



## RESEARCH ARTICLE

# Grazing increases evapotranspiration without the cost of lowering soil water storages in arid ecosystems

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## Abstract

Grazing is the predominant land use practice in arid environments; however, there are relatively few studies of grazing effects on ecosystem functioning. We assessed the impact of grazing on soil moisture, evapotranspiration (ET), canopy conductance ( $G_c$ ), and root water uptake in the Patagonian steppe. Studies were done in 3 sites along a gradient of grazing intensity. High grazing intensity increased the soil water storage by 24% and decreased the amount of water extracted from deep layers compared to the low grazing intensity. Grazing affected ET and its partitioning into transpiration (T) and evaporation. High shrub cover and  $G_c$  increased ET and T or ET partitioning in the heavily grazed site. Annual ET increased from 78% to 92% of the annual precipitation from the lowest to the highest grazing intensity, respectively. Total T was 21% higher in the highest intensity site compared to the lowest intensity site. Changes in  $G_c$  suggest that grazing modified the canopy architecture, and thus the response of vegetation to environmental factors. At the beginning of the growing season when moisture was high,  $G_c$  exhibited the highest value in the heavily grazed site, but a strong regulation of water losses was observed under drier conditions. This study emphasizes the need to assess simultaneously multiple factors for understanding regulatory mechanisms of grazing effects on hydrological processes. From a sustainable management point of view, we suggest that increasing the number of water sources, and thus spreading the sheep in a paddock, can enhance the stocking rate while maintaining soil water storage.

## KEYWORDS

canopy conductance, depth of root water uptake, evaporation, open top chamber, Patagonian steppe, root distribution, soil moisture, transpiration

## 1 | INTRODUCTION

Evapotranspiration (ET) is a key component of the hydrological cycle in water-limited regions that can return back to the atmosphere a substantial amount of precipitation inputs (Huxman et al., 2005; Wilcox & Thurow, 2006). Evapotranspiration can be partitioned into two components; one of physical nature: evaporation from surfaces such as soil (E), and the other of biological nature: transpiration (T) derived from root soil water uptake and the loss of water mainly from leaves in the form of water vapor and partially controlled by stomata. Evapotranspiration is limited by the atmospheric demand of water vapor, which is driven by advection and radiation, and/or by soil moisture. The relative magnitude of these ET controls depends on the structure

and species composition as well as human intervention on ecosystem processes.

Grazing is the most ubiquitous land use practice worldwide. Grasslands, shrublands, and open forests impacted by domestic animals occupy about 25% of the global land surface, making it the single most extensive land use form (Asner, Elmore, Olander, Martin, & Harris, 2004). Despite the importance of these types of ecosystems, there are contrasting evidences on effects of grazing on hydrological processes. Grazing can change the biophysical structure of the canopy through defoliation and replacement of species and can alter soil hydraulic properties through modifications in soil impedance. These changes can alter soil water fluxes, soil–plant–atmosphere interactions, and the magnitude of the soil water storage (SWS; Chen, Lee, Lee, & Oikawa, 2007;

Li et al., 2000). The water cycle can be modified in different forms due to grazing. For example, total ET can be reduced (Bremer, Auen, Ham, & Owensby, 2001; Frank, 2003; Li et al., 2015; Wang, Liu, Ketzner, Horn, & Bernhofer, 2012; Wang, Liua, & Bernhofer, 2016), can be increased (Day & Detling, 1994), or can be maintained constant (Chen et al., 2007; Ketzner, Liu, & Bernhofer, 2008; Stewart & Verma, 1992).

Grazing effects on plant composition and shrub–grass balance have been thoroughly studied, but the results are controversial. In arid and semiarid ecosystems, grazing can decrease shrub cover (Cesa & Paruelo, 2011; Cipriotti & Aguiar, 2005; Lezama et al., 2013) or enhance shrub encroachment by removing grasses and increasing the number of empty microsites for woody species establishment (Adler, Milchunas, Sala, Burke, & Lauenroth, 2005; Aguiar, Paruelo, Sala, & Lauenroth, 1996; Archer, 2010; Oñatibia & Aguiar, 2016; Oñatibia, Aguiar, & Semmartin, 2015). Given the tight interaction between relative abundance of grass and shrubs in steppe ecosystem functioning, grazing impacts can have profound effects on soil water dynamic and energy exchange with the atmosphere (see Asner et al., 2004 for an overview of grazing effects on hydrological processes). There are effects of grazing on properties related to water fluxes between soil to atmosphere that have been mostly overlooked such as changes in canopy conductance ( $G_c$ ) due to partial removal of leaves and changes in patterns of biomass allocation to roots. Canopy conductance is one of the main determinants of the energy partitioning (Monteith & Unsworth, 1990), and it is used to evaluate the relative contribution of physiological versus physical factors determining ET (Baldocchi, Luxmoore, & Hatfield, 1991). Changes in patterns of root distribution due to different biomass allocation to belowground and aboveground plant parts or in species composition may also alter water distribution within the soil profile and root water uptake patterns (Lu, Chen, Wilske, Sun, & Chen, 2011).

Substantial efforts have been made to evaluate the impacts of grazing on ecohydrological processes in grasslands of North America (e.g., Bremer et al., 2001; Frank, 2003) and China (e.g., Li, Asanuma, Kotani, Davaa, & Oyunbaatar, 2007; Wang et al., 2012) compared to other regions of the world. Patagonian steppes, in the southern part of Argentina, had supported a high sheep stocking rate since the end of the 19th century (Golluscio, Deregibus, & Paruelo, 1998). Although the effects of sheep grazing on structural aspects of these steppes are relatively well known (e.g., Adler et al., 2005; Aguiar et al., 1996; Cesa & Paruelo, 2011; Cipriotti & Aguiar, 2005; Lezama et al., 2013; Oñatibia et al., 2015), there is paucity of information about their consequences on ecosystem functioning, such as on ecohydrological processes. Indeed, this is a little-known ecosystem with respect to plant–atmosphere interactions (Cristiano et al., 2016; Paruelo & Sala, 1995; Verón, Paruelo, & Oesterheld, 2011), and there is no empirical information relying on field measurements of ET and its components. In this ecosystem, the precipitation is scarce and occurs mainly in winter when air temperature falls below 0 °C, and thus, available water as well as soil and air temperature play a key role in ecosystem functioning (Bucci, Scholz, Goldstein, & Meinzer, 2009; Bucci, Scholz, Iogna, & Goldstein, 2011; Scholz, Bucci, Arias, Meinzer, & Goldstein, 2012). Long-term heavy grazing along with climate change had led to changes in species composition of Patagonian steppes (Golluscio, Bottaro, & Oesterheld, 2015) and possibly, to changes in the soil–water balance and plant sensibility to water availability. The main objective of this

study was to assess the impact of different grazing intensities on water fluxes, mainly transpiration from shrubs and grasses, evaporation from bare soil, and distribution of moisture within the soil profile. Because transpiration is strongly coupled with the rate of carbon assimilation, and thus with primary productivity (Pieruschka, Huber, & Berry, 2010), another objective was to assess ET partitioning into transpiration and evaporation at different grazing intensities. Moreover, we evaluated the effects of grazing on deep root distribution for the first time till 2 m depth. The experimental design of this study involved the use of sites at different distance from a permanent water source to understand the impact of grazing on the water economy at different spatial and temporal scales. We expect to contribute to a better understanding of the complex relationships between belowground and aboveground biomass, grazing pressure, soil water content, and soil–plant–atmosphere interactions.

