



Full Length Article

Rangeland Grazing Management in Argentine Patagonia

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Abstract

Stocking rate adjustment in grazing management is recommended as a management tool to sustain productivity and improve soil health of permanent grassland ecosystems. The aim of this project was to assess the effect of stocking rates under continuous grazing or simple levels of rotational grazing systems on the local environment, when using a moderate or high grazing intensity in the Argentine Patagonia. The parameters investigated were: 1) soil water infiltration and water retention capacity, 2) soil organic matter, N, erosion, and respiration and 3) Plant composition profiles, aboveground net primary production (ANPP), biomass above- and below- ground, physical plant characteristics, and species diversity. In the humid Magellanic grass steppe static rotational grazing was found to increase soil water infiltration rates, N, proportions of forbs and shrubs, root/aerial plant ratio, number of plant species, and proportion of dead plant. Continuous grazing had a greater ANPP, proportion of bare soil, and grasses and graminoids. Under silvopastoral Andean vegetation conditions, rotational grazing resulted in increased root biomass, root/aerial plant ratio, and proportion of forbs compared to continuous grazing, which was found to increase soil organic matter, N, plant length, root depth, aerial plant biomass, soil respiration, proportion of bare soil and dead plants compared to rotational grazing. Intensive grazing negatively influenced soil water, soil and vegetation parameters. The results indicated that adjustment of stocking rate or rotational grazing has a potential to store more biomass than continuous grazing. © 2020 Friends Science Publishers

Keywords: Grassland management; Soil health; Patagonia; Grazing

Introduction

Patagonia is a sparsely populated region of over 1 million km² in Chile and Argentina. The landscape of Argentine Patagonia is arid (Aagesen 2000) and the vegetation cover of grasslands varies from 60% or more to less than 10% in the most arid areas. Southern Patagonia is dominated by extensive livestock production systems with a restricted grass growth production period of 5 to 7 months due to low winter temperatures and water stress (Aagesen 2000). The most frequently used management system in Patagonia is continuous grazing with fixed stocking rates in paddocks varying from 1,000 to 20,000 ha with only a few farmers practicing rotational grazing systems (Ormaechea and Peri 2015).

The southern part of Patagonia (Santa Cruz and Tierra del Fuego provinces) is predicted to experience temperature increases of 2–3°C in the next 65 years. This increase will have a critical effect on the desertification of ecosystems in the region (Peri 2011). Valle *et al.* (1998) mapped most of the Patagonian region according to the level of

desertification and found that 9.3% was undergoing light desertification, 17.1% moderate, 35.4% moderate to severe, 23.3% severe, 8.5% very severe, and only 6.4% of the region's land shows no signs of desertification.

The nutrient pools are relatively small in these arid rangelands, and any decline in nutrient stocks will have an impact on the annual plant productivity. A decrease in the aboveground biomass will involve a decline in both soil carbon and nitrogen. Soil nitrogen loss may be due to either nitrogen lost in surface runoff and vegetation removal by livestock or both (Gallardo and Schlesinger 1992).

Through history, sheep rearing has been thought to cause reduction of vascular plant diversity through extinction of preferred forage species (Bertiller and Bisigato 1998). Over-stocking or overgrazing is a factor that may degrade soils and increase soil compaction (Oliva *et al.* 2012). Invasion of shrubs has resulted in a significant loss of nutrient-rich topsoil (Aagesen 2000). Grazing is also deemed responsible for a trampling effect that has destroyed the soil crust components (Scutari *et al.* 2004), and increased soil compaction, which in turn may be the cause

of decreased infiltration and increased runoff (Schlesinger *et al.* 2000). Increased runoff creates faster flows in waterways, with more soil being lost, and sediment loads increased.

In the ecosystems of Patagonia, soil carbon represents 79–90% of the total carbon pool, depending on plant and environmental conditions (Peri 2011). Peri *et al.* (2015) found that, across Patagonia, there is a significant difference in the soil respiration rates of grasslands with different vegetation composition. A greater soil respiration was seen in grasslands with trees than in those with only grasses and forbs. In addition, Peri *et al.* (2015) found that long-term intensive grazing decreases the soil respiration rate in grassland ecosystems. However, a thorough characterization and relationship between grazing intensity, grazing management systems and indicators of ecosystem health has never been established for this area. Therefore, a study was conducted to establish the relationship between indicators of ecosystem health, grazing intensity, and management systems in Southern Patagonia.

Materials and Methods

The data was collected from 2012–2015 in Southern Patagonia in the province Santa Cruz, in permanent plots (Fig. 1) established as a part of PEBANPA network (Biodiversity and Ecological long-term plots in Southern Patagonia) (Peri *et al.* 2016). Each measured factor had 3–5 replicates per year, for 4 consecutive years, all measured in the spring (November–January).

Study sites

The study sites included four ecological areas between the latitudes 48°N and 55°S: Dry Magellanic grass steppe, humid Magellanic grass steppe, Mata Negra Matorral thicket, and silvopastoral Andean vegetation. Hereafter called: dry grass steppe, humid grass steppe, matorral thicket, and Andean vegetation.

The four ecosystems are grazed at three grazing intensity categories: intensive, moderate, and low. The grazing intensity categories are determined by the National Agricultural Technology Institute (INTA), and are based on forage capacity of the ecological areas.

The values for low, moderate and intensive grazing are, therefore, not equal in the four ecological areas. One site at each ecological area is managed with a 6-month rotational grazing management system, at the predefined moderate grazing intensity, while the other site is managed with continuous grazing. However, only data from the Andean and Humid grass steppe ecosystems were available for comparisons between grazing systems.

Characteristics of the ecological areas

The dry and humid grass steppe covers 3 million ha with

grasses and shrubs as the dominating plant types. The dominant tussock species of these ecosystems are *Stipa chrysophylla* and *Festuca pallescens*, commonly associated with cool season *Poa dusenii* and *Carex andina* short grasses (Peri 2011), and these grasses cover 85% of the area (Peri and Bloomberg 2002).

Matorral thicket consists of shrubland, dominated mainly by *Junellia tridens*. Matorral thicket covers 2.8 million ha. in between the grasslands. Water is the most important factor regulating primary production in this area (Food and Agriculture Organization of the United Nations 2005). Shrublands play an important role in the southern Patagonian landscapes by providing a large number of important ecosystem services, such as soil fertility and richness, as well as the bulk of the biomass in the understory plant communities (Soliveres and Eldridge 2014).

Andean vegetation consists of deciduous *Nothofagus antarctica* forests used for silvopastoral systems with livestock feeding on natural grasslands that grow in the understory of thinned forests. The forest is thinned by sheep producers to maximize understory forage production. Forest thinning is a matter of balance since too much thinning of the forest may increase the evaporation and decrease the forage production, while too little thinning will hamper light penetration through the canopy and reduce forage production (Peri 2011).

Climate conditions

The annual precipitation across the region varies from 4000 mm at the foot of the eastern Andes to 150 mm in the central plateau 180 km east of the mountains (Soriano 1983). The east coast is dominated by moist air from the Atlantic sea with annual precipitation evenly distributed (200–220 mm), in contrast to the seasonal winter rainfall in the remaining region (Soriano *et al.* 1980; Paruelo *et al.* 1998). The climate of the region is generally dry, cold and windy. The windy season is from November to March with south winds and frequent windstorms occurring in the summer and spring months, with intensities up to 120 km/h (Peri and Bloomberg 2002).

Data collection

Soil and water measurements: The *soil water retention capacity* (mm/cm) was measured in the top layer of the soil by taking soil profiles from 0–30 cm length. The profiles were air dried and sieved (< 2 mm) prior to the determination of water retention curves with plates as described by Richards (1948). This method determines the value of soil moisture depending on the matric potential (-1500, -300, -100, -33 and -10 kPa). Gravimetric moisture in the soil at field capacity (-10 kPa) and gravimetric moisture at permanent wilting point (-1500 kPa) were calculated from the water retention curves to determine the available water retention capacity where: Available retention capacity =

field capacity - permanent wilting point.

