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Ecohydrological conditions of wetlands along a precipitation gradient in Patagonia, Argentina

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ABSTRACT. Wetlands are an important component of the Andean ecology because of their wealth of biodiversity and endemisms, and the many environmental services they offer. However, baseline knowledge of the types of wetlands and their ecohydrological functioning is currently lacking. Therefore, the objective of this study was to characterize the types and the ecohydrological conditions of wetlands along a precipitation gradient in the Northern Patagonian Andes. This study took advantage of a strong precipitation gradient that occurs due to the rain shadow effect created by the Andes Mountains near the city of San Carlos de Bariloche. We selected five representative wetlands that are at similar elevations and latitudes, but under very different precipitation regimes. At each site, we sampled water and soil chemistry, water levels and floristic composition. We found that hydrological, chemical and vegetation parameters all varied with total precipitation. Sphagnum peatlands occurred in the wettest regions and had year round water saturated soils which formed a peat layer. Meadows were common in the driest regions. We sampled three distinct meadow communities: wet meadows with Juncus balticus, mesic meadows with Festuca pallescens and salt meadows with Distichlis spicata each with a distinct hydrological regime, water chemistry and floristic composition. Marsh/shrub wetlands occurred in the intermediate rainfall areas and had standing water, mineral soils and were vegetated by Nothofagus antarctica and Scirpus spp. Our results indicate the importance of precipitation on wetland structure and function and suggest that any change in precipitation regime will cause significant changes to these ecosystems.

[Keywords: Andes, meadows, mountains, peatlands]

RESUMEN. Condiciones ecohidrológicas de humedales a lo largo de un gradiente de precipitación en la Patagonia, Argentina: Los humedales representan un componente importante de los ecosistemas andinos debido a su biodiversidad y endemismos, y a los numerosos servicios ambientales que ofrecen. A pesar de esto, el conocimiento básico acerca de los tipos de humedales y su funcionamiento ecohidrológico es escaso. El objetivo de este trabajo fue caracterizar los tipos y condiciones ecohidrólogicas de humedales a lo largo de un gradiente de precipitación en el norte de Patagonia. Aprovechamos el gradiente de precipitación notable que existe como consecuencia de la barrera geográfica de la Cordillera de los Andes en las cercanías de la ciudad de San Carlos de Bariloche. Seleccionamos cinco humedales representativos a una altitud semejante, pero bajo regímenes de precipitación muy diferentes. En cada sitio realizamos análisis químicos de agua y suelo, y registramos los niveles freáticos y la composición florística. Todos los parámetros hidrológicos, químicos y de vegetación variaron con la precipitación. En las zonas más húmedas se encontraron las turberas de Sphagnum que durante todo el año presentaron el suelo saturado con un horizonte de turba. Los mallines se ubicaron en las zonas más secas. Muestreamos tres

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comunidades diferentes: mallines húmedos con Juncus balticus, mallines mésicos con Festuca pallescens y mallines salinos con Distichlis spicata, cada uno con un régimen hidrológico, química del agua y vegetación diferente. Encontramos pantanos en las zonas intermedias del gradiente, con agua en superficie y suelos minerales, vegetados con Nothofagus antarctica y Scirpus spp. Estos resultados indican la importancia de la precipitación en la estructura de los humedales y sugieren que cualquier modificación de los regímenes pluviométricos podría causar cambios significativos en estos ecosistemas.

[Palabras clave: Los Andes, mallines, cordillera, turberas]

INTRODUCTION

The Andes are a "global epicenter" of biodiversity as they are one of the most biologically rich and diverse regions and contain approximately 45000-50000 plant species, of which 20000 are endemics (Olson & Dinerstein 1998). Wetlands are an important component of the Andean ecosystems due to their wealth of biodiversity and endemic species, and because of the environmental services they directly or indirectly provide for more than 100 million people in South America. Services include: reservoirs and sources of water to the majority of larger Andean cities, irrigation water for agriculture, carbon sinks, habitat for native animals and primary pasture areas (Viviroli et al. 2003; Preston et al. 2003; Bonvissuto et al. 2008).