## 2 | MATERIALS AND METHODS

### 2.1 | Study site and experimental design

The study area was located at 35 km from the Río Mayo town, Argentina, inside the Río Mayo Experimental Station of the Instituto Nacional de Tecnología Agropecuaria (INTA; 45°22'28"S 70°14'42" W). The vegetation is a typical Patagonian steppe dominated by few grasses and evergreen and deciduous shrub species. The vegetation is sparse with a substantial percentage of bare soil. The most conspicuous shrubs are *Molinum spinosum* (Cav.) Pers, *Adesmia volckmannii* Phil, and *Senecio filaginoides* De Candolle, and the dominant grasses are *Pappostipa humilis* cayabilles, *Pappostipa speciosa* Trinius et Ruprecht, and *Poa ligularis* Nees. Most precipitation falls during winter, but isolated rain events occur during the latter part of the summer season. Annual precipitation in the study area is about 150 mm, and the mean annual temperature is 8.1 °C. There is a compacted soil layer between 50 and 100 cm depth cemented by calcium carbonate. A water table can be found at 2.5 m below the soil surface. The region has been under sheep rising since the end of the 19th century (Golluscio et al., 1998); however, stocking rates have decreased over time due to the decrease in the amount of palatable forage and economic restrictions (Borrelli, 2001).

Three sites of 200 × 200 m located at 300, 1,400, and 2,500 m away from a permanent water source were selected. Within each site, we selected three plots randomly located of 50 × 50 m to obtain replicates of soil water content, root biomass, evaporation, and transpiration. In dry ecosystems, water source exerts a strong influence on livestock distribution by limiting the distance that animals move away from watering point. We consider distance to water as a surrogate indicator of grazing intensity. Because grazing intensity is partially a function of the number of animals, with increasing distance from watering point, decreases grazing intensity. Grazing intensity is high close to a water source whereas far from the water source, it is light (Lange, 1969; Sasaki, Okayasu, Takeuchi, Jamsran, & Jadambaa, 2005). We avoided the area immediately adjacent to the water source where stocking density is several times higher than the average density. The study paddock has a stocking rate of 0.14 sheep per hectare

from May to October, a period characterized by relatively high precipitations and low temperatures. The animals are removed from the study area during the rest of the year and transported to sites with abundant forage and available soil water. This is currently the dominant livestock management practice in most of the region.

In addition to the permanent water source distance, density of sheep fecal pellets was used as an independent index of grazing intensity (Adler et al., 2005; Golluscio et al., 2009; Lange & Willcocks, 1978). We counted the density of sheep feces in 10 points along 12 transects of 100 m within each grazing intensity site. All individual sheep feces pellets on 50 × 50 cm frames were counted at each point. Feces count was performed during September when animals were grazing.

## 2.2 | Root biomass and plant cover

Belowground biomass was obtained from three replicate trenches per grazing intensity (one in each plot of 50 × 50 m). Root density distribution was determined from soil samples of 0.047 m<sup>3</sup>, which were obtained every 10 cm from the soil surface down to 200 cm depth. The soil samples were washed to isolate the roots from soil particles in the laboratory, and the root material was dried in an oven during 72 hr at 80 °C and then weighted.

To determine plant cover, we used 12 transects of 100 m in each study site. Grass cover, shrub cover, and dead material (standing dead plant and litter) were estimated inside 50 × 50-cm frames along each transect at every 10 m. We measured the cover of three shrub species (*A. volckmannii*, *S. filaginoides*, and *M. spinosum*) and two grass species (*Pappostipa speciosa* and *Poa ligularis*), which represent more than 95% of the species coverage in the study site. Forbs account for less than 1% of the total cover, and they were not taken into account in this study. The perimeter or diameter of canopy of each plant was measured within each frame.

## 2.3 | Soil impedance and water content

Soil impedance, which is related to soil compaction, was measured with a penetrometer (Copains S.R.L INTA Villegas model) at 10 and 15 cm depth. Three replicates per depth and site were used for the analysis.

Soil volumetric water content was monitored every 30 min from the beginning of May 2013 to the end of December 2014 with ECH<sub>2</sub>O probes (Decagon Devices, Inc.). The probes have an accuracy of 0.03 m/m and a maximum temperature sensitivity of 0.003 m<sup>3</sup>/m<sup>3</sup> per 1 °C. The probes were calibrated in the laboratory with soil samples obtained from the study site and installed in the field at 10, 50, 100, and 200 cm depth. They were connected to a CR1000 data logger (Campbell Scientific, UT, USA). Three replicate per depth and site were used. SWS (in mm) was calculated by summing the water content at each 10 cm along the whole soil profile at the end of each month. Because the sensors were not installed at every 10 cm, water storage in the intervening layers was interpolated as an average of the sensors above and below the layer summed over the 10-cm intervals in the layer (Meinzer et al., 2004). The maximum amount of stored water in the entire soil profile (0–200 cm) was observed during September, and it was considered as SWS at the end of winter. SWS decrease

was estimated as the difference between SWS at the end of two consecutive months.

## 2.4 | Soil evaporation and transpiration

Evaporation from bare soil and transpiration were estimated using an open top chamber (OTC). The chamber was similar to that described by Scholz, Bucci, Hoffmann, Meinzer, and Goldstein (2010) and Cristiano et al. (2016) having the shape of a cone with a cylindrical base of 0.80 m in diameter made from clear acrylic plastic and a metal frame supporting the clear plastic. Cristiano et al. (2016) includes a diagram with all the components of the OTC. The top of the cone had an opening (exit port) of 0.2 m in diameter. Total chamber height was 1.66 m, and the volume enclosed was 0.64 m<sup>3</sup>. Air was pumped into the chamber using an inlet fan mounted near its base, and the flow rates were measured at the exit port using a propeller anemometer. Water vapor densities of air entering and leaving the chamber were measured with a dew point hygrometer (HR 33 T, YES, Yankee Environment System, Ontario, Canada). Air streams were ducted to an enclosure containing the dew point hygrometer using Beva-Line tubing at flow rates of 8 L/min and controlled by a mass flow controller. Output from the hygrometer was recorded at 1-s intervals with a datalogger (CR10X, Campbell Scientific). The air stream to the hygrometer was switched between inflow and outflow every 2 min. Air temperature of the outgoing air stream was maintained between 1 and 2 °C above ambient. Water vapor fluxes of the vegetation and soil enclosed by the chamber (0.5 m<sup>2</sup>) was calculated using the difference between water vapor density of air entering and exiting the chamber. evapotranspiration (ET; transpiration [T] + evaporation [E]) was calculated as

$$ET = V(\rho_{out} - \rho_{in})/A,$$

where  $\rho_{out}$  and  $\rho_{in}$  are the water vapor densities (g/m<sup>3</sup>) of the outgoing and incoming air streams, respectively,  $V$  is the volumetric flow rate (m<sup>3</sup>/s), and  $A$  is the basal chamber area (m<sup>2</sup>).

To minimize the effects of changes in microclimatic conditions during measurements (e.g., temperature increase), chamber measurements were done during a time as short as possible (Denmead, Dunin, Wong, & Greenwood, 1993). We placed the chamber on microsites with and without plants for about 4 to 6 min to estimate transpiration from the vegetation and the evaporation from the soil surface, respectively. The microsites used to estimate evaporation from bare soil were small areas without vegetation. Three replicates per grazing intensity (one in each plot of 50 × 50 cm) were obtained on grasses and bare soil and 9 replicates on shrubs of the three dominant species (one replicate per specie and per plot) at 2-hr intervals from dawn to dusk during two consecutive days during May, July, September, December, January, and March to obtain daily values of evapotranspiration.

