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Soil Water Regime of Grassland Communities along Subtle Topographic Gradient in the Flooding Pampa (Argentina)

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Abstract

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Three plant communities positioned along a subtle topographic gradient, referred to as upland, intermediate, and lowland positions, characterize the landscape of the Flooding Pampa grasslands of Argentina. Although it is believed that the structure and functioning of the plant communities at each position are in close relationship with their hydric regime, this has never been quantified. More than 800 measurements of soil water content during four years, along with soil water retention curves, and physical and chemical parameters of soils were assessed at each position. Results showed that water availability during the year varied among the positions in accordance with differences in hydrological balance and soil water retention capacity of each of them. Water retention increased in relation to clay and organic matter content from the upland to the lowland position. The upland position, with more soil sand content, registered severe drought events during late spring and summer, without flooding periods in any season. The intermediate and lowland positions, with more soil clay content, remained flooded for several weeks during winter and spring, and they manifested less severe summer droughts than the upland position. Moreover, the lowland position was more hydromorphic than the intermediate one. These spatial and temporal variations of water regime and soil parameters characterizing the upland, intermediate, and lowland positions concur with different plant communities associated with each of them.

Keywords: drought; flooding; soil water retention curves

Structure and functioning of plant communities in grassland ecosystems are influenced by many factors as fluctuations in soil water content (*i.e.* hydric regime), nutrient availability, soil biota, and grazing (De Deyn *et al*. 2004; Di Bella *et al*. 2014). The spatial variations of hydric regime can explain functional differences (*i.e.* net primary production and seasonality) among vegetal communities at different topographic positions (Knapp *et al*. 1993). At the same time, hydric regime is often pointed out as a determinant factor enabling the presence (or absence) of species and/or local populations with different degrees of tolerance to drought and flooding in different types of grassland environments (Loreti & Oesterheld 1996; Di Bella *et al*. 2014).

The Flooding Pampa is a typical flat area with minimal slope of 0.1–0.3 m/km (Conzonno *et al.* 2001), which covers about 90 000 km^2 in Buenos Aires province (Argentina), mostly devoted to cattle breeding. This "Campos" ecosystem (also including a portion of Brazil and Uruguay), along with the Great Plains of North America and the veldts of South Africa, comprises the most important and extensive flat temperate grassland areas in the world (FAO 2005). In South American grasslands the floristic composition has been greatly diversified and a wide range of plant

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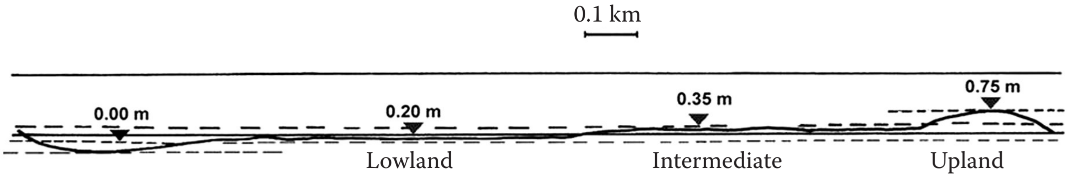
communities have been identified (Burkart *et al.* 1990; Perelman *et al.* 2001). This plant communities diversity is associated with subtle differences in the relative topographic position (Perelman *et al.* 2001; Debelis *et al.* 2005), different soil types (Berasategui & Barberis 1982), and consequently with a presumable difference in their hydric regime during the year (suggested by Burkart *et al.* 1990 and by Batista & León 1992). However, spatio-temporal variations in hydric regime among soils of different plant communities have never been characterized. Knowledge about such variations is important due to its ecological and agronomic implications, as they could explain changes in the structure and functioning of the grassland plant communities.

The aims of this study were (*i*) to characterize the soil hydric regime of the three major plant communities of the Flooding Pampa grasslands positioned along a subtle topographic gradient, and (*ii*) to establish relationships between soil physical-chemical properties and soil hydric regime of each plant community. Accordingly, we measured soil volumetric water content for four consecutive years (> 800 measurements), analyzed the soil water retention curves in relation with soil physical properties, and determined the correlation between hydrological balance and soil water content for each plant community.

