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Is forage productivity of meadows influenced by the afforestation of upstream hillsides? A study in NW Patagonia

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Abstract

Meadows are important reserves of water, with a key role in the maintenance of the biodiversity and productivity of ecosystems. In Patagonia, Argentina, afforestation with fast-growing exotic conifers has slowly but continuously increased over recent decades; though unfortunately, knowledge of the effects of afforestation on water resources remains scarce, with no information at all related to its impact on water dynamics and productivity of meadows located downslope to it. The effects of *Pinus ponderosa* afforestation on water dynamics (soil moisture contents and groundwater level) and productivity (aboveground forage productivity) of Northwest Patagonia meadows under xeric and humid conditions were analyzed. In the humid meadow, gravimetric soil water content, groundwater level and forage productivity were similar downslope of forested and non-forested slopes, with a trend towards higher forage productivity on the forested slope. In the xeric meadow, gravimetric soil water content was always higher downslope of the non-forested slope, with no difference in groundwater level between treatments. Forage productivity was statistically similar between situations (downslope of forested and non-forested slopes), with a trend towards higher productivity in the zone with higher soil water content. The main difference in the latter was related to differences in soil texture between zones. These results suggest that coniferous plantations located upstream of this type of meadow do not produce a direct effect on its aboveground forage productivity. These systems have high complexity linked to precipitation, geomorphology and previous history of land use, which determine primarily soil water dynamics and consequently, forage productivity.

Key words: *Pinus ponderosa*; groundwater; aboveground forage production.

Resumen

Afecta la presencia de forestaciones ubicadas en las laderas aguas arriba de mallines su productividad forrajera? Un estudio en el Noroeste Patagónico

Los humedales son importantes reservorios de agua, con un rol clave en el mantenimiento de la biodiversidad y la productividad de los ecosistemas. En Patagonia, Argentina, la forestación con coníferas exóticas de rápido crecimiento ha aumentado lenta pero constantemente en las últimas décadas, aunque desafortunadamente, el conocimiento de sus efectos sobre los recursos hídricos sigue siendo escaso, sin información en cuanto a lo relacionado con su impacto en la dinámica del agua y la productividad de los humedales situados ladera abajo de las mismas. Fueron analizados los efectos de la forestación con *Pinus ponderosa* sobre la dinámica hídrica (contenido de humedad del suelo y el nivel del agua subterránea) y la productividad de forraje aérea en humedales del noroeste de la Patagonia bajo condiciones xérica y húmeda. En el humedal húmedo, el contenido gravimétrico de agua del suelo, el nivel freático y la productividad de forraje fueron similares aguas abajo entre la ladera forestada y no forestada, con una tendencia hacia una mayor productividad de forraje en la ladera forestada. En el humedal xérico, el contenido gravimétrico de agua del suelo fue siempre más alto aguas abajo de la ladera no forestada, sin diferencia en el nivel freático entre los tratamientos. La productividad de forraje fue estadísticamente similar entre las situaciones (aguas abajo de la ladera forestada y no forestada), con una tendencia hacia una mayor productividad en la zona con mayor contenido de agua del suelo. Esta principal diferencia en el segundo caso se relaciona con diferencias en la textura del suelo entre las zonas. Estos resultados sugieren que las plantaciones de coníferas situadas aguas arriba de este tipo de humedales no producen un efecto directo sobre la productividad aérea de forraje. Estos sistemas tienen una alta complejidad vinculada a la precipitación, la geomorfología y la historia previa de uso de la tierra, que determinan principalmente la dinámica de agua en el suelo y, en consecuencia, la productividad de forraje.

Palabras clave: *Pinus ponderosa;* agua subterránea; producción de forraje.

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Introduction

A quarter of our planet consists of arid and semiarid regions and about 15% of the world population lives in them. Many dry lands are threatened by desertification, a phenomenon that is defined as land degradation in arid and semiarid regions caused by several factors, including climatic variations and the abuse of natural resources by humans (World Water Council, 2009). This is why dry lands are fragile ecosystems. Due to insufficient water resources, the shallowness of their arable land and low biomass productivity, these regions are highly vulnerable to harmful usage practices, such as overgrazing, deforestation and inappropriate irrigation systems. Additionally, changes in rainfall levels predicted by climate change models have an even greater impact on the already difficult water management challenges in these regions (World Water Council, 2009).