The *soil water infiltration* data was measured with the double-ring infiltrometer method (ASTM International D3385-09, 2009). The method consists of driving two open cylinders, one inside the other, into the ground, partially filling the rings with water and then maintaining the liquid at a constant level. The volume of liquid added to the inner ring to maintain a constant level, is the measure of the volume of liquid that infiltrates the soil. The volume that infiltrates the soil during timed intervals is converted to an incremental infiltration velocity, expressed in cm/h and plotted versus elapsed time (measured every 15 min, for one hour). The average incremental infiltration velocity of the test is equivalent to the infiltration rate. It is important to notice that the soil of the matorral thicket is sandier than the other soils, and the infiltration rate is therefore expected to be greater than in the other ecological areas.

To characterize *soil properties*, five random soil cores were taken (0.20 m) at each study site. Soil organic carbon was measured to determine the soil organic matter, by the traditional wet digestion method (Allison 1960). Soil organic nitrogen was measured using a LECO auto-analyser (LECO Corporation 2016).

The level of *soil erosion* was determined by the Grassland Regeneration and Sustainability Standard 2.0 (GRASS) protocol scoring system (Borrelli *et al.* 2013).

Soil respiration (from roots and microorganisms) was measured at with 5 randomly chosen stations at each site each spring (November). The CO₂ resulting from soil respiration was measured using the soda lime method (Edwards 1982). The method is described in detail in Peri *et al.* (2015). In short, it consists of a chamber made of a jar with a known amount or dried soda lime within a bucket placed in the soil. Carbon dioxide flow is measured after 24 hours by soda lime absorption through weight changes. Soil respiration (gCO₂ h⁻¹ m⁻²) is calculated by correcting the measured CO₂ for losses due absorption by soda lime upon drying (Keith and Wong 2006).

Plant measurements

The *vegetation type* was estimated in three randomly selected linear transects of 20 m at each study site using the point method (Levy and Madden 1933). A frame with a row of 10 steel pins spaced at 2 cm intervals was used. At each study site, each transect was divided into 20 cm intervals and vegetation cover was noted at each point on the frame at each 20 cm interval. All vegetation present was reported as: dwarf shrubs, shrubs, forbs, grasses and graminoids, litter, and bare soil. In this way, 100 points were recorded for each transect.

The *annual above ground net primary production* (ANPP) of grasses and graminoids (expressed as g C m⁻¹ yr⁻¹) was estimated after maximum plant growth which occurs in December–January. This was done by clipping peak live plant material (current year's green production, excluding

woody tissue) obtained from three randomized 0.2 m² in three permanent enclosures (1.5 × 1.2 m) that were randomly distributed in each site. The clipped vegetation was stored in airtight boxes to avoid respiration losses. The samples were dried in an oven at 60°C for at least 24 h, weighed and biomass produced per ha calculated.

The *areal plant biomass*, *plant diameter at base*, *plant length*, *proportion of dead plant*, *root length*, and *root biomass* was measured at each site, by harvesting 6 individual plants of the grass species *Poa spiciformis* during the main growth period (November–December) with a 10 cm diameter auger. The grass was cored at the centre to a depth of 20 cm. The diameter at the canopy and crown height (cm) of each individual grass sample was measured before harvesting, on site. Upon arrival at the lab, the percentage of the cored plant that was dead was measured by visual comparison on a 0.5 by 0.5 cm scaled transparent graph. Then, after removing soil and insects, the grass samples were separated into green leaves, dry leaves, and apical meristems, and maximum root length measured. Roots and apical meristems were dried and weighed. The leaf area of the grasses was determined (cm²) by scanning the total harvest of green leaves per plant, using a flat plate scanner.

The *dominant plant community* and *no. of plant species* were measured at each sampling location in a 20 m × 50 m quadrat (1000 m²). The taxonomic classification of the species was classified according to origin (native, endemic, exotic), life-form (herb, graminoids, tussock grass, fern, shrub, dwarf shrub, tree), life-span (perennial, annual, biennial), and location of the plant's growth-point (meristem), by using Raunkiaer's classification system (geophyte, chamaephyte, phanerophyte, hemicryptophytes, cryptophytes, therophytes) (Raunkiaer 1934). In order to detect changes in vegetation over time, a survey was conducted using a point-quadrat lines procedure (Levy and Madden 1933) at biomass peak (December to January). This was done using two transects, 50 m in each plot and 500 hits per transect to record the percentage of the ground covered by vegetation (plant life forms), bare soil, and litter.

Data analysis

Data was analysed using the software R (R Development Core Team 2012) with the NLME package for linear models (Pinheiro *et al.* 2016). Vegetation profiles were plotted using Excel. All analyses were performed under the assumption that the data follows a multivariate normal or elliptical distribution. Summary statistics give an overview of the dataset by ecological area. A hierarchical cluster analysis was undertaken to investigate the correlations between the measured factors (Wickham and Francois 2015).

Vegetation composition profiles were made to investigate botanical composition sensitivity to the measured grazing intensity, within each ecological area,

assuming that the differences are due to grazing. Additionally, vegetation profiles were used to compare rotational and continuous grazing management at moderate grazing intensity in humid grass steppe and Andean vegetation. A linear regression analysis was made to determine if the measured factors were influenced by the ecological areas and the grazing intensities. The natural log of the plant percentages was used to remove the implications of the lower limit boundary of the data. The following linear regression was used:

$$y_{(ijk)} = \mu + \alpha_i + \beta_j + \alpha\beta_{ij} + \varepsilon_{ijk} \quad [1]$$

where y_{ijk} denotes the ijk^{th} observation, α ($i=1-4$) ecological area, β ($j=1-3$) grazing intensity, and $\alpha\beta_{ij}$ the interaction between ecological area and grazing intensity. ε (i,j,k) $\sim N(0, \sigma^2)$ distributed residuals. Interactions were found between area and grazing intensity for almost all measured factors, and therefore the following model was used for each ecological area:

$$y_{ij} = \mu + \alpha_i + \varepsilon_{ij} \quad [2]$$

where y_{ij} denotes the ij^{th} observation in a given ecological area, α ($i=1-3$) the grazing intensity, and ε_{ij} the residual error with $\varepsilon_{ij} \sim N(0, \sigma^2)$. When the analyses were statistically significant, the post-hoc Tukey's multiple-comparison procedure test in R, using the multcomp package, was used for separation of the means (Hothorn *et al.* 2008).

A two-sample T-test was used to determine if significant differences existed between the means of the measured factors for rotational and continuous grazing management in Andean vegetation and humid grass steppe, where the following hypotheses were made:

$$H_0: \mu_1 = \mu_2 \quad H_A: \mu_1 \neq \mu_2$$

Results

Exploratory data analysis

The summary statistics revealed that the Andean vegetation had the highest grazing intensity and lowest measured erosion. Matorral thicket had the lowest grazing intensity, yet the highest erosion. Andean vegetation had the greatest soil water retention capacity, soil respiration, aerial plant biomass, root mass, root length, and plant length. In contrast, the matorral thicket had the least soil respiration, and dry grass steppe, the least amount of aerial plant, root mass, root length, and plant length. Matorral thicket had the largest proportion of dead plants and Andean vegetation the least.

The dendrogram (Fig. 2) shows four correlation groups of the measured factors: 1) ANPP, soil water retention capacity, soil N, plant length, soil organic matter and soil respiration. 2) % cover by forbs, root/aerial plant ratio, % cover by grasses and graminoids, number of plant

species, root biomass, and root length. 3) % cover by shrubs, proportion of dead plants, % cover by dwarf-shrubs, % cover by bare soil, and soil erosion. 4) % Litter cover, soil water infiltration, aerial plant, and diameter at base. Group 1 and 2 are more closely related to each other than to group 3 and 4, and group 3 and 4 are more closely related to each other than to group 1 and 2.