MATERIAL AND METHODS

Study area and grassland communities. Natural grasslands of the Flooding Pampa in Argentina have a temperate sub-humid climate with mean monthly temperatures ranging from 7°C (winter) to 22°C (summer). Mean annual rainfall is *ca.* 900 mm, evenly distributed throughout the year; however, variations among years are considerable. The study site (36°30'S, 58°30'W) is located in the central area of the Flooding Pampa, in the so-called landscape "Las Chilcas" (*sensu* Burkart *et al.* 1990). This landform is characterized by minor parts of higher lands resulting from eolian action (*i.e.* deflation-accumulation processes), surrounded by large areas of extreme flatness. Water regime and soil characteristics were studied at three different topographic positions corresponding to different plant communities along a subtle topographic gradient (Figure 1; Communities A1, B3 and C2 *sensu* Burkart *et al.* 1990). The "upland" position is located in the highest part of the topographic gradient and it is associated with polygenetic soils with roots commonly reaching a depth of up to 50 cm. The "intermediate" position and the "lowland" position are both located at lower parts of the topographic gradient, although the intermediate position is located by few centimetres higher than the lowland one (Figure 1). Both latter topographic positions have a slow to very slow water runoff and imperfect to poor drainage due to the presence of a B_n horizon (19–22 cm deep) of scarce permeability, which restricts root penetration and vertical movement of water in the soil profile (Debelis *et al.* 2005).

Soil chemical and physical parameters. At the beginning of the study, soil samples (*n* = 5) were taken in autumn to characterize soil chemical and physical parameters. At each position, soil samples of the first 15 cm were taken every 20 m along 100 m linear transects. The following chemical parameters were determined: organic carbon, pH on saturated soil paste, and electrical conductivity of saturation extracts (EC, dS/m) (Page *et al.* 1982). Soil particle size was analyzed by the pipette method (Klute 1986). Soil bulk density (modified by Taboada & Lavado 1993 for this soil type) and water retention curves were quantified for additional undisturbed soil samples taken in autumn from the first 10 cm of soil at each position. Water retention curves were measured according to Richards (1949) at equiva-



	Lowland	Intermediate	Upland
Soil classification	Natraquoll	Natraquoll	Thaptoargic Hapludoll
Water runoff	very slow	slow	medium
Drainage	imperfect–poor	imperfect	moderate

Figure 1. A scheme of "Las Chilcas" landscape indicating the three topographic positions evaluated (communities A1, B3, and C2 respectively *sensu* Burkart *et al.* 1990) of the Flooding Pampa grassland and their main soil characteristics (*sensu* Berasategui & Barberis 1982)

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lent tensions of –1.5, –0.5, –0.2, –0.1, –0.03, and –0.01 MPa and saturation. For each position, soil gravimetric water content (θ_g) was measured from three undisturbed samples at each tension value (Table 1) to calculate soil volumetric water content (θ_v). For these adjustments, at each position, θ_v was inferred from average soil bulk density (1.04, 0.996, and 0.94 for upland, intermediate, and lowland position, respectively) and θ_g. Inverse curve functions were adjusted in order to analyze θ_v at each position in relation to soil water matric potential (Ψ_m). For the three positions, the best adjustment corresponded to the general equation:

$$\Psi_m^{-1} = a + b \times \theta_v^3$$

where:
a = 2.993, 5.409, and 3.107 for the upland, intermediate, and lowland positions, respectively
b = –0.000947, –0.000821, and –0.000322 for the upland, intermediate, and lowland positions, respectively

At the upland position, the driest values of soil water content measured in the field fell below the limit of –1.5 MPa. Thus, a filter-paper technique (Deka *et al.* 1995) was used to measure soil matric potential at the lowest soil water content levels.

Soil water regime characterization. Soil volumetric water content (θ_v) to a depth of 0.15 m was monitored at each position during four years (from September in year 1 until April in year 4), using Time Domain Reflectometry equipment (Trase System I, Soil Moisture Equipment Corp., Santa Barbara, USA). At each position, measurements were taken every 10 m along 100 m linear transects (n = 10). Additionally, monthly hydrological balance for the studied period was calculated by subtracting the monthly potential evapotranspiration (PET) from the monthly precipitation (P). P and mean temperature data were provided by the meteorological station in Dolores (National Weather Service of Argentina), located approximately 80 km from our study site. PET was calculated following methodological considerations proposed by Black (2007). Values of θ_v corresponding to water saturated soil (WSS), field capacity (FC), and permanent wilting point (PWP) were determined to compare the adjusted relationships between monthly hydrological balance and soil water status among positions (Ratcliff *et al.* 1983).