Immediate threats to Andean wetlands are similar to other mountainous regions of the world that are under development pressure, such as expansion of agriculture and urbanization areas, water development, overgrazing (SAGyP-CFA 1995), mining, road construction and climate change (Chimner et al. 2010). Wetlands in mountainous regions are susceptible to even small hydrological disturbances that can cause wetland deterioration (Chimner & Cooper 2003; Greco 2004). Climate change is also an immediate threat to sustainability of Andean wetlands as mountain glaciers can be important drivers of the hydrological budgets (Servant-Vildary et al. 2001). However, glaciers throughout the Andes are melting at increasing rates (Francou et al. 2000; Thompson 2000). These immediate threats make the sustainable management of wetlands a matter of urgency (Junk 2002). Baseline knowledge is currently lacking to allow for the protection and sustainable management of these vital ecosystems. Therefore, the objective of this study was to characterize the hydroecological conditions of wetlands along a precipitation gradient in the Northern Patagonia Andes.

METHODS

Study sites

This study was conducted in the Cordillera (Andes mountains), Precordillera (Andean foothills) and Sierras y Mesetas (Hills and Plateaus) areas of Patagonia near the city of San Carlos de Bariloche. Bariloche (780 m.a.s.l.) is in the Lakes District of Northern Patagonia and receives an average of 877 mm of annual rainfall and the mean annual temperature is 8 °C (Bariloche Airport AG87765). This study takes advantage of the steep precipitation gradient that occurs due to the rain shadow effect created by the Andes. We chose five representative wetlands at similar elevations, but receiving different amounts of precipitation. The Puerto Blest wetland is located in the Andes within a glacial valley that connects Lake Frías and Lake Nahuel Huapi (765 m.a.s.l.). This site receives roughly 3000 mm of annual precipitation (Perotti et al. 2005). The next site (~1500 mm/yr) is located near Llao Llao close to the coast of Lake Nahuel Huapi (Figure 1). San Ramón wetland is located eight km northeast from the eastern shore of Lake Nahuel Huapi (Andean foothills) and receives a mean annual precipitation of 600 mm. Cañadón Bonito and Mamuel Choique are situated in the Hills and Plateaus area 50 km east and 125 km southeast of Lake Nahuel Huapi and receive ~300 mm/yr and ~150 mm/yr, respectively.

Vegetation sampling

Plant communities were quantified within each stand using the survey method (Mueller-Dombois & Ellenberg 1974). All vascular plant species were identified in each survey and their canopy cover was estimated. Surveys were located in a central and representative portion of the stand and survey size was determined by the dominant structure of vegetation to capture the full spectrum from large-patch forested stands to small-patch herbaceous stands. Voucher specimens of any unknown dominant plant species were collected for determination by a recognized taxonomic authority, Dr. Javier Puntieri of the Botany Department in the Universidad Nacional del Comahue, Bariloche, Argentina. Vegetation data from homogeneous stands were classified using agglomerative cluster analysis with Sørensen distance measure and flexible beta linkages method with β=-0.25, using the computer program PC-ORD 5.0 (McCune & Mefford 2006). Indicator species analysis was used to prune the dendrogram and optimize the number of clusters. We averaged p-values across all species for each cluster level using Monte Carlo analysis and the cluster level with the lowest average p-value was used as the optimal level.

Hydrology

We recorded water levels in the wetlands using a series of manually operated monitoring wells, PVC tape on bamboo rods (Belyea 1999), and a continuous recording pressure transducer. Ground water wells were constructed from 3.8 cm diameter slotted PVC pipes and installed by hand auguring with a standard bucket auger of the same diameter as the well casing. Wells were measured every few months during 2004 and 2005. Additional data were available for San Ramón, Mamuel Choique and Cañadón Bonito, which had been monitored monthly during periods of the 1990's. We incorporated this data to provide a longer term perspective on water table levels. It was not possible to monitor wells in Puerto Blest due to the remoteness of the site. So we used PVC tape stuck on bamboo rods that were inserted into the wetland to measure water table levels. The discoloration of the PVC tape indicates the maximum and minimum water table level (Belyea 1999). A Global Water (California, USA) recording pressure transducer was installed in Llao Llao to continuously measure water table levels.

Chemistry

The pH and conductivity of groundwater was measured using an YSI pH 100 handheld pH meter (Ohio, USA). Water chemistry samples were collected from each wetland for analysis of anion and cation concentrations. Measurements and water samples were taken from either purged soil pits or monitoring wells. Water samples were collected in 20-ml scintillation vials, sealed immediately, and kept refrigerated until ready for analysis. Water samples were analyzed for calcium, magnesium, potassium, sodium and iron using atomic emission spectrometry at the USFS Northern Research Station, Grand Rapids, MN, USA.