In arid and semiarid regions, regional variation of primary production is associated principally with rainfall (Lauenroth, 1979). However, primary production may vary according to spatial variations of soil water availability (Hong *et al.*, 2002; Lauenroth and Sala, 1992; Orwing and Abrams, 1997; Oesterhel *et al.*, 2001). The most extreme cases of this landscape-level variation are the azonal communities associated to streams or shallow groundwater immersed in a context of arid and semi-arid vegetation (Buono *et al.*, 2010).

The northern area of Patagonia (Argentina) has a semiarid climate, with water deficits in summer (Jobbágy and Sala, 2000), which is why water is considered the most limiting resource in the region. The presence of temperate meadows is very important from productive and ecological standpoints (Marcolín *et al.*, 1978; Raffaele, 1999). «Mallines» (as a typical kind of meadows in the Patagonian region are called) are ecosystems located in depressed zones or in valleys with high water availability (Raffaele, 1999; Brinson and Malvárez, 2002). They only cover 1.5% of Patagonia and have a vegetation-soil complex which is different from that of surrounding areas, representing an important source of resources for native terrestrial and aquatic species, and also from a productive standpoint. They are high-productivity sites with palatable species for cattle and sheep (10 to 20 times higher than the surrounding steppe; López *et al.*, 1998).

Patagonian meadows potentially differ from each other and are internally heterogeneous. Differences among meadows may be caused by contrasting locations in the vast region and/or due to differences in mean annual rainfall. The internal heterogeneity stems from a gradient of water availability from the central zone towards the periphery (Buono *et al.*, 2010). In the central zone there is excess moisture during winter and early spring, high soil organic matter, and vegetation dominated by sedges. The periphery is subject to water stress in summer, has lower soil organic matter, and is covered by open grassland dominated principally by the species *Festuca pallescens* (Bonvissuto *et al.*, 1992; Bonvissuto and Somlo, 1998; Buono *et al.*, 2010).

As a consequence of overgrazing, the productivity of «mallines» has deteriorated, causing a reduction in forage availability per unit area (Lanciotti *et al.*, 1999).

On the other hand, in northwest Patagonia, afforestation activities have increased over recent decades, with the introduction of exotic fast-growing species, mainly *Pinus ponderosa* (Doug. Ex P. and Laws; 80% of the current plantations in the region). Currently, *P. ponderosa* plantations cover approximately 80,000 ha, and it is expected that the surface planted will increase in the near future due to a forestry incentive policy by provincial and national governments (Godoy and Defossé, 2004). Therefore, the impact of forest plantations on the water resources represent a key point to take into account in order to guarantee the long-term maintenance of ecosystem functioning.

As a global pattern, it is known that the evapotranspiration of forests is higher than that of grasslands and, therefore changes in land use involving afforestation could cause a decrease in the water yield of catchments (Vertessy and Bessard, 1999; Jackson *et al.*, 2005). As an example of this, fast-growing species may use larger amounts of water than native vegetation, altering the water balance of a site (Jobbágy and Jackson, 2004; Gyenge *et al.*, 2002; Gyenge *et al.*, 2003; Gyenge, 2005; Gyenge *et al.,* 2009).

Considering the dynamics of the water resources at a regional level, the recharge of ecosystems downslope from the forest plantations might be negatively affected by an increase in the consumption of water (Bari and Schofield, 1991; Scott and Lesch, 1997; Scott *et al.*, 1998; Le Maitre *et al.*, 1999; Díaz and Reborí, 2002; Licata *et al.*, 2008). Likewise, the knowledge of the existing relationship between water availability and biological processes, such as productivity, would allow Patagonian forestry development in the framework of land-use planning taking into account catchment functioning.

Based on this background, the aim of this work was to determine the impact of the introduction of *P. ponde-*

rosa on the slopes of meadows of northwest Patagonia on groundwater levels, gravimetric soil moisture content, and above-ground forage productivity of these ecosystems located downslope of forested areas. Based on Scanlon *et al.* (2002), who pointed out that the water recharge generally occurs in topographic highs and discharge in topographic lows in humid regions, we hypothesized that afforestation could negatively affect the flow of both groundwater and surface water, decreasing the water recharge in the downslope grassland zone. We also expected that it could affect grass productivity in the peripheral areas of meadows, with a more marked influence in the xeric region than in the humid region. This information could contribute to afforestation planning by increasing the available knowledge on the effects of land use change on water resources and natural ecosystem functioning.