Statistical analyses. Soil chemical and physical variables were analyzed through one-way ANOVA. Subsequent mean comparisons were performed by Tukey's test (n = 5; P < 0.05). In all cases, normality and homogeneity of variances were previously verified. Variables involving proportions were arcsine $\sqrt{x}$ transformed before analyses. Relationships between θ_v and Ψ_m were adjusted by inverse curve functions using the Table Curve software (TBLCURVE 1992, Jandel Scientific, Corte Madera, USA). The analysis of θ_v as a function of time was performed using two-way ANOVA with "time" and "position" as main factors, because samples were taken, at each position and specific moment, from random sites. As an interaction between both factors was found, ANOVAs were performed among positions for each evaluated day. Relationships between θ_v and monthly hydrological balance were studied through correlation analyses. Statistical analyses were performed using Statistica package for MS Windows (StatSoft Inc., Tulsa, USA).

RESULTS AND DISCUSSION

Soil properties and water retention capacity. Particle size analysis, chemical parameters, and water retention curves of the studied soils showed a close relationship with the relative position along the gradient of topographic altitude (compare Figure 1 vs Figure 2 and Table 2). A decreasing sand content (simultaneously with increasing clay content) was registered from the upland to the lowland positions

Table 1. Soil gravimetric water content (%) at different matric potentials (MPa) of soils from three topographic positions (upland, intermediate, and lowland) of the Flooding Pampa grassland

Soil	Soil gravimetric water content						
	–1.5	–0.5	–0.2	–0.1	–0.03	–0.01	saturation
Upland	15.1 ± 0.6	15.9 ± 1.1	21.4 ± 1.5	21.7 ± 0.3	27.3 ± 0.6	35.5 ± 0.8	42.3 ± 1.8
Intermediate	19.6 ± 1.3	20.4 ± 1.6	24.9 ± 0.6	27.3 ± 1.3	33.5 ± 1.7	38.3 ± 2.6	47.2 ± 3.4
Lowland	24.1 ± 0.3	25.1 ± 1.8	30.2 ± 8.3	32.8 ± 5.7	36.7 ± 2.5	39.4 ± 1.2	48.4 ± 2.1

Values are means ± standard error of three replicates

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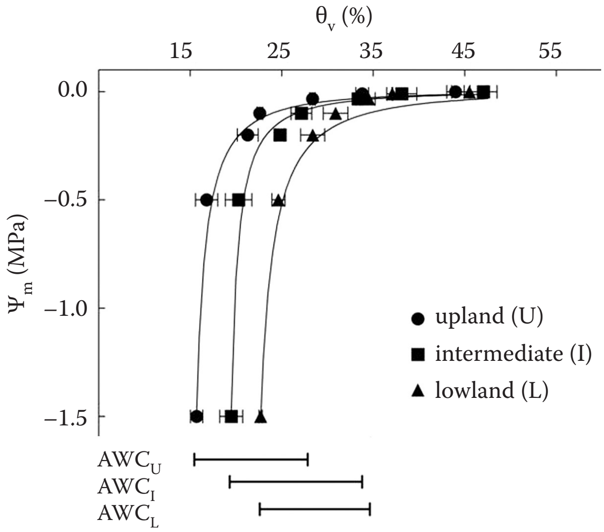

Figure 2. Relationships between soil matric potential (Ψ_m) and soil volumetric water content (θ_v) of soils from three topographic positions (upland, intermediate, and lowland) of the Flooding Pampa grassland; AWC – available water content (*i.e.* water retained between –0.033 MPa and –1.5 MPa); values are means ± SE of three replicates