Soil samples were collected from the top 10 cm of each wetland for analysis and transported immediately back to the lab for analysis. Soils were air dried and homogenized with large roots removed. Organic matter content was determined by the Walkley Black method. Total nitrogen was determined by Kjeldahl digest and available phosphorus was determined by NaHCO3 extraction at pH 8.2.

RESULTS

We determined five distinct plant communities: *Sphagnum, Nothofagus, Juncus, Festuca* and *Distichlis* (Table 1). They were arranged along a water table gradient with *Sphagnum* and *Nothofagus* communities occupying the wet and *Festuca* and *Distichlis* communities the dry end of the gradient (Figure 1). The dominant plants in the *Sphagnum* community were *Sphagnum magellanicum, Schoenus andinus* and *Fitzroya cupressoides.* The moss (*Sphagnum magellanicum)* occurred mostly on the hummocks while the sedge *(Schoenus andinus)* occurred in the pools and water tracks. The wetland was also forested

Table 1. Average cover class of plant species arranged by community type. Cover classes are as follows: 1=0-1%, 2=1-5%, 3=5-25%, 4=25-50%, 5=50-75% and 6=75-100% cover.

Tabla 1. Clases de cobertura promedio de las especies vegetales para cada tipo de comunidad. Las clases de cobertura son: 1=0-1%, 2=1-5%, 3=5-25%, 4=25-50%, 5=50-75% y 6=75-100% de cobertura.

	Community				
Species	Sphagnum	Nothofagus	Juncus	Festuca	Distichlis
Distichlis spicata					5
Boopis spp.					1
Nitrophilla australius					1
Azorella trifureata				2	1
Plantago spp.				1	1
Festuca pallescens				4	1
Rumex acetosella				1	
Cerastium arvense				1	
Rytidosperma spp.				1	
Carex subanartica				2	
Pratia repens			1	1	1
Acaema spp.			1		1
Poa pratensis			3	2	
Carex gayana			1	2	
Juncus balticus			3	1	3
Elocharis albibracteata			2	1	2
Taraxacum officinale			2	1	2
Trifolium repens			3	1	
Hordeum spp.			1		
Holcus lanatus			1		
Potentilla anserina			1		
Rumex crixpus			1		
Deschampia cesp			1		
Nothofagus antarctica		5			
Fomatia hirsuta		1			
Berberis spp.		1			
Austrocedrus chilensis		1			
Scirpus spp.		4			
Alopecuras pratensis		1			
Plantago lancedata		1			
Juncus balticus v. montanus		4			
Elocharis spp.		2			
Carex aematorrhyncha		2			
Carex darwiniix	1	2			
Sphagnum magellanicum	5				
Fitzroya cupressoides	4				
Nothofagus dombeyii	1				
Chusquea culeou	1				
Schoenus andinus	4				
Marsippospermum grandiflorum	1				
Myoschilos oblongum	1				
Pernettya mucronata	1				
Hipochoeris patagonica	1				
Carex magellanica	1				
Poa borchersii	1				
Carex barrosii	1				

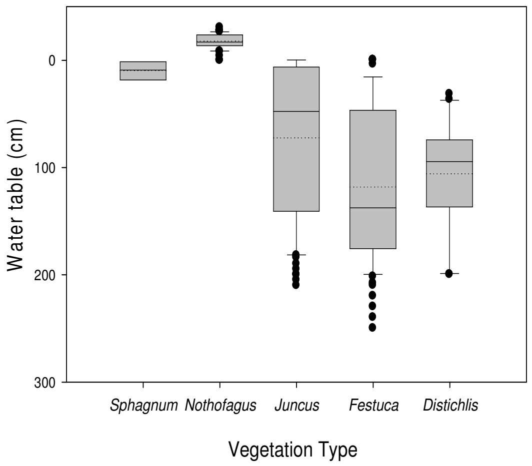

Figure 1. Water table levels of different vegetation communities. Dotted line is mean water table level, solid line is median, gray box is 5% and 95% quartiles and black circles are outliers.