Material and methods

Study area and meadows description

The study area is located in the pre-mountain area in northwest Patagonia (Argentina). This region is characterized by a Mediterranean-type climate, with cold, humid winters (4°C, 700 mm precipitation; De Fina, 1972), and hot, dry summers (16°C, 150 mm precipitation; De Fina, 1972). This region has mountains with valleys of glacial origin, terraces and flat terrain originated by glaciers or rivers, and more recent alluvial valleys (Reserva de Biosfera Andino Norpatagonica, 2007).

Within this region, we selected meadows that have both grassland areas downstream of a *P. ponderosa* plantation (forested slopes, FG) and grassland areas downstream of non-forested slopes (GG). The two slopes (forested and non-forested) had similar gradients and exposures to sun and wind. Additionally, and in order to analyze contrasting rainfall conditions, the two meadows studied had different annual rainfall. The following meadows were selected: one within «El Porvenir» ranch, called «humid meadow» in this paper (40° 06’ 50” S, 71° 09’ 56” W; 1,200 mm annual precipitation; Table 1; Fig. 1) and one within «La Veranada» ranch, called «xeric meadow» (41° 13’ 53” S, 71° 11’ 40” W; 800 mm annual precipitation; Table 1; Fig. 1). The historical mean precipitation for the period corresponding to the growing season (September to April) is 330 mm in the humid site and about 270 mm in the xeric site (period 1990-2000, National Weather Information System of Argentina).

In the humid meadow, winter rains erode the soil, generating grooves for water runoff and dragging fine material that is deposited downstream of the slope, more visibly on the hillside with grassland. The xeric meadow was highly heterogeneous at micro-site level,

Table 1. Characteristics of the meadows studied. Description of the two study sites, data were gathered from literature and from the analysis of samples taken at each meadow specifically for this study. F and G indicate forested and non-forested slopes

Features	El Porvenir		La Veranada	
Annual precipitation (mm year^{-1})	1,200		800	
Exposure	Northwest		Southwest	
Slope (%)	F: 14.3 ± 6.8	G: 16.3 ± 7.1	F: 16 ± 6.2	G: 8.1 ± 4.7
Bulk density (g cm$^{3\,-1}$)	F: 1.3 ± 0.3	G: 1.5 ± 0.1	F: 0.9 ± 0.1	G: 1.0 ± 0.2
Texture of soil	Loamy sand		Loamy sand	
Organic matter (%)	F: 7.7	G: 6.5	F: 15.1	G: 7.2
Nitrogen (%)	F: 0.3	G: 0.3	F: 0.3	G: 0.6
Carbon:Nitrogen	F: 14	G: 14	F: 14	G: 15
Field capacity (mm)	F: 343.4	G: 487.5	F: 263.1	G: 537.4
Permanent wilting point (mm)	F: 156.3	G: 202.9	F: 131.7	G: 257.9
Available water (mm in 1 m of depth)	F: 187.1	G: 284.6	F: 131.4	G: 279.5
Afforestation area (ha)	50		30	
Age of afforestation	20		20	
Density of afforestation (tree ha^{-1})	1,600 ± 329		909 ± 480	
Diameter at breast height (cm)	20.3 ± 1.3		22.8 ± 4.3	
% rainfall interception	45		56	
Potential forage productivity (Bonvissuto and Somlo, 1998) (kg ha^{-1} year^{-1})	1,000-2,000		1,000-2,000	
Livestock	Bovine		Sheep	