We removed soil evaporation from ET to obtain transpiration values taking into account the evaporation from bare soil and the percentage of bare soil on the places where the chamber was placed above grasses or shrubs. To obtain ET at ecosystem level, the values of soil evaporation, grass transpiration, and shrub transpiration obtained with the OTC were weighted by the percentage of cover each component of in the study sites.

We tested the reliability of the OTC estimates by comparing the soil gravimetric water loss from a container with the evaporated water measured with the OTC. To avoid underestimation of soil evaporation because chamber blocks natural wind speeds, the measurements were obtained during days with low wind velocity. The soil surface was graded slightly where it contacted the chamber edge, to obtain a good seal between the chamber and soil. In addition, values of ET determined with the OTC in a similar area to that of this study were closely correlated with modeled ET estimated from MODIS products obtained by remote sensors (Cristiano et al., 2016).

## 2.5 | Canopy conductance

Canopy conductance to water vapor ( $G_c$ ; mm/s) was calculated from average diurnal T (mm/d) and average diurnal air saturation deficits (D, kPa), using the Monteith and Unsworth (1990) equation:

$$G_c = K_c t_a (T/D),$$

where  $K_c = 115.8 + 0.4236 t_a$ ;  $\text{kPa}\cdot\text{m}^3\cdot\text{kg}^{-1}$ , is the conductance coefficient that accounts for temperature effects on the psychrometric constant, latent heat of vaporization, specific heat of air at constant pressure, and the density of air, and  $t_a$  is bulk air temperature (Phillips & Oren, 1998). Phillips and Oren (1998) showed that errors associated by lumping the temperature-dependent physical coefficients into  $K_c$  are negligible. This simplification requires that vertical gradients in D between the leaf surfaces and the bulk air above the canopy to be small. We assumed a relatively good aerodynamic coupling between canopy and the atmosphere because the canopy is open and sparse.

## 2.6 | Statistical analysis

The SPSS 11.5 statistical package (SPSS, Chicago, IL, USA) was used for statistical analysis. Analysis of variance with a confidence level of 95% was used to test the data for differences among sites with different grazing intensity and test for the interaction between sites and months. A posteriori Tukey test was used. Previously, the assumption of normality and homoscedasticity were tested. A student's  $t$  test was performed to compare plant cover and transpiration among grasses and shrubs and soil impedance at 10 and 15 cm depth within a site. Sigma Plot software (SPSS, Chigado, IL, USA) was used to fit mathematical algorithms to the regressions.

## 3 | RESULTS

### 3.1 | Livestock feces, plant cover, and root density

The density of feces, an indirect measurement of grazing intensity, decreased significantly with increasing distance from the study sites to the permanent water source (Table 1;  $F = 12.98$ ;  $p < .001$ ). The site closer to the water source (high grazing intensity) exhibited fourfold and 15-fold more feces than the intermediate and low grazing intensity sites, located at 1,400 and 2,500 m from the water source, respectively (Table 1,  $p < .001$ ).

**TABLE 1** Characteristics of the three study sites (high, intermediate, and low grazing intensity sites) defined as a function of the distance of each site to the permanent water source

	Grazing intensity		
	High	Intermediate	Low
Distance from water source (m)	300	1,400	2,500
Livestock feces (#/m <sup>2</sup> )	44 ± 10 <sup>a</sup>	10 ± 0.4 <sup>b</sup>	3 ± 0.2 <sup>b</sup>
Grass cover (%)	12.8 ± 1.1	13.3 ± 1.4	13.7 ± 1.1
Shrub cover (%)	22.3 ± 3.6	17.1 ± 2.7	15.7 ± 3.4
Dead material (%)	1.2 ± 0.78 <sup>a</sup>	6.4 ± 1.9 <sup>b</sup>	5.4 ± 1.76 <sup>b</sup>
Bare soil (%)	63.8 ± 3.6	63.2 ± 3.8	65.2 ± 3.4
Root density (g/m <sup>3</sup> )	8,185 ± 515	8,181 ± 818	8,519 ± 352
Mean height shrubs (cm)	68.3 ± 3.5	63.5 ± 2.1	59.1 ± 4.2
Leaf area index	0.87 ± 0.05 <sup>a</sup>	0.75 ± 0.05 <sup>b</sup>	0.71 ± 0.04 <sup>b</sup>
Soil impedance (MPa) at			
10 cm depth	0.71 ± 0.03 <sup>a</sup>	0.45 ± 0.02 <sup>b</sup>	0.4 ± 0.03 <sup>b</sup>
15 cm depth	1.44 ± 0.04 <sup>a</sup>	1.09 ± 0.06 <sup>b</sup>	0.85 ± 0.05 <sup>b</sup>

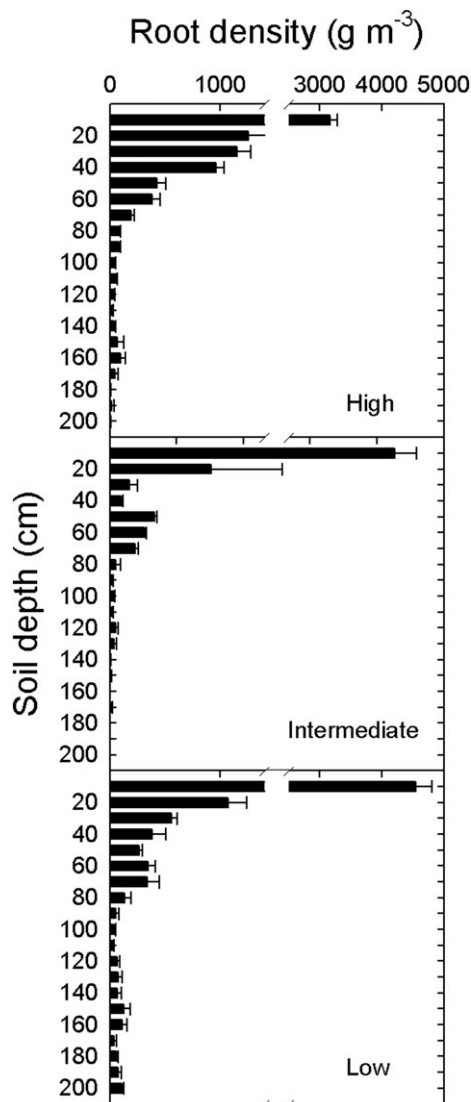
Note. Each variable value represents the mean ± SE ( $n = 12$ ). Different lowercase letters indicate statistically significant differences among grazing intensities at  $p < .05$ . Root density is for the entire soil profile (0 to 200 cm depth).

All sites regardless of grazing intensity showed similar total plant cover (grasses + shrubs) and amount of bare soil (Table 1,  $F = 0.138$ ,  $p = .8$ ), but there were differences between components (grass, shrub, dead material, and bare soil) within each grazing intensity site (high:  $F = 160$ ,  $p < .0001$ ; intermediate:  $F = 109$ ,  $p < .0001$ ; and low:  $F = 132$ ,  $p < .0001$ ). Shrubs exhibited higher cover than the grasses in the high intensity grazing site ( $t = -4.89$ ,  $p < .0001$ ). There were no significant differences between shrub cover and grass cover in the other two sites. The high grazing intensity site had a 42% more shrub cover than the low grazing intensity site. Dead material was significantly low in the site with the highest grazing intensity in relation to dead material in the low grazing intensity site ( $F = 4.6$ ,  $p < .05$ , Table 1). Leaf area index (LAI) differed among sites ( $F = 10.3$ ;  $p < .05$ ; Table 1). During the peak of the growing period, the high grazing intensity site had higher LAI than the others sites.