Vegetation composition

The vegetation profile for each area and grazing intensity showed enormous differences in the systems (Fig. 3a–d).

A larger percentage of bare soil and dwarf-shrubs cover was found with increasing grazing intensity in all ecological areas (Fig. 3a–d). The increase in the proportion of bare soil with increasing grazing intensity is relatively proportional to the decrease in grasses and graminoids, while the proportion of forbs, dwarf shrubs and shrubs and litter cover stayed relatively constant. This was not the case in Andean vegetation where the percentage of litter cover decreased from 75 to 15% when low was compared to moderate grazing. Humid grass steppe was the only vegetation system that had an increase of litter cover with increased grazing intensity, from 2 to 9% when low is compared to intensive grazing.

Linear regression analysis

Significant grazing intensity differences were found for 16 and 17 factors respectively for dry grass steppe and humid grass steppe, and for 16 factors in matorral thicket and Andean vegetation (Table 2). Model [2] was therefore sufficient to describe the differences for 76 and 81% of the measured factors (16/21 and 17/21). All factors, except dwarf-shrubs, showed significant differences according to grazing intensity in at least one ecological area, and soil organic matter, soil N, bare soil, grasses and graminoids, ANPP, soil erosion, aerial plant, root, root length, diameter at base, proportion of dead plant, and number of plant species showed significant difference within all four ecological areas by grazing intensity.

However, the differences were not consistent. Intensive grazing was significantly different from moderate grazing for 13 factors in dry grass steppe, 11 factors in humid grass steppe, 15 factors in matorral thicket, but only 10 factors in Andean vegetation. Dry grass steppe, humid grass steppe, and Matorral thicket showed significant difference between moderate and intensive grazing in the following factors: organic matter, soil respiration, bare soil, ANPP, soil erosion, aerial plant, root biomass, root depth, proportion of dead plant, and no. of plant species. Only percentage bare soil, shrubs, soil erosion, aerial plant mass, root length, grams root to grams aerial plant ratio, diameter at base, plant length, proportion of dead plant, and number of plant species were significantly different between moderate and intensive grazing in the Andean ecosystem.

Table 1: Summary statistics of vegetation and soil characteristics of selected ecosystems in the Argentine Patagonia

Dry Steppe	Grass intensity	Grazing intensity	Soil infiltration	water retention capacity	Soil water retention capacity	Soil organic matter	Soil N	Soil respiration	Bare soil	Litter cover	Grasses and graminoids	Forbs	Shrubs
Min.	0.18	1.55	1.25	2.9	0.1	0.4	4.4	3.2	52	2.5	0.6		
Mean	0.32	1.68	1.59	3.5	0.2	0.6	12.8	10.8	65	5.8	1.1		
Max	0.51	1.81	1.95	4.4	0.3	0.7	24.7	20.1	72	9.8	1.8		
SD	0.15	0.08	0.23	0.42	0.04	0.09	7.64	6.07	6.53	2.26	0.41		
	Dwarf shrubs	ANPP	Soil erosion	Aerial plant	Root	Root/aerial plant ratio	Root depth	Diameter at base	Plant length	Proportion of dead plant	No. plant species		
Min.	1.1	5.1	0	4.2	1.2	0.3	6.8	4.5	1.8	1.9	15		
Mean	4.7	8.8	6	5.4	2.2	0.4	10.9	5.4	2.3	8.5	23.2		
Max	15.9	16.3	16.2	7	3.2	0.5	14.5	7.1	2.5	19	30		
SD	4.66	4.58	6.90	0.84	0.69	0.08	2.74	0.75	0.19	6.85	5.38		
Humid Steppe	Grass intensity	Grazing intensity	Soil infiltration	water retention capacity	water retention capacity	Soil organic matter	Soil N	Soil respiration	Bare soil	Litter cover	Grasses and graminoids	Forbs	Shrubs
Min.	0.10	0.74	1.73	3.5	0.5	0.5	0.1	1.9	66	4.4	0.1		
Mean	0.42	1.40	1.99	4.7	0.2	0.7	3.4	5.5	77	8.7	1.8		
Max	0.78	2.10	2.31	5.7	0.3	0.9	12.5	9.5	91	19.2	6.2		
SD	0.25	0.54	0.17	0.62	0.03	0.13	4.63	2.76	8.53	5.41	2.11		
	Dwarf shrubs	ANPP	Soil erosion	Aerial plant	Root	Root/aerial plant ratio	Root depth	Diameter at base	Plant length	Proportion of dead plant	No. plant species		
Min.	0.1	7.1	0	3.9	2.2	0.5	9.9	3.1	1.2	1.6	18		
Mean	3.2	13.3	2.5	6	3.8	0.65	14	4.9	4.4	5.9	33		
Max	7.9	21.1	8.8	10.1	6.0	0.82	16.6	7.6	7.9	16.9	42		
SD	2.49	5.58	3.36	1.98	1.18	0.09	1.73	1.40	2.15	5.35	8.21		
Matorral Thicket	Grass intensity	Grazing intensity	Soil infiltration	water retention capacity	water retention capacity	Soil organic matter	Soil N	Soil respiration	Bare soil	Litter cover	Grasses and graminoids	Forbs	Shrubs
Min.	0.15	2.36	0.98	1.89	0.1	0.3	16	3.8	18	0.5	17.7		
Mean	0.28	2.69	1.33	2.5	0.1	0.4	27	6.6	33	4.3	22.6		
Max	0.49	3.08	1.64	3.1	0.2	0.57	36	10.2	45	7.8	28.1		
SD	0.16	0.22	0.20	0.35	0.03	0.09	7.24	2.10	9.78	2.75	3.86		
	Dwarf shrubs	ANPP	Soil erosion	Aerial plant	Root	Root/aerial plant ratio	Root depth	Diameter at base	Plant length	Proportion of dead plant	No. plant species		
Min.	0.3	2.2	0	3.5	1.1	0.3	9.3	4.1	2.1	12	13		
Mean	7.2	4.7	12	6.8	2.6	0.4	12.6	6.1	3.1	23	18.4		
Max	15.3	8.4	33	10.9	4.5	0.5	16.7	8.9	3.9	39	23		
SD	4.99	2.27	13.91	2.49	1.28	0.06	2.08	1.49	0.60	9.15	3.81		
Andean Vegetation	Grass intensity	Grazing intensity	Soil infiltration	water retention capacity	water retention capacity	Soil organic matter	Soil N	Soil respiration	Bare soil	Litter cover	Grasses and graminoids	Forbs	Shrubs
Min.	0.0	1.98	2.61	3.1	0.2	0.5	0.3	11	11	0.8	0.0		
Mean	0.48	2.26	3.05	5.2	0.5	1.0	4.3	30	55	10.9	0.1		
Max	0.85	2.83	3.80	7.2	0.8	1.6	10.6	77	79	29.9	0.6		
SD	0.31	0.255	0.36	1.24	0.19	0.35	3.29	26.96	23.43	10.05	0.21		
	Dwarf shrubs	ANPP	Soil erosion	Aerial plant	Root	Root/aerial plant ratio	Root depth	Diameter at base	Plant length	Proportion of dead plant	No. plant species		
Min.	0.5	7	0.0	5.9	2.5	0.34	10.1	4.4	3.4	0.8	13		
Mean	3.3	17	1.6	8.2	4.3	0.6	13.4	6.0	7.0	2.6	10.4		
Max	8.6	5.4	5.4	11.7	7.3	1.0	17.7	8.4	10.1	7.3	28.0		
SD	2.51	9.71	2.07	1.84	1.50	0.25	2.22	1.18	2.05	2.52	5.48		

Rotational grazing management compared to continuous grazing

Less grasses and graminoids were detected in the continuous compared to the rotational grazing management system (Fig. 4), respectively 81 versus 71% in humid grass steppe, and 78 versus 52% in Andean vegetation. More forbs were found in the rotational grazing sites at both ecological areas and barer soil in the continuous grazing sites.