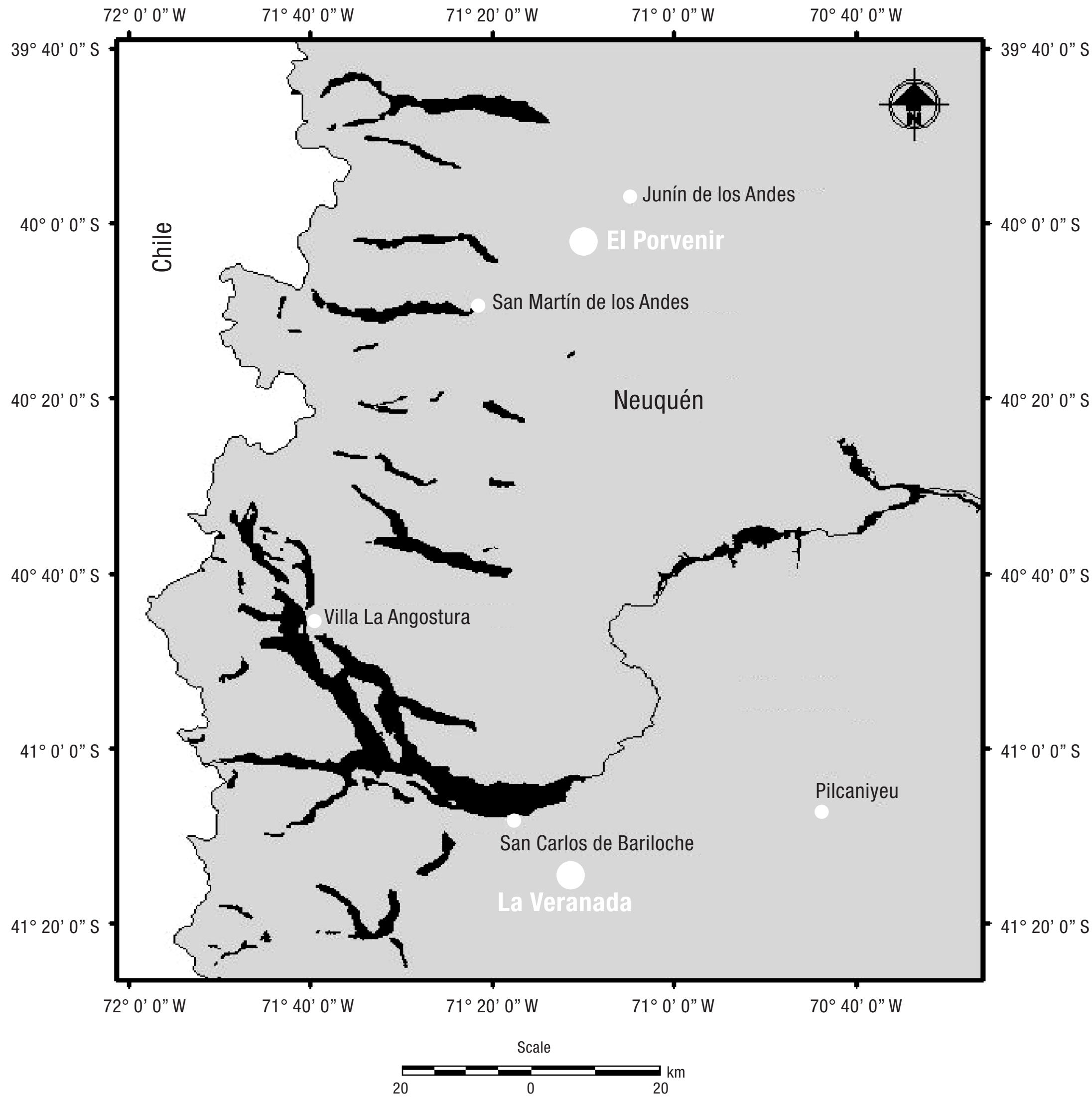

Figure 1. Spatial location of the two meadows («mallines») at xeric («La Veranada») and humid («El Porvenir») sites.

and differences in soil characteristics (textural classes and nutrient content) were related to the previous history of land use. The currently forested zone was previously subject to strong grazing pressure, leading to desertification processes due to overgrazing, commonly observed in other areas of Patagonia (Ares, 2007).

The main herbaceous species in both meadows are *Festuca pallescens*, with a lower proportion of *Poa* spp., *Carex* spp., *Taraxacum officinale* and *Trifolium repens*.

Variables recorded

In order to analyze the effect of afforestation on the recharge of water, measurements were taken in both meadows during three consecutive growing seasons on the two slopes (GG and FG; Fig. 2) every fifteen or thirty days. Throughout the austral spring, summer and autumn (total growing season) of 2006 to 2009, the following variables were recorded periodically: a) Precipitation level was recorded using three pluviometers per slope condition (GG, FG) in each meadow (Fig. 2); b) gravimetric soil moisture content was recorded by colleting soils samples every 20 cm up to the maximum soil depth, determined by the presence of clay in the soil profile, at 4 points per slope of each meadow using soil borers (Fig. 2). Gravimetric soil moisture content was estimated by weighing soil samples before and after drying at 60°C during at least 48 hours; c) Groundwater level was registered using five piezometers (PVC tubes with holes)