Total root density in the 0- to 200-cm soil layers did not differ among sites (Table 1 and Figure 1). Root distribution within the soil profile varied in a similar way in the three sites with different grazing intensities (Figure 1). Highest root density was observed in the upper soil layer (0–10 cm) in the three sites and decreased exponentially with increasing depth. Root density in the upper soil layer (0–10 cm) varied among sites ( $F = 8.11$ ,  $p < .05$ ). The high intensity grazing-site had lower root density in this soil layer than the site with low grazing intensity ( $p < .001$ ; Figure 1). There was a lower percentage of deep roots (only 5% in the 100- to 200-cm soil layer) in the high grazing intensity site compared to the 10% of the roots found in the same soil layer in the low grazing intensity site ( $p < .05$ ; Figure 1).

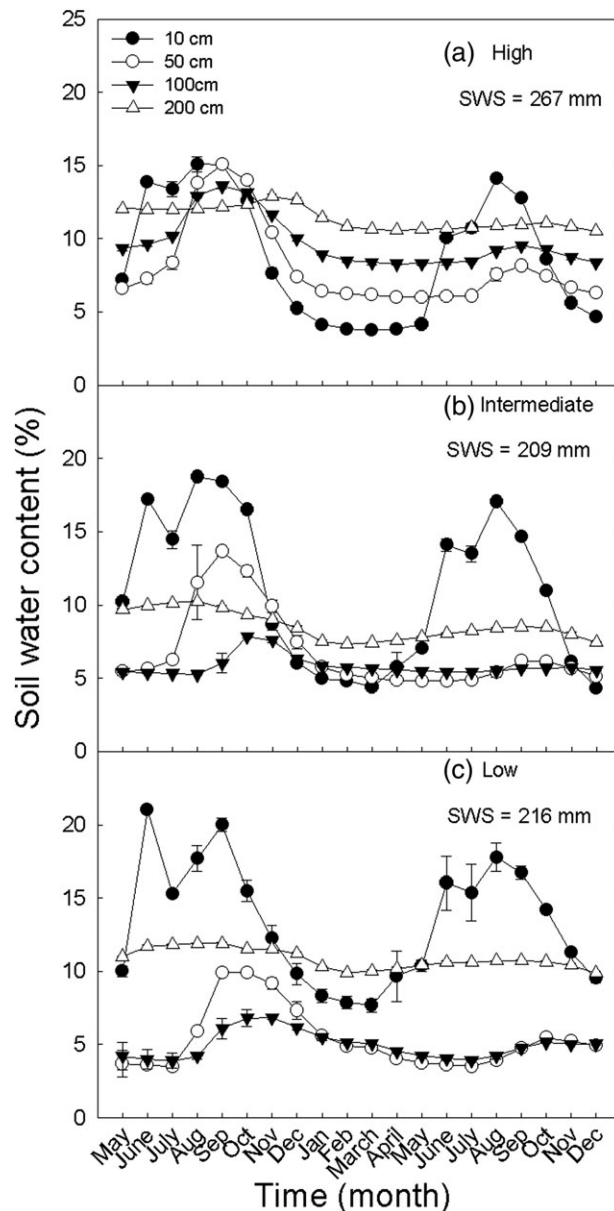
### 3.2 | Soil impedance and water content

Soil impedance at 10 cm depth ( $F = 12.6$ ,  $p < .01$ ) and 15 cm depth ( $F = 16.8$ ,  $p < .01$ ) varied among sites. Shallowest soil layers exhibited higher impedance in the highest grazing intensity site than in the other



**FIGURE 1** Vertical root density distribution in the three study sites differing in grazing intensity according to distance from the water source (high, intermediate, and low intensity). Each bar represents the mean value  $\pm$  SE ( $n = 3$ )

sites ( $p < .01$ , Table 1). Soil at 15 cm depth was significantly more compacted than soil at 10 cm depth across sites ( $t = 5.44$ ,  $p < .001$ ). Soil water content increased from May to September, mostly at 10, 50, and 100 cm depth in the three sites and reached its maximum values in September (Figure 2). Soil water content remained relatively constant throughout the year and close to 10% at the deepest soil layer (200 cm) across the three sites. The average water content throughout the year at 10 cm depth was  $8.8 \pm 0.9\%$  in the high grazing intensity site and  $13.3 \pm 0.9\%$  in the low grazing intensity site. There were differences in the magnitude of seasonal variations in water content across soil depths down to 200 cm depth. Higher net recharge during winter and higher net discharge during the dry period were observed in the high intensity grazing site compared to those in the low intensity grazing site (Figure 2). The amount of stored water in the soil profile (SWS) at the end of the winter season was 267 mm in the high grazing intensity site and 216 mm in the low grazing intensity site (Figure 2).

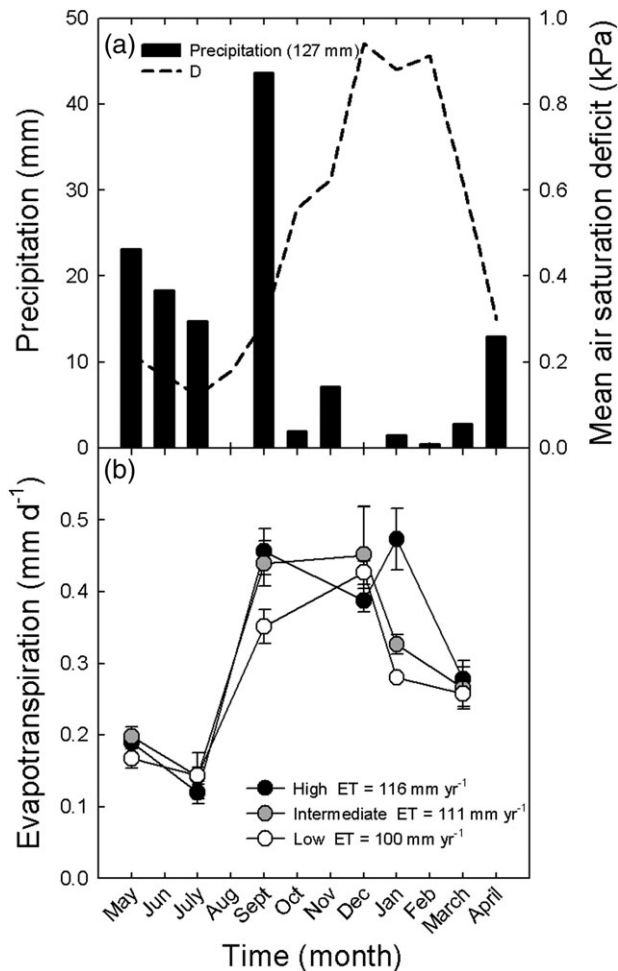


**FIGURE 2** Variation in soil water content from May 2013 to December 2014 at 10, 50, 100, and 200 cm depth in the three studied sites differing in grazing intensity: (a) high, (b) intermediate, and (c) low intensity. Each point represents the mean value  $\pm$  SE ( $n = 3$ ). Soil water storage (SWS) at the end of winter is indicated in each panel

### 3.3 | Evapotranspiration

Over 89% of the precipitation occurred from April to September, and mean monthly air saturation deficit increased to about 1 kPa during the summer period (Figure 3a). The seasonal pattern of ET differed among sites (Figure 3b). The two-way analysis of variance indicated significant differences between grazing intensities ( $F = 17.46$ ,  $p < .0001$ ) and months ( $F = 35.03$ ,  $p < .0001$ ) with significant grazing-month interactions ( $F = 2.39$ ,  $p < .05$ ). Minimum water loss occurred in winter (May and July) when air temperatures and air saturation deficits were low, whereas the maximum ET was recorded during spring and summer (Figure 3b).