Differences between grazing management

Significant differences according to grazing management for 10 of the 21 measured factors were seen in the humid grass steppe ecosystem (Table 3). Seven of these factors (soil water infiltration, soil N, forbs and shrubs cover, root/aerial plant ratio, proportion of dead plants, and number of plant species) were greater for rotational grazing and

three for continuous (bare soil, grasses and graminoids, and ANPP).

Eleven factors were significantly different by grazing management in the Andean vegetation (Table 3). The three factors that were found greater for rotational management included forbs cover (%), root biomass (g), and root/aerial plant ratio (g/g) and eight factors were greater in continuous grazing management (soil organic matter, soil N, soil respiration, proportion of bare soil, aerial plant biomass, root and plant length, and portion of dead plants).

Discussion

The differences found in the four ecological areas in this project, regardless of grazing intensity, demonstrated that Matorral thicket was found to be different from the other systems in vegetation types, soil measurements, and soil degradation (Fig. 2). This was due to more shrubs, less soil organic matter, barer soil, and soil erosion. Herrick (2000)

Table 2: Linear model significance for effect of grazing intensity on measured factors within ecosystem. L = Low grazing intensity. M= Moderate grazing intensity. I= Intensive grazing intensity

Characteristics	Dry grass Steppe				Humid grass steppe				Matorral thicket				Andean vegetation			
	L	M	I	P	L	M	I	P	L	M	I	P	L	M	I	P
Soil water infiltration (cm/h)	1.72	1.70	1.62	0.357	1.86 ^a	1.07 ^{ab}	0.78 ^b	0.022	2.79	2.71	2.57	0.514	2.50	2.14	2.26	0.080
Soil water retention capacity (mm/cm)	1.70	1.65	1.40	0.247	2.09 ^a	1.97 ^{ab}	1.79 ^b	0.043	1.46	1.40	1.14	0.114	3.37	2.96	2.82	0.170
Soil organic matter (%)	3.44 ^b	3.96 ^a	3.20 ^b	*0.003	5.20 ^a	4.80 ^a	3.85 ^b	*<0.001	2.80 ^a	2.50 ^b	2.10 ^c	*<0.001	6.54 ^a	5.80 ^b	4.80 ^b	0.007
Soil N (%)	0.17 ^b	0.24 ^a	0.14 ^c	*<0.001	0.21 ^b	0.25 ^a	0.19 ^{ac}	<0.001	0.16 ^a	0.15 ^a	0.11 ^b	*<0.001	0.75 ^a	0.54 ^b	0.44 ^b	<0.001
Soil respiration (g C/m ² /h)	0.65 ^a	0.55 ^b	0.44 ^c	*<0.001	0.85 ^a	0.62 ^b	0.53 ^c	*<0.001	0.52 ^a	0.44 ^b	0.33 ^c	*<0.001	1.18	1.41	0.71	0.102
Bare soil (%)	5.90 ^b	10.17 ^b	22.47 ^a	*<0.001	0.39 ^b	1.87 ^b	10.90 ^a	*<0.001	19.27 ^b	25.90 ^b	34.50 ^a	*0.004	2.87 ^b	4.77 ^b	8.33 ^a	*0.012
Litter cover (%)	17.90 ^a	9.90 ^b	4.50 ^c	*<0.001	2.47 ^b	7.33 ^{ab}	8.17 ^a	0.019	8.40	6.17	5.23	0.162	74.17 ^a	15.60 ^b	12.47 ^b	<0.001
Grasses and graminoids (%)	68.80 ^a	66.90 ^{ab}	57.50 ^b	0.020	88.20 ^a	81.33 ^b	69.03 ^b	0.004	42.47 ^a	35.00 ^b	20.90 ^c	*<0.001	12.13 ^b	76.13 ^a	66.40 ^a	<0.001
Forbs (%)	3.27 ^b	8.03 ^a	6.13 ^a	0.004	5.48	6.00	5.82	0.150	0.97 ^b	6.03 ^a	5.80 ^a	0.006	8.27	1.47	7.03	0.580
Shrubs (%)	0.83	1.40	1.13	0.274	0.30	0.67	1.30	0.217	25.20	19.50	23.03	0.199	0.03 ^b	0.03 ^b	0.47 ^a	*<0.001
Dwarf-shrubs (%)	2.30	3.60	8.27	0.288	3.16	2.80	4.78	0.452	3.70	7.40	10.03	0.272	2.53	2.00	5.30	0.299
ANPP (gC/m ²)	6.10 ^b	14.80 ^a	5.50 ^b	*<0.001	8.40 ^b	19.50 ^a	7.90 ^b	*<0.001	4.10 ^b	7.50 ^b	2.50 ^c	*<0.001	32.30 ^b	12.80 ^b	0.015	
Soil erosion (%)	0.00 ^c	3.00 ^b	15.00 ^a	*<0.001	0.00 ^c	1.00 ^b	8.00 ^a	*<0.001	0.00 ^c	5.07 ^b	29.80 ^a	*<0.001	0.00 ^c	0.50 ^b	5.00 ^a	*<0.001
Aerial plant (g)	4.75 ^b	6.38 ^a	5.10 ^b	*<0.001	9.13 ^a	5.17 ^b	4.27 ^c	*<0.001	9.76 ^a	6.61 ^b	4.08 ^c	*<0.001	10.90 ^c	8.37 ^b	6.48 ^a	*<0.001
Root (g)	1.33 ^c	2.92 ^a	2.22 ^b	*<0.001	5.42 ^a	3.15 ^b	2.56 ^c	*<0.001	4.18 ^a	2.35 ^b	1.23 ^c	*<0.001	3.80 ^b	4.08 ^a	2.74 ^a	<0.001
Root/aerial plant ratio	0.29 ^a	0.46 ^b	0.43 ^b	<0.001	0.59	0.61	0.60	0.061	0.43 ^a	0.36 ^b	0.30 ^c	*<0.001	3.05 ^b	0.49 ^a	0.42 ^b	*0.002
Root depth (cm)	13.21 ^a	12.02 ^a	7.42 ^b	*<0.001	15.42 ^a	14.10 ^a	11.70 ^b	*<0.001	14.50 ^a	13.08 ^a	10.30 ^b	*<0.001	11.20 ^b	15.40 ^a	12.10 ^b	*<0.001
Diameter at base (cm)	4.96 ^b	6.18 ^a	4.92 ^{bc}	*0.002	7.06 ^a	3.46 ^b	4.40 ^b	<0.001	7.75 ^a	6.08 ^b	4.55 ^c	*<0.001	7.65 ^a	5.86 ^b	4.75 ^c	*<0.001
Plant length (cm)	2.29	2.16	2.31	0.389	5.05 ^a	7.18 ^a	1.74 ^b	*<0.001	3.19 ^b	3.63 ^a	2.35 ^c	*<0.001	9.20 ^a	8.05 ^b	6.80 ^{bc}	*0.009
Proportion of dead plant (cm ²)	5.70 ^b	2.20 ^c	17.60 ^a	*<0.001	4.5 ^b	1.80 ^c	14.70 ^a	*<0.001	34.20 ^a	13.50 ^c	20.60 ^b	*<0.001	1.10 ^b	1.50 ^b	6.80 ^a	*<0.001
No. of plant species	28 ^a	25 ^b	17 ^{ac}	*0.002	36 ^a	34 ^a	20 ^b	*<0.001	21 ^a	20 ^a	14.00 ^b	*0.009	16 ^b	27 ^a	15 ^b	*<0.001

Table 3: Differences between rotational and continuous grazing in the humid grass steppe and Andean ecosystems. Positive differences (RG-CG) signify rotational grazing management has the highest value and negative that continuous grazing management has the highest value. Significant levels shaded