Figura 1. Nivel freático de diferentes comunidades vegetales. La línea punteada indica el nivel de freática promedio, la línea continua es la mediana, la caja gris representa desde el percentil 5% al 95% y los círculos negros son los valores atípicos.

with a canopy of *Fitzroya cupressoides*. Other common plants include: *Poa borchersii, Nothofagus dombeyii, Chusquea culeou, Carex magellanica* and *Carex darwinii.*

The dominant species in the *Nothofagus* shrub community were: *Nothofagus antarctica, Scirpus* spp., *Juncus balticus* v. *montanus, Lomatia hirsuta, Eleocharis* spp., *Carex darwinii* and *Carex aematorrhyncha*. Most of the wetland area was shrub covered with a small portion that was shrub free where the water was ponded the deepest. The *Juncus* community was dominated by *Juncus balticus,* with other common species being: *Eleocharis albibracteata, Trifolium repens, Taraxacum officinale, Rumex crispus, Poa pratensis* and *Holcus lanatus*. The *Juncus* community was found in San Ramón and Cañadón Bonito wetlands. The *Festuca* community was dominated by the grass *Festuca pallescens* and the sedge *Carex gayana.* Other common species found were: *Cerastium arvense, Poa pratensis, Trifolium repens, Taraxacum officinale* and *Rumex acetosell*a. *Festuca* communities were also found in San Ramón and Cañadón Bonito wetlands. The *Distichlis* community type was dominated by the halophytic grass *Distichlis spicata* and was only found at Mamuel Choique wetland. Other species commonly found were: *Azorella trifurcata, Eleocharis albibracteata, Poa pratensis, Nitrophila australis, Pratia repens* and *Taraxacum officinale*.

The hydrological characteristic of the studied wetlands showed a high variation along the precipitation gradient (Figure 2). The western study sites, which receive significantly higher amount of precipitation, were characterized by a higher and more constant water table. The changes in water table levels directly influenced the type of vegetation growing. The *Sphagnum* site received sufficient precipitation to maintain constant saturation (Figure 1). Water levels were near the soil surface for the entire year, dropping only ~7-10 cm during the summer. This constant saturation allowed the accumulation of over 2 m of peat.

The *Nothofagus* wetland had standing water for most of the year (Figure 1). We measured water levels in two vegetation communities, an herbaceous and a shrub community. The maximum water table in the herbaceous vegetation was 10 cm above and the minimum level 1 cm below the soil surface. On average, the water table in the shrub community was 12 cm lower than the herbaceous vegetation type.

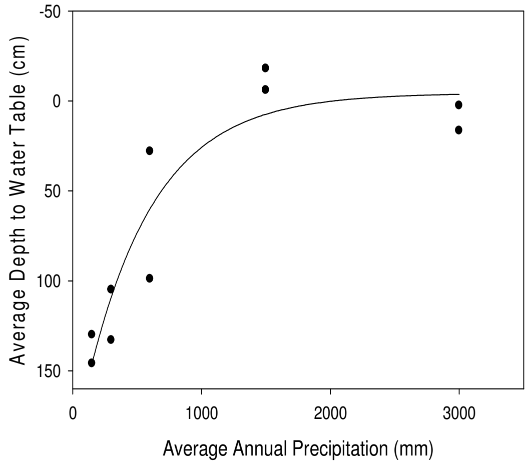

Figure 2. Relationship between average annual precipitation and average water table level.

Figura 2. Relación entre precipitación media anual y profundidad del nivel freático promedio.

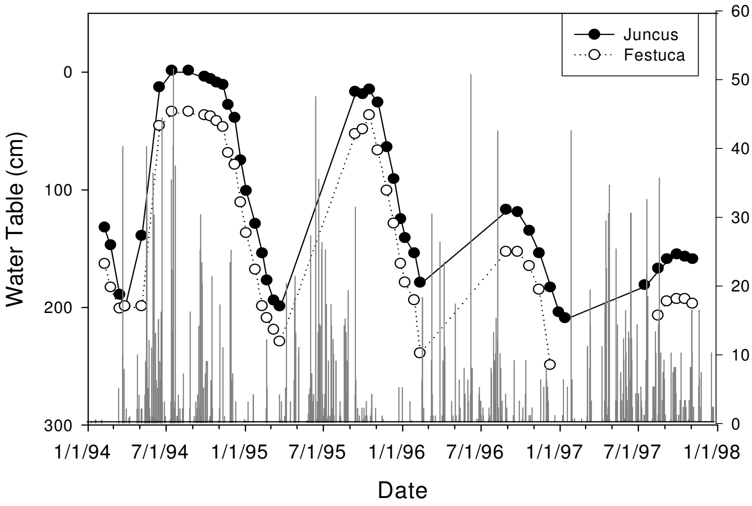

Figure 3. Water levels in a wet meadow dominated by *Juncus* and a mesic meadow dominated by *Festuca* in Cañadón Bonito from 1994-1997. Gray bars are daily precipitation totals from Bariloche Airport.