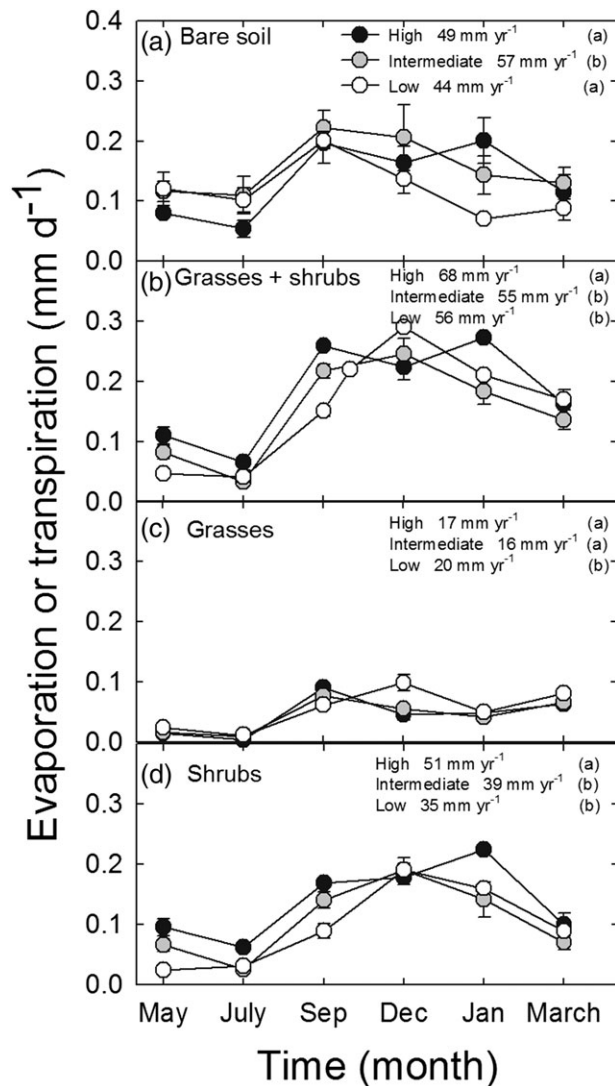
The highest total yearly ET was observed in the high grazing intensity site (116 mm) compared to the lowest grazing intensity site



**FIGURE 3** (a) Precipitation and mean air saturation deficit (dash line) and (b) total mean evapotranspiration (ET) per day from May 2013 to March 2014 in three sites differing in grazing intensity (high, intermediate, and low intensity). Each point in Figure 3b represents the mean value  $\pm$  SE ( $n = 15$ ). The total annual accumulated ET per year and site is indicated in panel B

(100 mm) and to the intermediate (111 mm) grazing intensity site ( $F = 22.5$ ,  $p < .0001$ ; Figure 3b). Evapotranspiration was similar between high and intermediate grazing intensity sites. On an annual basis, ET accounted for 92% and 78% of the annual precipitation (127 mm during the study period), from the highest to the lowest grazing intensity site. The ET at the intermediate site was 87.5% of the annual precipitation.

Annual bare soil evaporation (E) varied among sites ( $F = 5.6$ ,  $p < 0.05$ ) and was significantly higher in the intermediate grazing intensity site compared to the low intensity grazing site ( $p < .05$ ; Figure 4a). The larger differences in E among sites occurred during the middle of the dry season (January), when E was threefold higher at the high than at the low grazing intensity site. Annual transpiration of shrubs was significantly higher than annual transpiration of grasses in all sites ( $t = -16$ ,  $-17$ , and  $-14$  for high, intermediate, and low grazing intensity sites, respectively,  $p < .01$ ). Total transpiration (T, shrubs + grasses) differed significantly among sites ( $F = 22.3$ ,  $p < .05$ ), and it was 21% higher at the highest grazing intensity site compared to the lowest grazing intensity site (Figure 4b). Although analyzing plant components



**FIGURE 4** (a) Direct evaporation from bare soil, (b) total transpiration of grasses + shrubs, (c) transpiration of grasses, and (d) transpiration of shrubs from May to March, in each site differing in grazing intensity (high, intermediate, and low intensity). Each point represents the mean value  $\pm$  SE ( $n = 3$  for bare soil and grasses and  $n = 9$  for shrubs). In each panel, it is indicated with the accumulated evaporation or transpiration during 1 year (mm/year). Different lower case letters within parenthesis indicate significant differences between sites ( $p < .05$ )

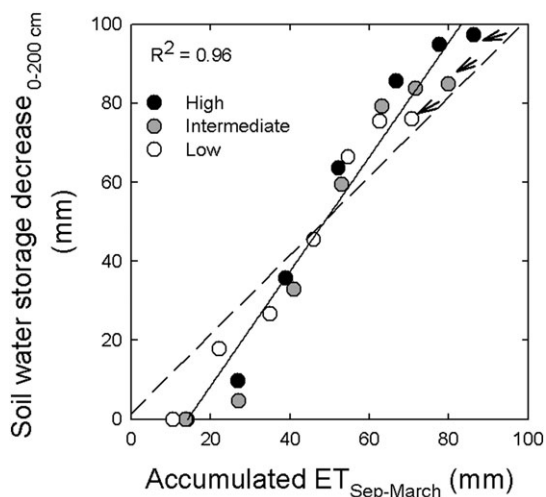
separately, grasses and shrubs, they both differed among sites ( $F = 43.43$ ;  $p < .001$  and  $F = 7.92$ ;  $p < .05$ , respectively; Figure 4c,d). Annual transpiration of grasses was 15% lower in the high grazing intensity site compared to the low grazing intensity site ( $p < .05$ ; Figure 4c). Annual shrub T was 43% higher in the high grazing intensity site compared to the low grazing intensity site (Figure 4d). Contribution of grass + shrubs T to ET varied between 58% (high grazing intensity) to 49% (intermediate grazing intensity). Shrubs contributed 12% more to the total T in the high grazing intensity site compared to the low grazing intensity site. Contribution of shrubs to total ET differed marginally in the three grazing intensity sites ( $F = 3.87$ ;  $p = .08$ ). Similarly, transpiration of grasses had different contribution to ET depending on grazing intensity ( $F = 35$ ;  $p < .001$ ), but it was lower in the high compared to the low grazing intensity site.