($P < 0.05$; Table 2). EC was significantly higher at the intermediate position than at the other positions, and pH values were higher at the intermediate and lowland position than at the upland one ($P < 0.05$; Table 2). Soil salinization in the intermediate position could be related to the occurrence of salt rise by capillarity from the close water table (Lavado & Taboada 1988). These results contrast with the situation at the upland and lowland positions because the former is associated with polygenetic and deeper soils, and the latter is subjected to a more hydromorphic condition, avoiding salt rise and accumulation in the profile (Alconada *et al.* 1993). Moreover, a gradient of organic matter accumulation was found from the upland to the lowland position ($P < 0.05$; Table 2), also pointing to the hydromorphic environment and the occurrence of longer periods of anaerobic conditions, which reduce the potential for organic matter decomposition at the lower position (Chapin *et al.* 2002). A general view of soil parameters shows clear differences of agriculture aptitude among the studied plant communities: light and deep soils with more sand content at the upland position (used for agriculture), and a gradient of heavy and hydromorphic soils with more clay content at the lowland position, together with a higher level of salinity at the intermediate position (used for cattle breeding based on forage of natural grasslands).

As expected, soil particle size was closely related to the water retention capacity of the studied soils (Figure 2; Hanks & Ashcroft 1980). The adjusted functions for each soil revealed that for similar θ_v, water is less retained in the soil of the upland position, which has more sand content, than in the intermediate and lowland soils (Figure 2). At FC, the θ_v at a depth of 0.15 m (A horizon) was 28.4 ± 0.5% for the upland, 33.3 ± 1.4% and 34.5 ± 1.7% for the intermediate and lowland positions, respectively (Figure 2). Moreover, as θ_v decreases, soil matric potential (Ψ_m) of the upland position drops abruptly, the decrease being smoother as the clay content of the soil increases (Figure 2). It is known that soils with more clay content (intermediate and lowland positions) have a higher absolute capacity of water retention due to their higher microporosity (and total porosity) than soils with more sand content (upland position), which have a lower amount of capillary pores (Hanks & Ashcroft 1980; Fernández-Gálvez & Barahona 2005). In addition, the higher organic matter content registered at the lowland position would also contribute to a higher water retention capacity, as the presence of organic compounds increases soil water retention. Therefore, for the first time in this region, our results showed great differences in water retention

Table 2. Physical and chemical parameters of the topsoil (0.15 m depth) from three topographic positions (upland, intermediate, and lowland) of the Flooding Pampa grassland

Soil	Particle size analysis			Organic carbon	pH (1:5)	EC (dS/m)
	sand	silt	clay			
	(%)					
Upland	44.0 ± 1.5[a]	37.5 ± 0.9[a]	18.5 ± 1.1[b]	1.8 ± 0.1[c]	6.3 ± 0.1[b]	0.34 ± 0.01[c]
Intermediate	37.0 ± 1.5[b]	39.2 ± 1.2[a]	23.8 ± 1.4[a]	2.6 ± 0.2[b]	7.1 ± 0.1[a]	1.15 ± 0.04[a]
Lowland	35.6 ± 1.1[b]	40.0 ± 0.9[a]	24.4 ± 1.4[a]	3.8 ± 0.1[a]	7.1 ± 0.1[a]	0.67 ± 0.01[b]

Values are means ± standard error; different letters indicate significant differences among soils based on the Tukey's test ($P < 0.05$); EC – electrical conductivity

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curves among soils along a subtle topographic gradient, which certainly influence the floristic composition of plant communities at each site (Burkart *et al.* 1990; Perelman *et al.* 2001).