Characteristics	Humid grass steppe				Andean vegetation			
	RG μ	CG μ	RG-CG	$\mu \pi - \sigma \alpha \lambda \nu \epsilon$	RG μ	CG μ	RG- CG	$\mu \pi - \sigma \alpha \lambda \nu \epsilon$
Soil water infiltration (cm/h)	1.92	1.06	0.86	0.005	2.33	2.14	0.19	0.61
Soil water retention capacity (mm/cm)	2.10	1.97	0.13	0.3	3.05	2.96	0.09	0.994
Soil organic matter (%)	4.90	4.80	0.1	0.269	3.5	5.8	-2.3	<0.001
Soil N (%)	0.26	0.25	0.01	0.008	0.3	0.5	-0.2	<0.001
Soil respiration (g C/m ² /h)	0.65	0.62	0.03	0.735	0.6	1.4	-0.8	<0.001
Bare soil (%)	0.4	1.9	-1.5	0.046	0.8	4.8	-4	0.001
Litter cover (%)	4.0	7.3	-3.3	0.232	16.6	15.6	1	0.122
Grasses and graminoids (%)	71.0	81.3	-10.3	0.024	52.8	76.1	-23.1	0.907
Forbs (%)	17.4	6.0	11.4	0.004	26.7	1.5	24.94	0.001
Shrubs (%)	5.0	0.7	4.3	0.039	0.0	0.0	0	0.052
Dwarf-shrubs (%)	2.1	2.8	-0.7	0.154	3.3	2.0	1.3	0.994
ANPP (gC/m ²)	17.4	19.5	-2.1	0.038	16.4	32.3	-15.8	0.759
Soil erosion (%)	1.0	1.0	0	0.153	1.1	0.5	0.6	0.386
Aerial plant (g)	5.6	5.2	0.4	0.299	6.9	8.4	-1.5	0.007
Root (g)	4.3	3.2	1.1	0.171	6.7	4.1	2.6	<0.001
Root/aerial plant ratio	0.78	0.61	0.17	<0.001	0.96	0.49	0.47	<0.001
Root depth (cm)	14.7	14.1	0.6	0.122	15.1	15.4	-0.3	0.041
Diameter at base (cm)	4.8	3.5	1.3	0.749	5.9	5.9	0.0	0.664
Plant length (cm)	3.7	7.2	-3.5	0.219	4.1	8.1	-4	<0.001
Proportion of dead plant (cm ²)	2.7	1.8	0.9	0.012	0.9	1.5	-0.6	0.006
No. of Plant species	40.7	34.0	6.7	0.003	39.9	27.0	12.9	0.074

demonstrated that shrubs tend to produce larger amounts of standing dead foliage and dead root biomass than grasses. This leads to greater amounts of above- and below-ground organic matter, which enhances the soil and water infiltration and improves soil fertility. Matorral thicket was found, in this study, to have less soil organic matter (Table 1) than the other ecological areas. However, the matorral thicket had the highest infiltration rate of the four ecological areas (Table 1). This is likely due to the sandy soils in this system which will influence the soil physical parameters

and hydrological properties (Blackburn 1975).

The Andean vegetation system included native forest vegetation, which may be the reason for the greater level of soil organic matter, soil infiltration, litter cover, soil water retention capacity, aerial plant production, plant length, root biomass and length, ANPP and the lower degree of soil erosion. The greater amount of litter cover, soil organic matter and the lower level of bare soil can be explained by the plant and litter cover that enhances soil infiltration rates and decreases evaporation, which ensures soil moisture is



Fig. 1: Data collection sites in Santa Cruz, southern Patagonia, Argentina. IG: Intensive grazing, MG: Moderate grazing, LG: Low grazing. Dry steppe: dry grass steppe. Humid steppe: humid grass steppe. Thicket: matorral thicket. Andean: Andean vegetation

retained after each precipitation event (Sacks *et al.* 2014). This increases soil microbial activity, which promotes soil stability, preserves plant nutrients and availability, increases plant-growing conditions, and leads to incorporation of more organic matter into the soil (Teague *et al.* 2011).

In this study matorral thicket with shrub vegetation had the lowest soil respiration rate followed by dry grass steppe, humid grass steppe, and Andean vegetation. Annual net plant productivity, soil water retention capacity, and soil respiration were found to be correlated (Fig. 2). Cao *et al.* (2004) demonstrated a link between soil respiration and level of vegetation cover and ANPP, based on the influence of root respiration, where Buyanovsky and Wanger (1983), demonstrated a correlation of moisture content in the soil and soil respiration, which both supports the finding in this study.

As regards grazing intensities, a general increase in the measured indicators suggest that increasing ecosystem health occurred with the increase from light to moderate grazing. This is in contrast to the change in the indicators suggesting a decline in ecosystem health that was generally

seen when comparing moderate to intensive grazing. However, this was not consistent within each ecosystem.

Aagesen (2000) and Basher and Webb (1997) found in Patagonia and New Zealand respectively that grazing intensity which removes large amounts of grasses, leads to bare soil patches and plant death. In both ecosystems, bare soil patches were invaded by less preferred forage species such as dwarf-shrubs and shrubs. This was seen when sheep started feeding on the tussocks when no preferred species were available, which usually occurs in the winter period in Argentine Patagonia. When the preferred grasses are removed and grazing on the base of the tussock begins, the tussocks form pedestals due to wind erosion. This exposes the roots, causing plant death and increased soil erosion (Basher and Webb 1997; Aagesen 2000). Results of this study are in an agreement with Aagesen (2000) and Basher and Webb (1997), in that soil erosion, bare soil, dwarf-shrubs, shrubs, and proportion of dead plant were closely correlated (Fig. 2).

In this study, it was found that the change from light to moderate grazing in the evaluated ecological areas generally

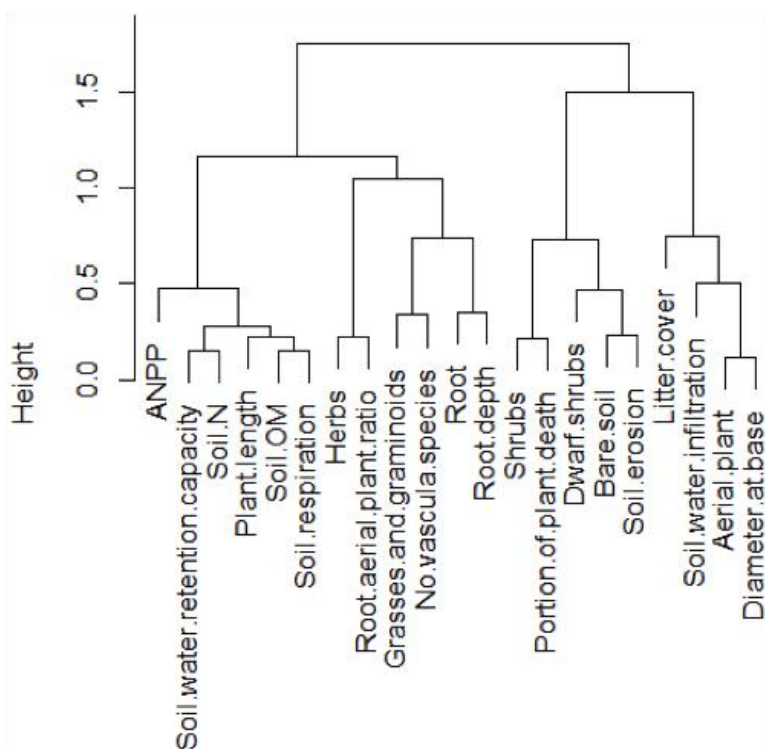


Fig. 2: Hierarchical dendrogram of measured factors for 4 ecological areas in the Argentine Patagonia

stimulated plant growth which in turn stimulated aerial plant, root biomass, and diameter of individual grass plants. The increased plant growth stimulated ANPP, soil organic matter, soil N, and in turn reduces soil respiration. This is in line with the results of Bertiller and Bisigato (1998), who found a reduction in number of plant species and changes in plant composition from grasses to shrubs and bare soil with increased grazing disturbance in Patagonia. The cover composition change found in this study are in line with the results of Aagesen (2000), who also documented an increase in shrubs and dwarf-shrubs cover and decrease in grasses with increased sheep grazing intensity in Patagonia. However, the decrease of grasses was not applicable to the Andean vegetation in this study, because the forest is selectively thinned when it is to be used for grazing to promote a higher forage production for silvopastoral use (Peri *et al.* 2016). The removal of trees increased the amount of grass cover from low to moderate grazing but decreased from moderate to intensive.