### 3.4 | Relation between evapotranspiration and soil water content

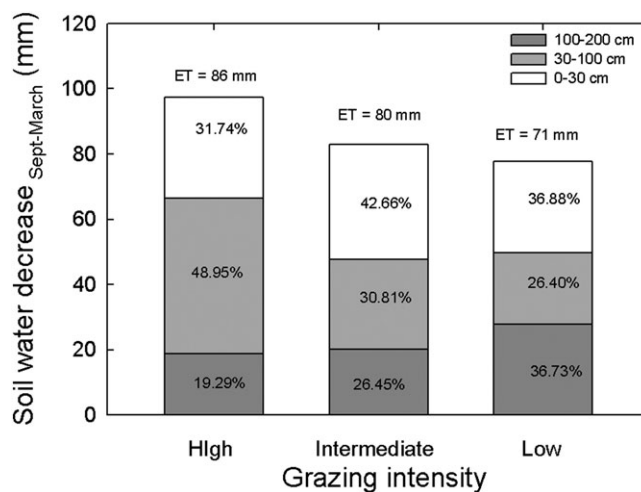
There was a positive and linear relationship between the amount of SWS decrease in the 0- to 200-cm soil profile and the accumulated ET from September to March for all grazing intensities ( $p < .05$ ; Figure 5). A single mathematical function was fitted to the three grazing intensity sites, which did not differ from the 1:1 relationship. The accumulated ET at the end of the summer (March) was 86, 80, and 71 mm at high, intermediate, and low grazing intensities, respectively, consistent with a decrease in soil water content from 98% to 76% (values indicated by arrows in Figure 5). The relative contribution of changes in soil water content of the 0- to 30-, 30- to 100-, and 100- to 200-cm soil layers to ET from September to March differed depending on grazing intensity (Figure 6). For example, in the high grazing intensity site, the 30- to 100-cm soil layer contributed substantially more to ET than in the low grazing intensity site. On the other hand, the deepest soil layer (100–200 cm) had a lower contribution to total ET in the high grazing intensity site compared to the low grazing site (19% and 37%, respectively).

### 3.5 | Canopy conductance

Canopy conductance ( $G_c$ ) of shrubs and grasses decreased exponentially with increasing D and air temperatures at all grazing intensities (Figure 7). Grass canopy conductance was significantly lower than shrub canopy conductance at the three grazing intensities ( $p < .001$ ). Canopy conductance of shrubs was consistently higher at the high grazing intensity, particularly at low D and air temperatures (September; Figure 7a,c). Only one function was used to describe the relationship between grass  $G_c$  and air saturation deficit (Figure 7b) and between grass  $G_c$  and air temperature (Figure 7d). The effects of soil water moisture in the shallowest soil layer (0–10 cm) on shrub + grass  $G_c$  were similar for all



**FIGURE 5** Relationship between soil water storage decrease in the 0- to 200-cm soil layer and accumulated evapotranspiration (ET) determined during the growing season (September to March) for each grazing intensity site (high, intermediate, and low intensity). The solid line is the linear regression fitted to all data ( $y = -21 + 1.5x$ ;  $p < .01$ ). The dashed line is the 1:1 relationship. The arrows indicate maximum values of accumulated ET for each site in March



**FIGURE 6** Soil water decreases from September to March for 0- to 30-cm, 30- to 100-cm, and 100- to 200-cm soil layers. The percentage of contribution to total evapotranspiration (ET) of each soil profile during this time period is indicated inside each bar. Total ET at each grazing intensity site from September to March is shown above each bar

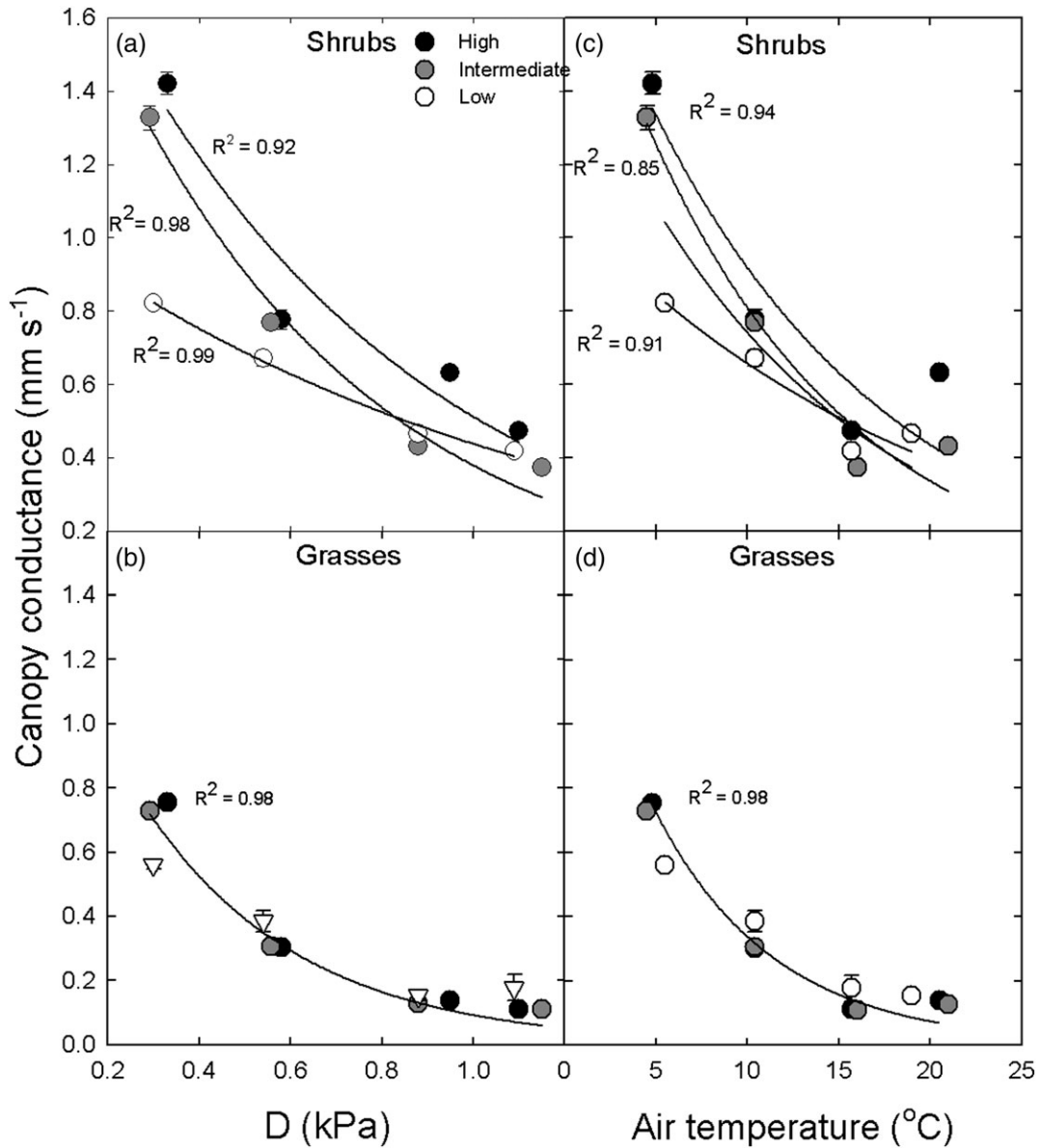
study sites ( $SWS = 0.015G_c - 0.35$ ;  $R^2 = 0.69$ ;  $p < .001$ ). Canopy conductance also declined with the SWS decrease in the 0- to 100-cm soil layer for shrubs in the high and intermediate grazing intensity sites and with SWS in the entire soil profile (0–200 cm) for shrubs in the low grazing intensity site (Figure 8a). Canopy conductance of grasses declined with declining water content in the 0- to 30-cm soil layer (Figure 8b). A single function was fitted for all grazing intensity sites.