Figura 3. Profundidad de la freática en un mallín húmedo dominado por Juncus y en un mallín mésico dominado por Festuca en Cañadón Bonito entre 1994-1997. Las barras grises representan las precipitaciones diarias totales en el Aeropuerto de Bariloche.

Juncus typically had shallow standing water present in the spring, but water levels often dropped more than one meter below the surface during the summer (Figure 1). *Festuca* communities rarely had standing water, but were usually saturated to the surface in the spring (Figure 1). Water levels in the *Festuca* communities often dropped more than two meters below the soil surface during the summer. The *Distichlis* community had more stable water levels than either *Juncus* or *Festuca* communities; however, the water level was seldom higher than 50 cm below the surface (Figure 1).

Our long-term monitoring indicates that interannual variability of water levels is high for wet meadows. For instance, the wet meadows at Cañadón Bonito had much higher water tables in the spring during 1994 and 1995 compared to 1996 and 1997 (Figure 3). Maximum water levels in 1994-1995 were at the surface in the *Juncus* community and 35 cm for the *Festuca* community. However, maximum water levels in 1996-1997 were a meter lower in both communities due to lower annual precipitation in those years. The interannual variability in water levels is due to large variations in annual precipitation (Figure 3).

Water chemistry of the wetlands varied across the longitudinal precipitation gradient (Table 2). Groundwater pH, conductivity and cation concentrations all increased as the precipitation decreased (Table 2). While total soil carbon (OM) and nitrogen increased as the precipitation increased (Figure 4, Table 2). Available phosphorus did not show much of a trend with precipitation.

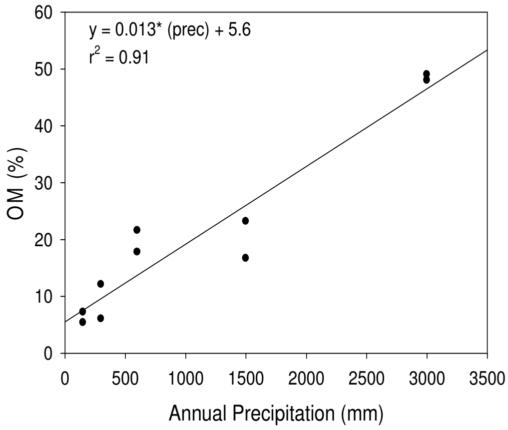

Figure 4. Relationship between average annual precipitation and percent soil organic matter.

Figura 4. Relación entre la precipitación media anual y el porcentaje de materia orgánica del suelo.

Table 2. Average water and soil chemical characteristics for different vegetation communities (OM=organic matter content and Cond=Specific Conductivity).

Tabla 2. Características químicas promedio del agua y del suelo para las diferentes comunidades vegetales (OM = contenido de materia orgánica y Cond = Conductividad Eléctrica de la suspensión).

	Soil			Water						
	OM g/kg	N g/kg	P mg/kg	pH	Cond µS/cm	Ca mg/l	Mg mg/l	K mg/l	Na mg/l	Fe mg/l
Distichlis	65	2.9	102.5	7.9	704.5	82.40	46.70	17.30	128.45	7.33
Festuca	119	4.9	124.6	7.2	479.0	23.55	18.60	3.70	28.60	<0.05
Juncus	168	5.7	150.4	7.3	537.5	34.50	15.40	2.71	24.50	0.07
Nothofagus	199	9.8	50.2	6.8	106.5	12.20	3.64	0.88	5.28	0.17
Sphagnum	647	1.1	6.2	6.0	28.5	4.25	0.64	0.73	3.07	<0.05

DISCUSSION

This study showed that hydrological, chemical and vegetation characteristics of the wetlands varied with total precipitation and further modified by landscape position. Peatlands (commonly called "turberas" or "bofedales" in South America) are common in the mountains surrounding San Carlos de Bariloche. Peatlands also appear to be common along the entire length of the Andes range. Tropical and subtropical mountain peatlands are found in the páramo regions of Colombia, Venezuela and Ecuador, usually above 3500 m.a.s.l. (Samaniego et al. 1998; Cooper et al. 2010; Chimner & Karberg 2008). Peatlands have also been found in the high elevation (4400 m.a.s.l.) puna regions of Chile, Perú and Bolivia (Topic et al. 1987; Prestone et al. 2003; Earle et al. 2003). Andean peatlands reach their greatest extent in the cold and wet climates of Southern Patagonia and Tierra del Fuego where peatlands cover large expanses (Coronato et al. 2006; Kleinebecker et al. 2008).