This can be explained by light normally being the primary limiting factor for plant growth (Seastedt and Knapp 1993), and the forest and sward canopy therefore limit the light penetration to the understory. Both thinning the forest and low intensity grazing can remove this light impedance and allow plant growth. This, in turn, allows above- and belowground biomass accumulation with water retention and nitrogen accumulation. When light is not a limiting factor, because the top part of the vegetation has been removed by grazing, nitrogen becomes the limiting

factor instead (Blair 1997). The highest levels of nitrogen are therefore most commonly measured in un-defoliated or very lightly defoliated grasslands (Teague *et al.* 2011). This is also the case for this study where the highest nitrogen measurements are found in low grazing followed by moderate and intensive grazing.

Intensive grazing in this study was associated with negative impacts in all factors (Table 2), that showed significant difference, compared to moderate grazing. The negative impacts that are seen with the use of intensive grazing in this study can, as in agreement with Teague *et al.* (2008), be attributed to a degree of overgrazing where the plants are exposed to multiple severe defoliations without sufficient time to recover between the events. This can then lead to a decline in plant productivity and root biomass, which is in line with the study of Briske *et al.* (2008). Thus, if livestock regularly removes large amounts of plant biomass and litter, a degradation spiral can be initiated, especially in the most used patches. The degradation spiral is characterised by replacement of taller perennial grasses by shorter grasses, annual grasses and forbs, and finally bare ground (Teague *et al.* 2004). This effect may be what is visible where the proportion of grasses decreases but bare soil increases with grazing intensity as well as forbs (Fig. 2; Table 2).

Several of the measured factors in this study are related to soil function, which is important since maintaining a normal soil function in rangeland ecosystems is critical for the overall health of the ecosystem (Barrett

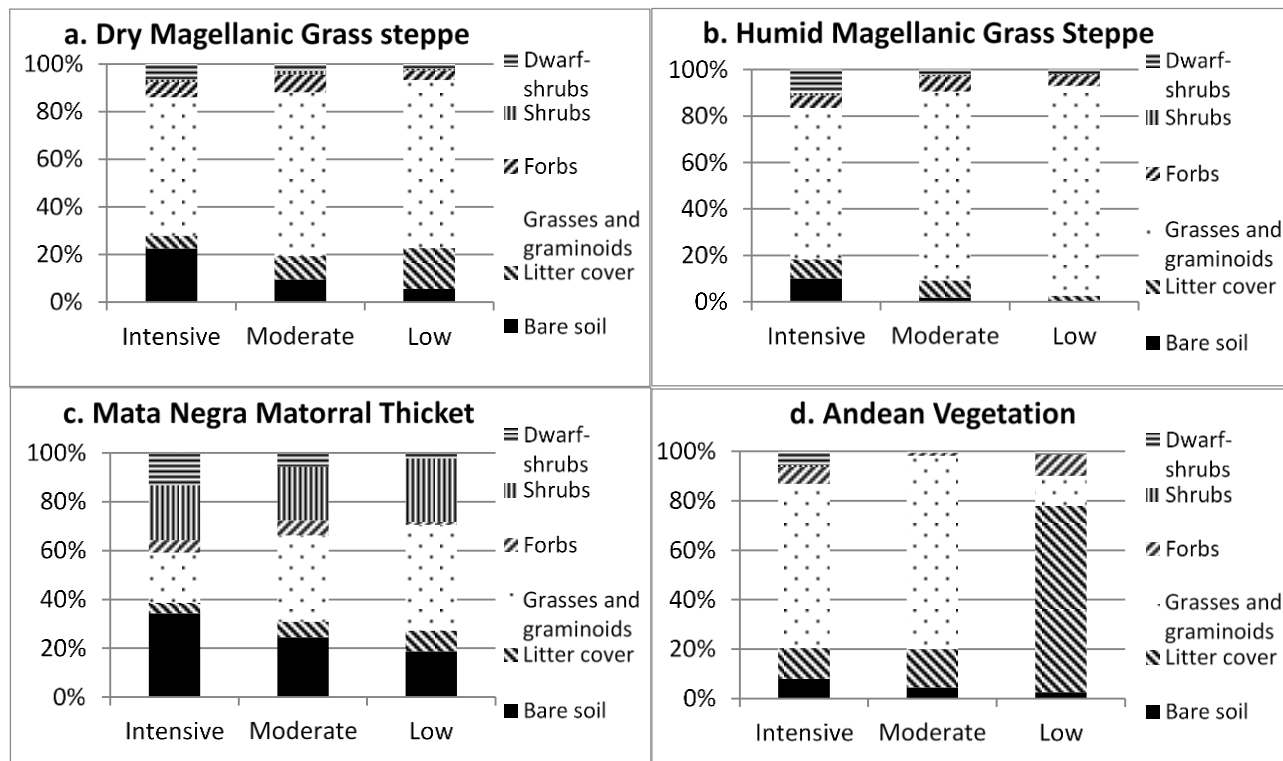


Fig. 3 a-d: Composition profiles of dry grass steppe (a), humid grass steppe (b), matorral thicket (c) and Andean vegetation (d) depending on grazing intensities

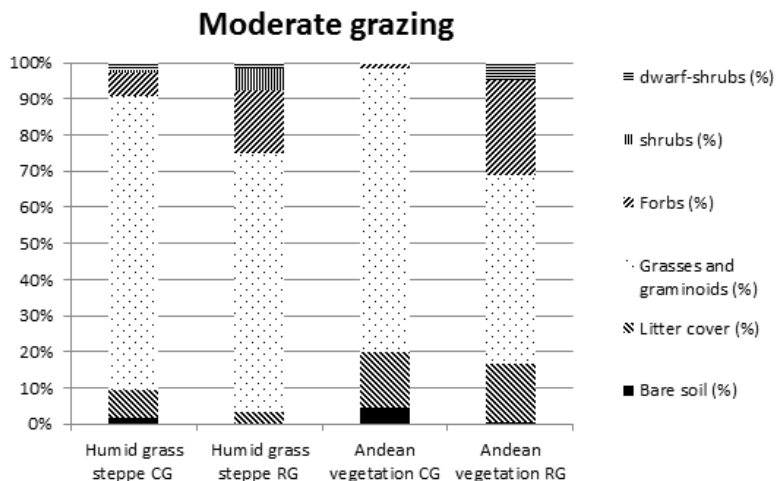


Fig. 4: Vegetation profiles of humid grass steppe and Andean vegetation with continuous (CG) and rotational grazing (RG) at a moderate intensity

2001). Barrett (2001) demonstrated that it is only possible to maintain a normal soil function if the soil has an adequate plant and litter cover to provide protection from soil loss, and thereby allows soil microorganisms to perform optimally. Soil respiration is therefore, not an absolute indicator of ecosystem health, as a decrease can be considered a health indicator under growth conditions, but may also be an indication of poor health during conditions

of drought and loss of biomass.

A correlation between the factors bare soil, soil erosion, and proportion of dead plant, and the factors litter cover, aerial plant, and soil water infiltration was found in this study (Fig. 2). It was demonstrated that these two groups of factors are closer correlated than to the rest of the factors. This is because their dependence on each other for soil functions. Asner *et al.* (2003) found that bare soil can be

seen as an indicator for soil function and for the risk of erosion. The risk of erosion increases if the soil cover is insufficient to disperse raindrops before reaching the soil (Schlesinger *et al.* 2000). The increased soil temperature and soil loss leads to negative effects on infiltration rates, soil evaporation, nutrient retention, and therefore the general biological functions that contribute to ecosystem function (Peri *et al.* 2015).