## 4 | DISCUSSION

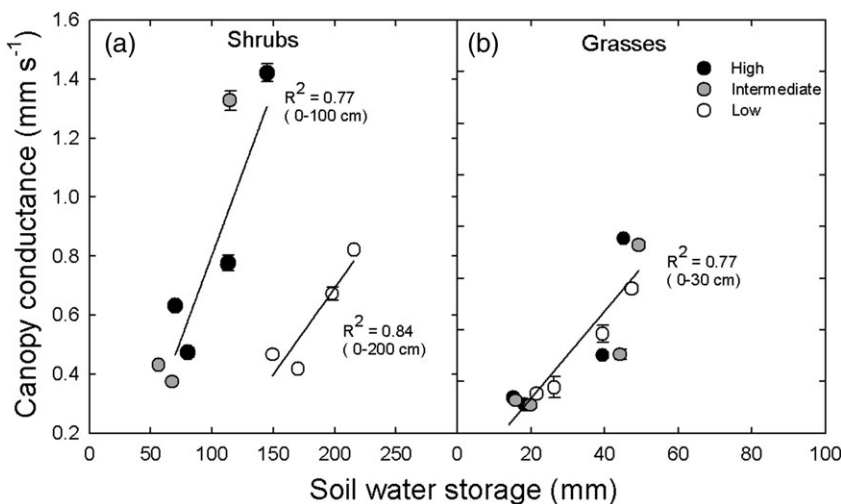
Studies along grazing intensity continuums can reveal realistic variations of long-term effects on ecosystem functions that would not be discernible through experimental studies such as with enclosures. The sites analyzed in this study, located at 300, 1,400, and 2,500 m away from a permanent water source, represented a spatial gradient of the cumulative impact of long-term exposure to livestock activity, which resulted in structural and hydrological functioning changes along the grazing intensity gradient. Although the number of feces does not translate directly into the number of grazing animals in a site, the accumulation of livestock feces provides a good index of the amount of time that livestock spends grazing in a particular area (Lange & Willcocks, 1978; Morton & Baird, 1990; von Müller et al., 2012). Thus, this metric was considered here another relative estimate of grazing intensity. The higher number of sheep feces, the differences in soil impedance, the larger abundance of nonpalatable grasses, and the larger shrub cover were consistent with the distance to the water source.

### 4.1 | Response to evapotranspiration and its partitioning to grazing intensity

The average annual ET rates across the three sites ( $<0.5$  mm/d) were consistent with those estimated using remote sensing in a nearby area of our study site (Cristiano et al., 2016) but were low compared to



**FIGURE 7** (a) Shrub and (b) grass canopy conductance at each grazing intensity site as a function of air saturation deficit (D). (c) Shrub and (d) grass canopy conductance at each grazing intensity site as a function of air temperature. Each point is the mean value  $\pm$  SE;  $n = 9$  in (a) and (c), and  $n = 3$  for grasses in (b) and (d). All functions fitted to the data are exponential functions. In (b) and (d), one function fitted all data in the three studied sites



**FIGURE 8** (a) Shrub and (b) grass canopy conductance at each grazing intensity site as a function of soil water storage. Each point is the mean value  $\pm$  SE;  $n = 9$  in (a), and  $n = 3$  in (b). In (a), all functions fitted to the data are linear functions. In (b), only one function was fitted to all data in the three studied sites



those reported for other steppes with relatively similar precipitation and LAI (e.g., average 0.8 mm/d for Mongolian steppes; Li et al., 2007; Yang & Zhou, 2011). Evapotranspiration accounted for 92% of the annual precipitation at the site with high grazing intensity and 78% at the site with low grazing intensity. On an annual basis, the vegetation returned 116 mm of water to the atmosphere through evapotranspiration in the high grazing intensity site whereas the site with the lowest grazing pressure returned 100 mm. Larger differences in ET between sites in this study occurred during the period of active plant growth (September) and in the middle of the dry season (January). Direct measurements of ET using an OTC allowed us to partition ET into T and E for the different functional groups (e.g., shrubs and grasses) and thus helped us to understand the mechanisms underlying the differences found in ET among sites. The analysis of individual components of ET in the three study sites revealed that shrub T was the basis for the ET increase in the high intensity grazing site. The transpiration fraction (T/ET) reflects the influence of vegetation on the hydrological cycle (Wang, Good, & Caylor, 2014; Wang et al., 2016). A recent global survey on ET partitioning into E and T (Schlesinger & Jasechko, 2014) showed a 51% average contribution of T to ET for semiarid ecosystems (steppe, desert, and shrubland). By using the DINAQUA model, Paruelo and Sala (1995) predicted that the contribution of T to ET is lower than the contribution of E to ET in an area similar to our study site. However, our field measurement results showed a higher (58% in the high grazing intensity site) or similar (in the intermediate grazing intensity site) water loss by T than by E. This result highlights the role of vegetation in the water balance in water-limited environments. Several ecosystem changes due to biomass removal and trampling, including changes in plant cover and species composition, canopy architecture and conductance, vertical patterns of root distribution, and physical soil properties, were partially responsible for the high water loss by ET in the high grazing intensity site.

Changes in grass composition (but not in grass cover) are typical responses to grazing (Aguiar & Sala, 1998; Cipriotti & Aguiar, 2005; Golluscio et al., 2009; Milchunas & Lauenroth, 1993; Schlesinger, Reynolds, Cunningham, et al., 1990). Generally, there is a replacement of more palatable species that have morphological and physiological traits tending to have a more conservative use of water resources (Mitchell, Veneklass, Lambers, & Burgess, 2008) than less palatable species. These changes in grass composition probably have resulted in a reduction of grass T in the high intensity grazing site but does not help to explain the increase in total T observed in this site. Shrubs appear to have a significant role in water losses from this ecosystem. A generalized response to grazing is the increase in shrub abundance in arid and semiarid environments (Archer, 2010), a pattern that has been previously observed in Patagonian steppes (e.g., Adler et al., 2005; Aguiar et al., 1996; Golluscio et al., 2009; Perelman, León, & Bussacca, 1997). Although the differences in shrub coverage were not significant across the grazing gradient, a 42% increase in the high grazing intensity site has an ecological importance due to the larger leaf surface area for water loss. On the other hand, in the low grazing intensity site, there was a significantly higher cover of standing dead material that did not contribute to transpiration and thus in turn reduced soil water evaporation. Other reasons contributing to high T in the high grazing intensity site was higher soil water availability.