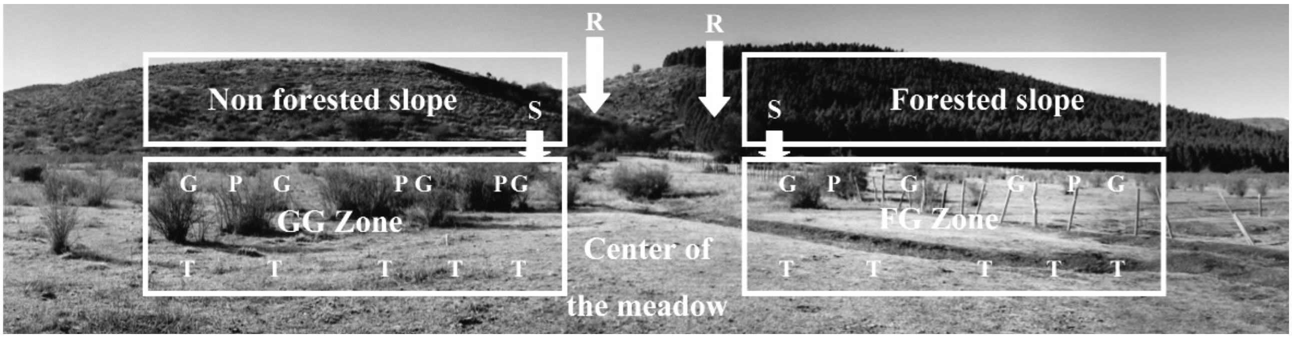

Figure 2. Schematic sampling design specifying the non-forested slope, forested slope, and grasslands downslope of non-forested zones (GG) and downslope of forested zones (FG). Exclosures were located in GG and FG zones. Arrows indicate the direction of the water flow in the slope around the meadows. R: runoff. S: sub superficial water flow. G: indicates the points at which soil samples were taken to determine gravimetric soil moisture content. P: indicates the position of rain collectors. T: indicates the location of piezometer. Photo of the humid meadow.

3.5 m in depth per meadow and slope condition (Fig. 2). The depth of the groundwater level (free water) was measured considering the soil surface as the zero level.

One composite soil sample from FG and GG per meadow was used to determine water retention curves standard parameters (field capacity = FC; 0.03 MPa and permanent wilting point (PWP 15 MPa) for 0-40, 40-80 and 80-120 cm soil layers at the Soil Laboratory of the EEA Bariloche INTA (National Institute for Agricultural Technology, Argentina). Water retention parameters were acquired using the methodology described by Baver *et al.* (1972), Stackman (1980) and Hillel (1984). Organic matter (OM), total nitrogen and organic carbon were determined from composite samples of the upper 40 cm. These samples were dried and sifted with a 0.5 mm mesh. The organic C content was measured using Walkley-Black's technique and total nitrogen by means of the semi-micro Kjeldahl technique.

To estimate annual forage productivity, ten 6 m^2 grazing exclosures were installed (5 in FG and 5 in GG zone) in each meadow at the beginning of the study. Each exclosure was placed in the peripheral zone of meadows (close to the slope zone; Fig. 2). The annual above-ground biomass inside the exclosures was harvested in autumn, end of the growth period (Bonvissuto pers. com.) in each of the three growing seasons. To estimate dry above-ground biomass production, the harvested material was oven-dried to a constant mass at approximately 60°C for 48 hours, and then weighed.

Statistical analysis

Differences in gravimetric soil moisture content, groundwater level and above-ground forage productivity between zones of each meadow (FG *vs.* GG) were statistically analyzed using one-way analysis of variance (ANOVA). When the data did not meet statistical assumptions, we used the non-parametric Kruskal-Wallis test. Above-ground forage productivity comparisons between years (growing seasons) within each zone were done with paired *t*-tests. The accepted significance level was $\alpha = 0.05$.

Results

During the periods measured, the precipitation levels were below the historical mean precipitation level (Table 1), at 247, 113 and 212 mm in the humid meadow and, 208, 207 and 129 mm in the xeric meadow for the seasons 06-07, 07-08, 08-09, respectively.

During spring, at the beginning of measurements in both meadows, soils were water saturated (gravimetric soil moisture content was higher than the FC value, Table 1; Fig. 3). After that, gravimetric soil moisture content diminished until the values were close to and even under PWP (Table 1; Fig. 3). In the humid meadow, the values of gravimetric soil moisture content were not statistically different between zones on either date ($p > 0.05$), they fluctuated similarly in the three growing seasons studied, but decreased below PWP at different sampling dates depending on the season (Fig. 3a). On the other hand, in the xeric meadow, gravimetric soil moisture content was significantly higher in the GG than in the FG zone on most of the measurement dates (Fig. 3b). In the FG zone, soil gravimetric water content decreased throughout the season, reaching values close to or even below the PWP. In contrast, in the GG zone, soil moisture never reached values below the PWP (Fig. 3b).