A decrease of infiltration rate and soil respiration with increased grazing intensity was found in this study (Table 2). One reason for this may be that the soil function can be inhibited by excessive trampling during heavy livestock use of an area (Asner *et al.* 2003). This can lead to soil degradation by increased soil compaction, which can elevate penetration resistance (Herrick 2000). It is difficult to tell from present study if this is the reason for the decreased infiltration rate, but the decreased respiration is in line with the results found by Peri (2015) and Cao *et al.* (2004), who found soil respiration to decrease with increased grazing intensity in Patagonia.

This study demonstrates that grazing intensity has an influence on the plant composition in all the investigated ecological areas and that intensive grazing is associated with negative impacts in all measured factors when compared to a moderate grazing intensity.

Grazing management strategies

The comparison of rotational and continuous grazing (Table 3) showed significant differences in humid grass steppe and Andean vegetation. The rotational grazing resulted in increased negative ecosystem health indicators for humid grass steppe (increase in proportion of shrubs and dead plants) but none for Andean vegetation and increased positive indicators in humid grass steppe (increased proportion of forbs, soil N, species diversity, soil water infiltration rate, and root/aerial plant rate) and Andean vegetation (increase in proportion of forbs, increased root biomass, and root/aerial plant ratio), compared to continuous grazing.

Continuous grazing also led to, more negative health indicators for humid grass steppe (increased proportion of bare soil) and Andean vegetation (increased proportion of bare soil, and proportion of dead plant) as well as increased positive indicators for them both (humid grass steppe: ANPP, increased proportion of grasses and graminoids. Andean vegetation: increased soil organic matter soil N, plant length, root length, aerial plant, and soil respiration) compared to rotational grazing.

The results for soil organic matter, soil water infiltration rate, and soil water retention capacity are in contrast to the study of Weber and Gokhale (2011), who found rotational grazing enhanced soil organic matter and soil-water content. This is supported by the study of Teague *et al.* (2011), who found rotational grazing in semi-arid rangeland to decrease impact on soil physical properties and

infiltration rates compared to continuous grazing at the same stocking rate. On the other hand, Carter *et al.* (2014) found no differences between rotational grazing and continuous grazing in terms of soil organic matter, soil water infiltration in soil, or soil erosion.

The lower levels of bare soil and proportion of dead plant found in this study with the use of rotational grazing are consistent with the study of Teague *et al.* (2011) and Teague *et al.* (2010), who found rotational grazing to maintain plant cover, decrease bare soil paths and soil erosion, provide lower soil temperatures, and increase soil carbon compared to continuous grazing at the same stocking rate. The lower proportion of dead plant in this study, however, only applies to Andean vegetation since continuous grazing had a lower proportion of dead plant in humid grass steppe. The level of soil erosion and litter cover was not significantly different with the two management strategies in neither humid grass steppe nor Andean vegetation.

This study found that rotational grazing influences several factors positively in humid grass steppe where the effect in Andean vegetation is limited to less bare soil and a lower proportion of dead plant (Table 3). In the comparison of continuous grazing and rotational grazing (Table 3) it was found that lands managed with rotational grazing had a plant composition with less grasses and graminoids and bare soil, but more forbs and litter cover. Teague *et al.* (2011) found rangelands managed with rotational grazing to have a higher proportion of desirable grasses and a lower proportion of less desirable grasses and forbs than lightly stocked continuous grazing. In this study, the percentage of grasses has not been differentiated into desired and less desired grasses, and both humid grass steppe and Andean vegetation were found to have a higher proportion of forbs when rotational grazing is compared to continuous grazing. The results of this analysis are therefore in contrast to the results of Teague *et al.* (2011).

Carbon content in soils can be seen as an indicator for soil health, plant production, water catchments, and even more importantly, as a sink for atmospheric carbon to offset climate changes (Janzen 2004). The management and use of rangelands is therefore crucial for the land's ability to sequester and retain organic carbon. Management that increases plant productivity increases carbon inputs to the soil, and decreases soil exposure to erosion and sunlight, allows higher levels of carbon accumulation in the soil (Parton *et al.* 1987). This analysis cannot clearly determine if there are higher levels of carbon in lands managed with rotational grazing compared to continuous grazing. However, the soil organic matter content showed a difference for Andean vegetation where continuous grazing had the highest content, but no difference was found in humid grass steppe, and the results are therefore inconclusive.

The decreased level of bare soil with the use of rotational grazing in both humid grass steppe and Andean

vegetation may indicate a positive influence on carbon sequestration and retention of organic carbon. Jones and Donnelly (2004) found that soil carbon availability is regulated by plant production and the amount of plant litter cover to provide physical protection of the soil. This analysis did not find a significant difference for litter cover but only a tendency for differences in the vegetation profiles (Fig. 3a–d), but the decreased level of bare soil can be a reason to believe that the rotational grazed lands may be able to sequester more carbon.

In this analysis, it was found that rotational grazing in Andean vegetation resulted in increased root biomass compared to continuous grazing, but in the humid grass steppe no significant difference was found. Sacks *et al.* (2014) found that increased root biomass growth causes stronger and more drought resistant plants. Wang and Fang (2009) found respiration produced primarily by roots and soil organism to be the primary pathway for CO₂ fixed by plants to return to the atmosphere (Wang and Fang 2009). Increased root biomass can therefore help to a greater carbon fixation. This may indicate that rotational grazing in Andean vegetation, which has significantly more root biomass than continuous grazing, is able to fixate more carbon.

Conclusion

Success of a static rotational or a continuous management system to sustain and improve soil health is dependent on the ecosystem. Intensive grazing influences the measured parameters negatively for soil water, soil health, and vegetation compared to moderate and low grazing. Thus, after 4 years of evaluation, results indicated that the light to moderate grazing intensity compared with intensive grazing has benefits to the ecosystem health. Multiple indicators of ecosystem health, as defined in this study, should be monitored in order to develop an efficient management strategy. The long-term goals of the local people and ranchers, food needs, and environmental concerns must be balanced in short-term management plans.

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References

Aagesen D (2000). Crisis and conservation at the end of the world: Sheep ranching in Argentine Patagonia. *Environ Conserv* 27:208–215
 Allison LE (1960). Wet-combustion apparatus and procedure for organic and inorganic carbon soil. *Soil Sci Soc Amer J* 24:36–40
 Asner GP, CE Borghi, RA Ojeda (2003). Desertification in Central Argentina: Changes in ecosystem carbon and nitrogen from imaging spectroscopy. *Ecol Appl* 13:629–648