## 4.2 | Controls of canopy conductance

The amount of water transport from soil to atmosphere depends also on canopy conductance ( $G_c$ ), which comprises the total water vapor transfer conductance from the “average” stomata of the canopy and includes both surface boundary layer and stomatal components. Physiological changes as well as changes in the canopy architecture as a result of grazing can affect  $G_c$ . Estimated canopy conductance was significantly higher (twofolds) in the site with high grazing intensity, with larger differences at the beginning of the growing period, when D was relatively low. However, when water deficit increased during the summer period, the relative differences in  $G_c$  between sites with different grazing intensity disappeared. This suggests a substantial physiological regulation of water loss by stomata in canopies with certain amount of leaves removed by herbivores. Stomatal regulation could be strong under water deficits occurring during the summer, which can be seen from the slope of the linear relationship between  $\delta G_c$  and  $\delta \ln D$ . A steeper slope suggests that conductance declines more rapidly from its maximum value as D increases (1.52 and 0.5  $\text{mm}\cdot\text{s}^{-1}\cdot\text{kPa}^{-1}$ ) for the high and low grazing intensity site, respectively (data not shown). However, site-specific differences in responsiveness of  $G_c$  to changes in D do not necessarily imply that inherent stomatal response to atmospheric water demand differed among sites. The sensitivity of changes in D by stomata can vary according to the degree of coupling between the canopy surface and the bulk atmosphere, which is revealed by the decoupling factor ( $\Omega$ ; Jarvis & McNaughton, 1986). Changes in plant cover and composition as a consequence of high grazing intensity probably favored the development of canopy architecture with a relatively thin boundary layer and high roughness length (high aerodynamic conductance) that allowed a stronger coupling with the atmosphere. Taking into account that aerodynamic roughness length depends on canopy height (Szeicz, Endrodi, & Tajchman, 1969), the high grazing intensity site with taller shrubs would have a higher roughness and consequently higher degree of coupling with the atmospheric conditions than the low grazing intensity site.

Soil water content was also a key factor controlling  $G_c$ . Most of the leaves are fully developed during the spring when soil water content begins to decline, which may increase canopy sensitivity to soil moisture. On the other hand, leaves and roots of these shrub species are particularly vulnerable to cavitation (Bucci et al., 2013) and must adjust their water relations responses to soil moisture changes to avoid the loss of hydraulic conductivity.

## 4.3 | Root distribution and water uptake as affected by grazing

Less attention has been placed on grazing impact studies on the belowground biomass than on the aboveground biomass. Few studies evaluating the root biomass in grazing ecosystems (e.g., Bai et al., 2015; Larreguy, Carrera, & Bertiller, 2014; Oñatibia, 2013; Rodríguez, Bertiller, & Sain, 2007) had considered only those roots exploring the upper soil layers (10 to 50 cm), without taking into account deep roots of woody species and even less their impact on the hydrological cycle. In a meta-analysis with worldwide 236 sites, Milchunas and Lauenroth (1993) found both positives and negatives responses of belowground

biomass to grazing. Our results on the changes in plant composition and in the balance between grasses and shrubs as a consequence of different grazing pressures were reflected on root distribution as well as in the patterns of water uptake within the soil profile. Total root biomass did not vary among sites; however, there was a change in the pattern of root distribution with depth depending on the grazing intensity. Root biomass was higher in the 20- to 100-cm soil layer in the high grazing intensity site compared to the low grazing intensity site. Nonpalatable grasses in the study area, which are more abundant in sites close to the water sources (Oñatibia, Aguiar, Cipriotti, & Troiano, 2010), exhibit lower root biomass than palatable species (Reyes, 2015). Although grasses and shrubs have a vertical root distribution that partially overlaps (Bucci et al., 2009; Cipriotti, Aguiar, Wiegand, & Paruelo, 2014; Leva, Aguiar, & Oesterheld, 2009), the low abundance of grasses with high palatability in the site with high livestock pressure would allow shrubs to explore shallow soil layers with little competition for water resources from the grasses. On the other hand, when grazing intensity is low, the high abundance of relatively shallow roots of palatable grasses will allow the shrubs to tap deeper water resources. The 37% of ET was derived from water lifted by deeper roots in the site with the low grazing intensity. On the other hand, in the high grazing intensity site, the soil water was obtained mainly from the first 100 cm of the profile (>80% of total water use) and only a 19% from the deepest soil layers.

#### 4.4 | Effects on SWS

In addition to modify the depth of plant water uptake in the soil profile, high grazing intensity increased SWS despite the higher water consumption. In contrast to the effect of grazing in other ecosystems (e.g., Gan, Peng, Peth, & Horn, 2012; Zhao et al., 2007, 2010), the presence of livestock in this Patagonian steppe does not appear to have a negative impact on soil water availability as long as the herbivore pressure is not extremely high (e.g., 0.6 sheep per hectare for paddocks in the study region). To explain why the sites subjected to relatively high grazing pressure exhibited larger SWS than the sites with relatively low grazing pressure, despite its higher soil impedance and thus lower infiltration and more rapid evaporation from the soil surface, we proposed three alternative hypotheses. In the first place, the lower root density below 100 cm in the site with high grazing site can reduce deep drainage. It is generally assumed that little or no deep drainage occurs in arid and semiarid ecosystems; however, substantial deep drainage can occur in ecosystems where precipitation is concentrated in winter, such as in the study area. For this ecosystem, water balance models indicate that deep drainage can account for about 10% of the total precipitation (Aguiar et al., 1996; Paruelo & Sala, 1995). A 5% more roots below 100 cm in the low intensity grazing site could enhance the downward movement of water across the bottom of the rooting zone (deep drainage; Seyfreid et al., 2005), resulting in lower SWS compared to sites with high grazing intensity. Other plausible explanation for such apparent inconsistency between ET and SWS can be attributable to a larger water redistribution via stemflow to deep soil layers along root channels (Pressland, 1976; Martinez-Meza & Whitford, 1996), after canopy interception, mostly during large rain events. This mechanism would be the main pathway for water entry into the soil in the

site with 42% more shrubs. Although these differences in shrub cover were no significant between grazing intensity sites, the proportion of shrub or grasses was higher in the high grazing intensity site, which allowed us to hypothesize this. Net water recharge during winter (May to September) was 10 mm larger in the high grazing site than in the low grazing site, which provides some support to this hypothesis. The lower amount of standing dead material covering the ground in the high intensity grazing site can be another plausible explanation to the differences in SWS across sites. We are assuming that a decrease in dead biomass on the soil surface will increase infiltration, considering that less water will be held by the standing dead biomass, which contributes to evaporation, and thus, it is available for infiltration.

Designed to move livestock on a predetermined schedule through a sequence of fence paddocks, rotational grazing schemes were promoted few decades ago as a new approach for managing extensive grazing systems. These systems however did not reliably increased plant or livestock production in arid and semiarid rangelands (e.g., Briske et al., 2008; O'Regain & Turner, 1992). From a sustainable management point of view, we suggest that increasing the number of permanent water sources and thus spreading the sheep in the paddock can enhance the stocking rate of livestock while maintaining water storage in the entire soil profile and could represent a better alternative method than rotational grazing.

## 5 | CONCLUSIONS

Grazing affected ET and its partitioning into T and E for the different plant functional groups in the Patagonian steppe. High shrub cover and high  $G_c$  at the beginning of the growing period increased the ET and T or ET partitioning in the heavily grazed site. Changes in  $G_c$  suggest that grazing modified the structure of canopy and its response to environmental factors, which led to higher  $G_c$ , when soil moisture was abundant and air saturation deficit, and temperatures were relatively low. Grazing pressure changed the patterns of belowground biomass allocation, which modified the soil water distribution and storage as well as the depth of water extraction by roots. Grazing intensity as it occurs in the study site closer to the water source increased the ET but did not result in a trade-off between water loss and water storage. Increasing shrub cover and enhancing the degree of coupling between the vegetation and the atmosphere appears to be a compensatory response to grazing. Our results suggest that grazing pressure results in a strong regulation of water losses in the high grazing intensity site under dry conditions. This study further reinforces the need to assess simultaneously multiple environmental and plant factors at different levels of resolutions, from plants to ecosystems, for understanding regulatory process of grazing effects on hydrological processes.

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## CONFLICT OF INTEREST

We have no conflict of interests to declare.

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