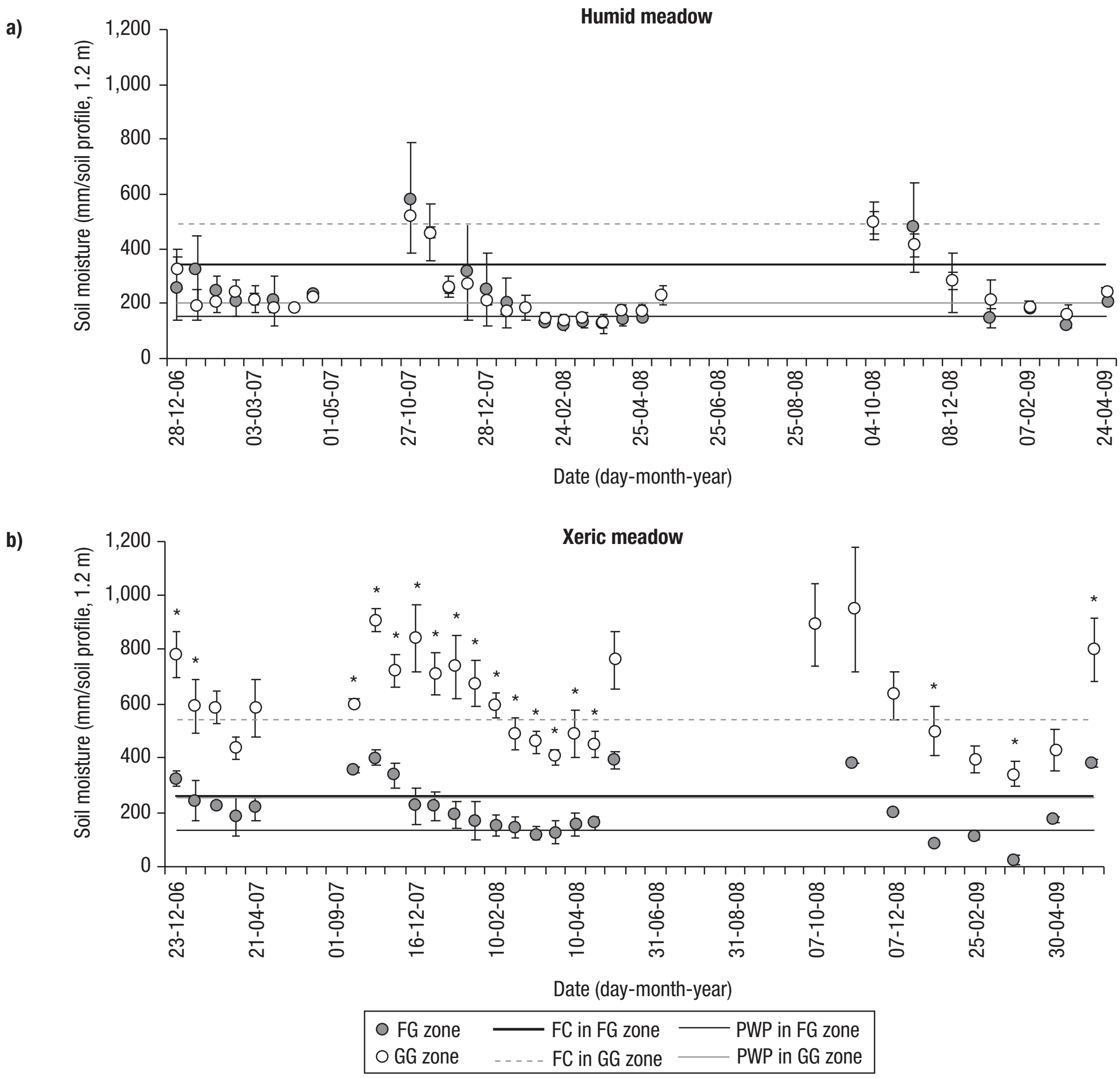

Figure 3. Gravimetric soil moisture content (mean ± Standard deviation) in meadows grasslands downslope of a forested slope (FG) and a non-forested slope with grassland (GG). Values of field capacity (FC) and permanent wilting point (PWP) were detailed on the figure. Asterisks in the graph (*) show dates of significant statistical differences between zones (FG *vs.* GG).

