993). In our study, the soil pH increased the second year after the application of N and P fertilizers to the intensive-grazing treatment. Only on the fourth year of the experiment did soil acidity decrease under IG and EX conditions in a way comparable to that seen under the IGF treatment, as measured by EC (Table 2). The slow but progressive change in soil pH both upon EX and IG treatments suggested that changes in floristic composition might be leading an autogenic reparation of the system. The IG exposure, having a long period of rest after 2-3 weeks in summer, could possibly have acted over the short term mainly as a form of EX. The explanation would be that since the litter from graminoids decomposes faster than the litter from evergreen shrubs, the increment in graminoids with all treatments but EG that was accelerated by fertilizing would have changed the quality of the litter incorporated into the soil so as to accelerate nutrient cycling and increase the soil pH (Hobbie, 1996; Heal & French, 1974). In acidic soils of dry heath tundra, where evergreen shrubs dominated, N fertilization was seen to enhance productivity and species diversity, thus increasing the abundance of grasses; but species richness remained unchanged (Gough *et al*., 2002). In acidic soils, the activity of nitrogen-fixing bacteria is restricted, while the predominance of fungi might promote litter decomposition because of the specific fungal metabolic capability to decompose lignin and ability to penetrate fresh litter via hyphae (Hobbie & Gough, 2004). The results of those studies were consistent with the present findings and may explain the high values of the arbuscular mycorrhizae (26-48%) present and the dark septate endophyte (19–39%) colonization found in the roots along with the elevated N in the tissues of *Avenella flexuosa*, a palatable soft grass distributed along the degraded grasslands in the acidic soils of the Magellanic steppe of Tierra del Fuego (Mendoza *et al*., 2011; García *et al*., 2012).

The pronounced increment in grasses effected by the simulated trampling and fertilization in the IGFT treatment (Table 4) had been performed underscored the role of soil compaction (Willatt & Pullar, 1984; Greenwood & McKenzie, 2001). Since the pressure exerted by the hoof of a sheep on the soil surface while walking depends on many variables, no specific level of pressure on the ground can be computed. Nevertheless, sheep may in general exert a pressure of 0.05 to 0.08 MPa, but values could become as high as 0.20 MPa with varied slopes and the end points of the animal when waking (Willatt & Pullar, 1984; Greenwood & McKenzie, 2001). These pressures modify soil porosity, increase compaction plus moisture retention, and hence augment the floristic composition of the pasture (Cattle & Southorn, 2010). In our experiment, pastures in an adjacent paddock that had supported heavy stocking rates during several decades (*i. e.*, historical intensive grazing) reached SPR values of 1.67 MPa. Recent studies in the same area reported SPR values of 3.21-3.03 MPa in paddocks used as concentration areas for sheep for 2-3 weeks in the early summer on the way to shearing. In those paddocks, the number of animals per hectare was quite high, and substantial stocking rates such as those have consequential effects because the numbers of grazers can open the canopy, disturb the cover of prostrate shrubs, increase soil compaction so as to enhance water retention, and augment the soil fertility by their droppings and urine depositions (Mendoza *et al*., 2011). The vegetation of the present paddocks was dominated by soft grasses, while the soils had greater potential nitrification after 70 days of incubation (*e. g.*, 0.23-0.24 g $NO_3^-.kg^{-1}$) compared to soils subjected to the traditional EG of SPR values at 1.00-0.95 MPa with nitrification levels of 0.004-0.005 g $NO_3^-.kg^{-1}$ of soil (Mendoza *et al*., 2011). Measurements of soil nitrification are associated with the potential fertility of soil, and the present values were consistent with previous findings in which short-term grazing served to accelerate N recycling from dung and urine excretions (Day & Detling, 1990). This information would enable inferences regarding the effects of the different grazing modes on the basis of the data collected from our experiment. After 4 years of this trial, sheep trampling failed to change soil compaction with EG (0.64 to 0.65 MPa) or IG (0.71 to 0.78 MPa). When, however, simulated trampling was applied together with fertilization in the IGFT treatment, the grass cover increased 42% compared to the cover reached one year after fertilization in the IGF treatment (Table 4). This growth enhancement could be attributed to the increment in soil bulk density along with the accompanying decrease in porosity and increase in water retention.

Species composition has been shown to exert a substantial influence over litter and soil dynamics in various studies (Evans *et al*., 2001; Scott *et al*., 2001), but differences in bulk density and N availability in soil for plant growth between sites may also play a key role in soils that are acidic (Bridgham *et al*., 1998; Hobbie & Gough, 2004). These two variables are intimately associated and their interrelationship is consistent with our results. In light- and low-bulk-density soils, as are found in the degraded grasslands of Tierra del Fuego, the diffusion of nutrients through the soil to roots is often the rate-limiting step for the nutrient uptake of plants (Chapin, 1980). This limitation can be even more marked in the dry climate of the study area and—together with the low levels of N mineralization reported in soils subjected to EG—may lead to dramatic differences compared to soils subjected to compaction by heavy trampling or artificial means and/or given fertilizer or fertilized by animal action; where the bulk density, water retention, and the N-diffusion rate to plant roots have been seen to be increased.

The DCA diagrams clearly separated the five different grazing modes studied, each of which was associated with specific plant life-forms (Fig. 2). The traditional grazing (EG) was separated from the other modes and was associated with vegetation rich in cushion and prostrate-shrub growth forms, thus favoring nutrient-conserving plants of low forage value that accentuated the poor quality of the surface litter. In contrast, N- and P-fertilization combined with intensive grazing and/or simulated trampling (IGF, IGFT) became separated to the side opposite the other grazing modes and associated with palatable soft and short grasses of high relative growth rate, favoring a nutrient cycling that increased the quality of the litter. The non fertilized EX and IG treatments were both associated with growth forms suggesting that either short-term intensive grazing or long-term exclosure may lead to a restoration of certain basic ecologic processes over time —such as an increase in soil pH, species diversity, grass cover, and an enhanced forage value of these degraded grasslands— those having been invaded by cushion and prostrate evergreen growth forms as a consequence of the extensive grazing during the last 60 years. If the positive feedback leading to *Empetrum* heath could be shifted to another one leading to the establishment of grassland, a reparation of the system could follow a form of autogenic development, without the need of continuous nutrient subsidies, as noted by Whisenant (1999).

This field experiment constitutes a first step toward designing a process of rehabilitation to restore these degraded grasslands, which have been invaded by cushion and prostrate evergreen growth forms as the consequence of a long-term exposure to traditional extensive grazing. The strategy proposed here consists in an enhancement of the forage quality of the existing cover through an increase in soil fertility and water retention purely via animal action involving nutrient enrichment by their droppings and urine depositions and soil compaction from trampling. Further research is needed in the form of long-term experiments in order to confirm and extend the results of the present work.

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Acknowledgements

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