Water regime characterization. The importance of describing water availability regime at each position is related with the plant zonation, identification of locally adapted populations, and different agricultural uses along the topographic gradient (Loreti & Oesterheld 1996; Casanova & Brock 2000; Mollard *et al.* 2010). Besides, water availability regime can influence annual and seasonal aerial net primary productivity (ANPP) of each plant community (Knapp *et al.* 1993). θ_v responded differently among positions reflecting the measurement periods (position × time: $P < 0.0001$, Figure 3). In dry months (November to February of year 1–2 and year 3–4, Figure 3A), the positions markedly differed in the relative water content of their soils ($P < 0.0001$). The upland position registered the lowest values of θ_v in relation to the intermediate ($P < 0.001$) and lowland ($P < 0.001$) positions, but no differences were detected between the latter ones ($P > 0.05$). The most severe drought stress in the upland position was confirmed if the lower values of θ_v (8.8% and 7.3% in late spring of year 1 and 3, respectively) were transformed to water matric potential. On that note, only at the upland position, the driest values of soil water content fell below the limit of –1.5 MPa (out of the range of the water retention curves, Figure 4A). It was found that with a soil gravimetric content of 7.7% (which corresponds to a θ_v of 8%), the soil matric potential fell below –2 MPa, (< PWP). These results confirmed the significantly lower water availability for plants at the upland position in the driest periods of summer. Both the intermediate and lowland positions also suffered from dry periods, but they were considerably less intense than in the upland position (no points below the level of PWP, see Figure 4B and C). In periods of water excess (e.g. see winter and early spring in year 1 and 2, Figure 3A) differences between the intermediate and lowland positions appeared ($P < 0.05$), indicating a more pronounced water excess in the latter (Figure 3B).

At the upland position, the lower soil water content would be explained by the expected lateral movement of water (medium water runoff) due to the higher position in the relief (Figure 1), and the lower field capacity (or higher drainage) due to the higher soil sand content (Figure 4). Conversely, at the intermediate and lowland positions, the higher water content was related with the slow water runoff received from the upland position, and the higher field capacity due to the higher content of clay and soil organic matter. Besides, they also have the water table near the surface (approximately 1 m deep or less, depending on the water table fluctua-

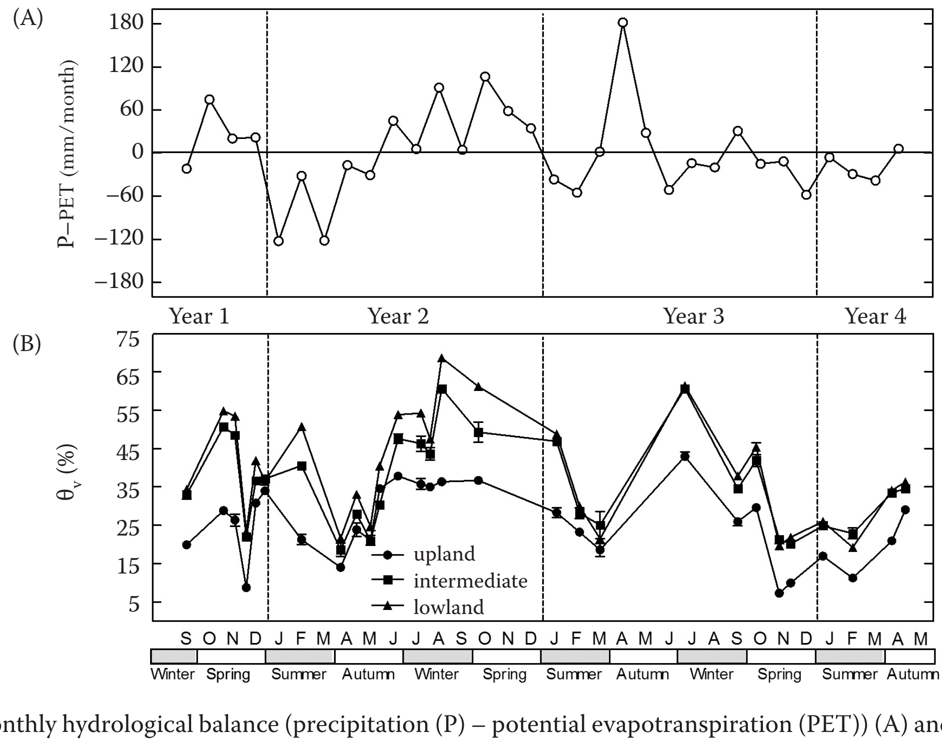

Figure 3. Monthly hydrological balance (precipitation (P) – potential evapotranspiration (PET)) (A) and soil volumetric water content (θ_v) (B) from September of year 1 to April of year 4, of soils from three topographic positions (upland, intermediate, and lowland) of the Flooding Pampa grassland; values are means ± SE