A similar general pattern of groundwater level was observed during all the growing seasons and meadows studied, receding during the dry months of the year (Fig. 4). In the humid meadow, at the beginning of the growing season groundwater level was close to the surface in both the FG and the GG zone (Fig. 4a). During the first season studied, the groundwater level reached its maximum detectable depth in the FG zone in March, whereas maximum depth was recorded a month earlier during the second season (Fig. 4b). In the GG zone, the maximum depth was observed earlier than in the FG zone.

In the xeric meadow, significant differences in the groundwater level between zones were recorded at the beginning of the second and third seasons, showing deeper groundwater level in the FG than in the GG zone. In this case, the groundwater level in the FG zone was even deeper at the beginning of the warm period, characterized by a high amount of free water due to spring snowmelt recharge and low evapotranspiration.

Above-ground forage productivity in the humid meadow was higher in the FG than in the GG zone (3,839.5 and 1,655.5 kg ha^{-1}, respectively, the mean value for the three seasons studied). However, statistical differences between zones were only detected during the second growing season (2007-2008), which was characterized by the lower precipitation level recorded during the study period (FG: 2,738.5 kg ha^{-1}-GG: 1,488.3 kg ha^{-1}; $p < 0.05$) (Fig. 5a). For both treatments,

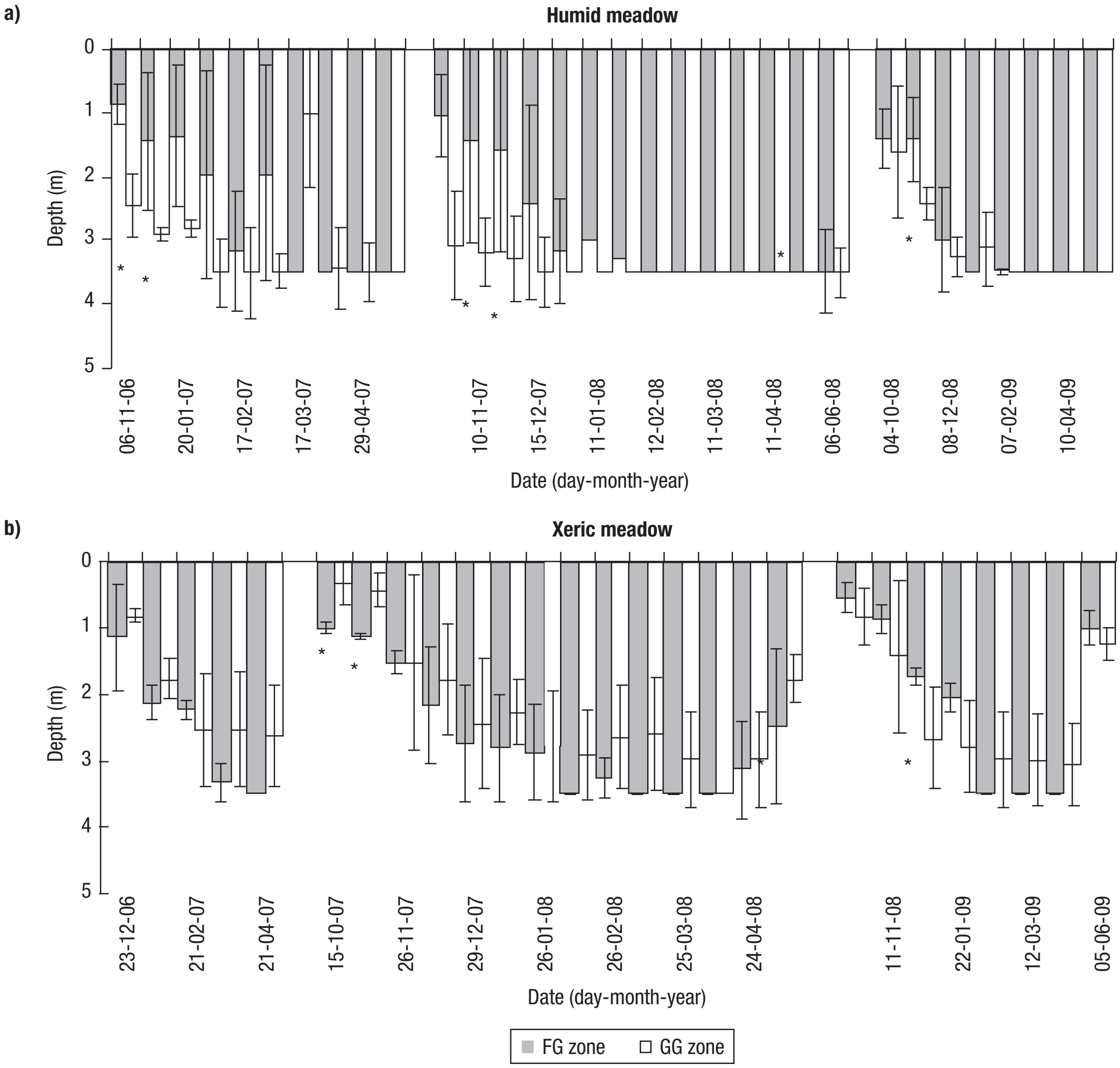

Figure 4. Groundwater levels (mean ± Standard deviation) of meadows downslope of the forested slope (FG) and non-forested slope with grassland (GG). Asterisks in the graph (*) show dates of significant statistical differences between zones (FG *vs* GG).

FG and GG zones, there was lower productivity in the second dry season, but these differences were not statistically significant between seasons ($p > 0.05$).