The Puerto Blest peatland is located at the base of a mountain in a hydrogeomorphic toe-slope position in a glacial valley. This in conjunction with the pH level of 6 and a Ca/Mg ratio of 6.6, indicates that this peatland receives some groundwater influx, in addition to copious rainfall (Verhoven 1986; Chimner et al. 2010). Given the pH and Ca^{+2} levels, this peatland would be considered a poor fen, not a rain fed bog that should have a lower pH (<4.5) (Glaser et al. 1990). The landscape position also indicates that it is not fed by the nearby large mountain glaciers from Mt. Tronador just to the south west. Instead, the saturated conditions are likely due to a combination of deep winter snow and high precipitation during most of the year. However, it is generally unknown if other Andean wetlands are fed by mountain glaciers and what the impacts will be if the glaciers disappear.

Although peatlands are numerous, other wetland types also exist in and around the Southern Andes including marshes, shrub swamps, mountain meadows and meadows (Raffaele 1996; Perotti et al. 2005; Clausen et al. 2006). These other non-peatland types are collectively called "mallines" in Patagonia and cover roughly 5% of its surface (Perotti et al. 2005). Mallines occur from wet high elevation mountain settings with 2000 mm/yr of precipitation situated in *Nothofagus* forests to steppe areas with less than 600 mm/yr of precipitation (Perotti et al. 2005). Mountain meadows typically have high soil organic matter content, but not as high as peatlands, and can occur in isolation or adjacent to peatlands. Vegetation in mountain meadows is diverse and dominated by species of the genera *Juncus, Schoenoplectus, Carex* and *Nothofagus* (Raffaele 1996; Perotti et al. 2005; Clausen 2006).

We found three types of low elevation meadows, which varied in their wetness, vegetation and chemistry. Wet meadows with *Juncus balticus* were the wettest and often occurred in the middle of valleys. *Festuca* meadows occurred in slightly drier areas, and often upslope of the *Juncus* wet meadows. Salt meadows were the driest of the low meadows and contained the halophytic salt tolerant grass *Distichlis spicata*.

Threats to Andean wetlands are numerous and include: development, mining, grazing, water diversions and alterations, and climate change. All these issues are important, but grazing is currently the major factor influencing wetlands in Patagonia, and possibly much of the Andes range (Preston 2003; Raffaele 2004). Wetlands are economically important in Patagonia, especially in the arid steppe area, where wetlands are the most productive ecosystems and contain the most palatable species for both native and domestic grazing (Raffaele 2004). Because of this, many wetlands are used for domestic grazing, supporting many rural communities. Grazing impacts in wetlands typically vary with grazing intensity. Naturalization of exotic species was the most common impact from low intensity grazing (Bonvissuto et al. 2008). Common exotic species introduced were: *Trifolium repens, Taraxacum officinale, Poa pratensis* and *Holcus lanatus.* Heavy grazing often increases the cover of bare soil, invasive species, and causes the formation of gullies that can drain large areas of wetlands (Cremona et al. 1996; Lanciotti et al. 1998; Bonvissuto et al. 2008).

Although grazing intensity is heaviest in the steppe wetlands (Perotti et al. 2005), grazing occurs in all wetland types including mountain wetlands. Grazing in mountain wetlands is less common, but it can be more damaging to these high organic wetlands, particularly peatlands (Raffaele 2004; Perotti et al. 2005). Grazing in mountain peatlands has been found to trample and kill plants, introduce invasive species, and create gullies in the soft soil that increases soil erosion and alters hydrology. Because grazing is so widespread, and economically important, considerable effort is being made to improve sustainable grazing practices in Patagonian wetlands. These practices involve, among others, fencing the meadows for a separate management, stocking rate adjustment, deferred grazing and rotation grazing (Giraudo et al. 1999; Villagra 2002; Villagra 2005).

Our results indicate the importance of precipitation on wetland structure and function. It also underscores the importance of landscape position and groundwater inflow as they also modify the amount of water in a wetland. Therefore, any modification to precipitation amounts or timing will likely cause changes to these ecosystems. Conditions in northern Patagonia are predicted to become warmer and drier as a result of climate change (IPCC 2007). Warmer and drier conditions can be expected to strongly affect many wetlands in Patagonia due to either direct hydrological changes as a consequence of reduced water availability, or indirectly due to human use.

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