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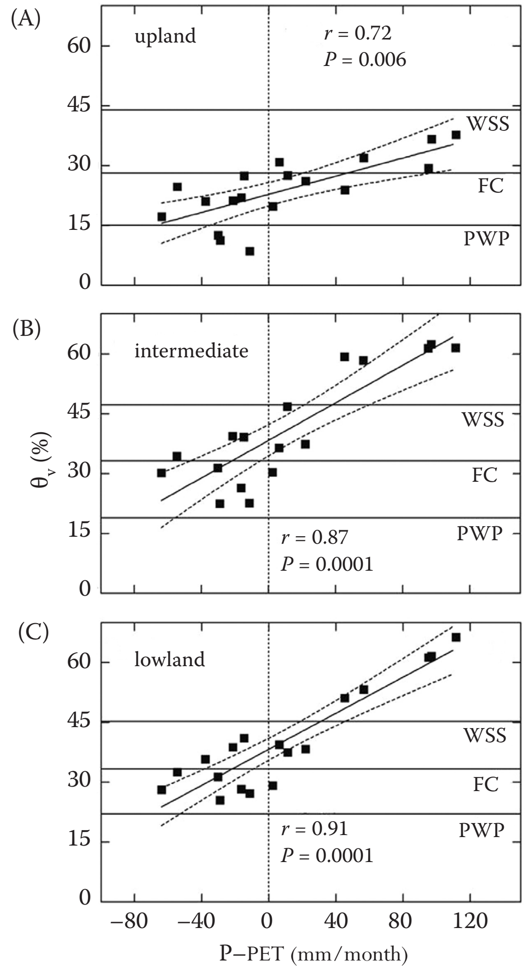

Figure 4. Relationships between soil volumetric water content (θ_v) and monthly hydrological balance (precipitation (P) – potential evapotranspiration (PET)) of soils from three topographic positions (upland (A), intermediate (B), and lowland (C)) of the Flooding Pampa grassland; WSS – water saturated soil, FC – field capacity (Ψ_m= –0.033 MPa), PWP – permanent wilting point (Ψ_m= –1.5 MPa); dashed lines indicate 95% confidence interval for the fitted lines (n = 18)

tions during the year), which facilitates hydromorphic conditions and flooding (Lavado & Taboada 1988; Paruelo & Sala 1990). Therefore, soil flooding events are expectable in these plant communities (Figures 3 and 4), especially when precipitation is intense. However, it is important to notice that the lowland position remains flooded longer than the intermediate one, which would have implications in the ANPP and seasonality of the vegetal communities. In this respect, Aragón and Oesterheld (2008) have shown that the upland plant community exhibits high Normalized Difference Vegetation Index (NDVI, a surrogate for aerial biomass and vegetation cover) in winter and spring, and decreasing NDVI in summer, when water content in soils becomes a constraint (Figure 4). In contrast, the intermediate and lowland positions remained humid for a longer period of time in summer, showing higher ANPP (Irisarri *et al.* 2013).

Finally, a strong positive correlation was found between the monthly hydrological balance and the soil volumetric water content for all plant communities ($P < 0.001$, Figure 4). For the upland position, no average value overcame the WSS threshold at a higher water excess (Figure 4A), denoting that at this position flooding is not an expectable event. At the other extreme, the report of θ_v values below the PWP indicates that at the upland position, severe drought events seem to be a regular situation in late spring and summer months (see also Figure 3B). Conversely, 10 out of 18 θ_v values were above the FC for the intermediate and lowland topographic positions (Figures 4B and C), indicating that water excess leading to flooding events is common when precipitation is higher than the evaporative demand, as it commonly occurs in this region during winter and early spring (Figure 3A).

CONCLUSIONS

Soils of the three analyzed plant communities showed significant differences in water retention capacity and consequent water availability for plants during the year. Soils of the upland plant community underwent the most severe drought periods in summer and never overcame saturation soil water capacity. On the contrary, soils of the plant communities positioned in intermediate and lowland positions suffered less pronounced droughts in summer and remained flooded for several weeks in winter and early spring, the lowland position being more prone to suffer from longer flooding events. Our results, in terms of soil water availability in the course of the year, agree with the seasonality of the ANPP among plant communities already documented for this region (Aragón & Oesterheld 2008; Irisarri *et al.* 2013).

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