ASTM International D3385-09 (2009). *Standard Test Method for Infiltration Rate of Soils in Field using Double-Ring Infiltrometer*. ASTM International, West Conshohocken, Montgomery County, Pennsylvania, Pennsylvania, USA
 Barrett JR (2001). Livestock farming: Eating up the environment? *Environ Health Perspect* 109:312–317
 Basher L, T Webb (1997). Wind erosion rates on terraces in the Mackenzie basin. *J Roy Soc New Zeal* 27:499–512
 Bertiller MB, A Bisigato (1998). Vegetation dynamics under grazing disturbance. The state-and-transition model for the Patagonian steppes. *Ecol Aust* 8:191–199
 Blackburn W (1975). Factors influencing infiltration and sediment production of semiarid rangelands in Nevada. *Water Res Resour* 11:929–937
 Blair JM (1997). Fire, N availability, and plant response in grasslands: A test of the transient maxima hypothesis. *Ecology* 78:2359–2368
 Borrelli P, P Boggio, P Sturzenbaum, M Paramidani, R Heiken, C Pague, M Stevens, A Nogués (2013). *Grassland Regeneration and Sustainability Standard (GRASS)*, 2.0: The nature conservancy and Ovis 21, Argentina
 Briske DD, JD Derner, JR Brown, SD Fuhlendorf, WR Teague, KM Havstad, RL Gillen, AJ Ash, WD Williams (2008). Rotational grazing on rangelands: Reconciliation of perception and experimental evidence. *Rangel Ecol Manage* 61:3–17
 Buyanovsky G, G Wagner (1983). Annual cycles of carbon dioxide level in soil air. *Soil Sci Soc Amer J* 47:1139–1145
 Cao G, Y Tang, W Mo, Y Wang, Y Li, X Zhao (2004). Grazing intensity alters soil respiration in an alpine meadow on the Tibetan plateau. *Soil Biol Biochem* 36:237–243
 Carter J, A Jones, M O'Brien, J Ratner, G Wuerthner (2014). Holistic management: Misinformation on the science of grazed ecosystems. *Intl J Biodivers* 2014:1–10
 Edwards NT (1982). The use of soda-lime for measuring respiration rates in terrestrial systems. *Pedobiologia* 23:312–330
 Food and Agriculture Organization of the United Nations (2005). *Grasslands of the World 34*. Rome, Italy
 Gallardo A, WH Schlesinger (1992). Carbon and nitrogen limitations of soil microbial biomass in desert ecosystems. *Biogeochemistry* 18:1–17
 Herrick JE (2000). Soil quality: An indicator of sustainable land management? *Appl Soil Ecol* 15:75–83
 Hothorn T, F Bretz, P Westfal (2008). Simultaneous Inference in General Parametric Models. *Biometric J J Mathemat Meth Biosci* 50:346–363
 Janzen HH (2004). Carbon cycling in earth systems - a soil science perspective. *Agric Ecosyst Environ* 104:399–417
 Jones MB, A Donnelly (2004). Carbon sequestration in temperate grassland ecosystems and the influence of management, climate and elevated CO₂. *New Phytol* 164:423–439
 Keith H, SC Wong (2006). Measurement of soil CO₂ efflux using soda lime absorption: Both quantitative and reliable. *Soil Biol Biochem* 38:1121–1131
 LECO Corporation (2016). *TruMac carbon/nitrogen/protein/sulfur in macro organic samples*. Available at: <https://www.leco.com/product/928-series> (Accessed: 04.05.2020)
 Levy EB, EA Madden (1933). The point method of pasture analysis. *New Zeal J Agric* 20:267–279
 Oliva G, D Ferrante, S Puig, M Williams (2012) Sustainable sheep management using continuous grazing and variable stocking rates in Patagonia: A case study. *Rangel J* 34:285–295
 Ormaechea S, P Peri (2015). Landscape heterogeneity influences on sheep habits under extensive grazing management in Southern Patagonia. *Livest Res Rur Dev* 27:1–11
 Parton WJ, DS Schimel, C Cole, D Ojima (1987). Analysis of factors controlling soil organic matter levels in great plains grasslands. *Soil Sci Soc Amer J* 51:1173–1179
 Paruelo JM, EG Jobbágy, OE Sala (1998). Biozones of Patagonia (Argentina). *Ecol Aust* 8:145–153
 Peri PL (2011). Carbon storage in cold temperate ecosystems in Southern Patagonia, Argentina. In: *Biomass and Remote Sensing of Biomass*, pp:213–226. Atazadeh E (Ed.). InTech Publisher, Croatia

- Peri PL, M Bloomberg (2002). Windbreaks in Southern Patagonia, Argentina: A review of research on growth models, windspeed reduction, and effects on crops. *Agrofor Syst* 56:129–144
- Peri PL, H Bahamonde, MV Lencinas, V Gargaglione, R Soler, S Ormaechea, GM Pastur (2016). A review of Silvopastoral systems in native forest of *Nothofagus antarctica* in Southern Patagonia, Argentina. *Agrofor Syst* 90:933–960
- Peri PL, H Bahamonde, R Christiansen (2015). Soil respiration in Patagonian semiarid grasslands under contrasting environmental and use conditions. *J Arid Environ* 119:1–8
- Pinheiro J, D Bates, S DebRoy, D Sarkar, RC Team (2016). *NLME: Linear and Nonlinear Mixed Effects Models*. R package version 3.1-131. Available at: <https://CRAN.R-project.org/package=NLME> (Assessed: 04.05.2020)
- Raunkiaer C (1934). The Life Forms of Plants and Statistical Plant Geography, being the collected papers of C. Raunkiaer. In: *The life forms of plants and statistical plant geography; being collected papers of C. raunkiaer*. ISBN 0-405-10418-9.
- R Development Core Team (2012). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, Available at: <http://www.R-project.org>. (Assessed: 04.05.2020)
- Richards L (1948). Porous plate apparatus for measuring moisture retention and transmission by soil. *Soil Sci* 66:105–110
- Sacks AD, R Teague, F Provenza, S Itzkan, J Laurie (2014). Restoring atmospheric carbon dioxide to pre-industrial levels: Re-establishing the evolutionary grassland-grazer relationship. *Geotheropy* 27:1–92
- Schlesinger WH, TJ Ward, J Anderson (2000). Nutrient losses in runoff from grassland and shrubland habitats in Southern New Mexico: II. field plots. *Biogeochemistry* 49:69–86
- Scutari NC, MB Bertiller, AL Carrera (2004). Soil-associated lichens in rangelands of north-eastern Patagonia. Lichen groups and species with potential as bioindicators of grazing disturbance. *Lichenol* 36:405–412
- Seastedt TR, AK Knapp (1993). Consequences of non-equilibrium resource availability across multiple time scales: The transient maxima hypothesis. *Amer Nat* 141:621–633
- Soliveres S, DJ Eldridge (2014). Do changes in grazing pressure and the degree of shrub encroachment alter the effects of individual shrubs on understory plant communities and soil function? *Funct Ecol* 28:530–537
- Soriano A (1983). Deserts and semi-deserts of Patagonia. In: *Ecosystems of the World - Temperate Deserts and Semi-Deserts*, pp:423–460. West NE (Ed.). Elsevier Scientific, Amsterdam, The Netherlands
- Soriano A, OE Sala, RJC Leon (1980). Vegetacion actual y vegetacion potencial en el pastizal de coiron amargo (*stipa* spp.) del sw. de chubut. *Bol Soc Argent Bot* 21:309–314
- Teague WR, SL Dowhower, SA Baker, N Haile, PB DeLaune, DM Conover (2011). Grazing management impacts on vegetation, soil biota and soil chemical, physical and hydrological properties in tall grass prairie. *Agric Ecosyst Environ* 141:310–322
- Teague WR, SL Dowhower, SA Baker, RJ Ansley, UP Kreuter, DM Conover, JA Waggoner (2010). Soil and herbaceous plant responses to summer patch burns under continuous and rotational grazing. *Agric Ecosyst Environ* 137:113–123
- Teague WR, F Provenza, B Norton, T Steffens, M Barnes, M Kothmann, R Roath (2008). Benefits of multi-paddock grazing management on rangelands: Limitations of experimental grazing research and knowledge gaps. In: *Grasslands: Ecology, Management and Restoration*, pp:41–80. Nova Science Publishers. NY, USA
- Teague WR, SL Dowhower, JA Waggoner (2004). Drought and grazing patch dynamics under different grazing management. *J Arid Environ* 58:97–117
- Valle HF, NO Elissalde, DA Gagliardini, J Milovich (1998). Status of desertification in the Patagonian region: Assessment and mapping from satellite imagery. *Arid Soil Res Rehabil* 12:95–122
- Wang W, J Fang (2009). Soil respiration and human effects on global grasslands. (special issue: Changes in land use and water use and their consequences on climate, including biogeochemical cycles). *Glob Planet Change* 67:20–28
- Weber KT, BS Gokhale (2011). Effect of grazing on soil-water content in semiarid rangelands of Southeast Idaho. *J Arid Environ* 75:464–470
- Wickham H, R Francois (2015). *DPLYR: A Grammar of Data Manipulation*. R package version 0.4.3. Available at: <https://CRAN.R-project.org/package=dplyr> (Assessed: 04.05.2020)