In the xeric meadow, contrary to what was observed in the humid meadow, higher above-ground forage productivity was observed in the GG than in the FG zone (3,309.8-1,811.8 kg ha^{-1}, mean value for the three seasons studied), showing statistical differences only during the growing season 2006-2007 (2,743.4-821.4 kg ha^{-1}, $p < 0.05$). Additionally, there was an increase in above-ground forage productivity throughout seasons (Fig. 5b).

Soil texture and nutrient availability were different between zones in each meadow, and also between meadows (Table 1, Fig. 6). In the humid meadow, a higher proportion of sand was observed in the soils of GG zone, resulting in lower water retention capacity. The organic matter content, total nitrogen and carbon-nitrogen ratio were similar in both zones within this meadow. Differences in soil texture and nutrient composition were more pronounced than in both zones in the xeric meadow, in which the proportion of sand was higher in FG zone (Table 1, Fig. 6). In addition, the organic matter content and nitrogen in the GG zone were double that recorded for soils from the FG zone.

Discussion

The results do not support the proposed hypothesis that afforestation negatively affects water recharge in

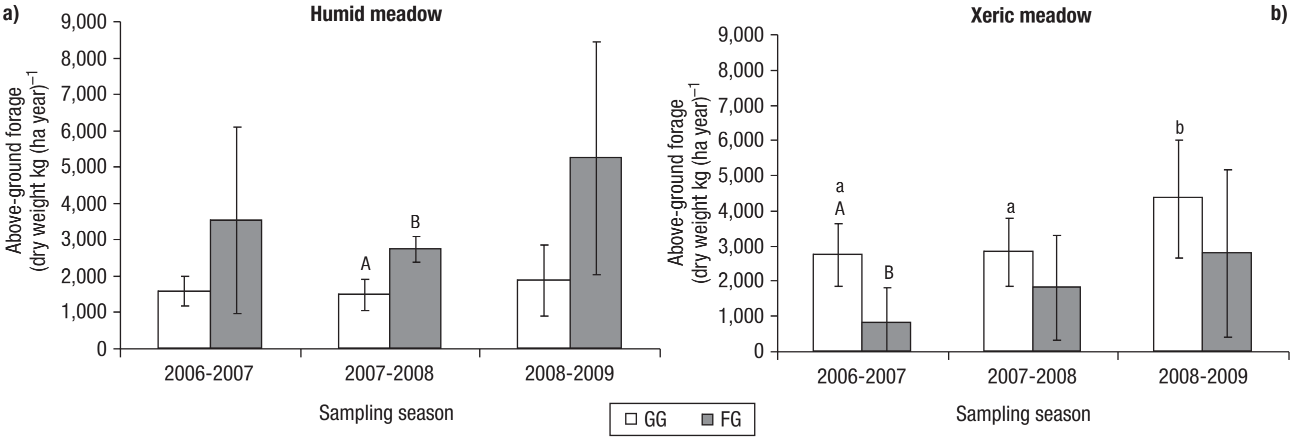

Figure 5. Above-ground forage productivity of grassland (mean± Standard deviation) downslope of a forested slope (FG) and of a non-forested slope with grassland (GG) during the seasons 2006-2007, 2007-2008 and 2008-2009 in the humid (a) and xeric (b) meadows. Different capital letters on the graph show statistically significant differences between zones in a year. Different lower-case letters on the graph show statistically significant differences between years comparing similar zones.

the downslope grassland zone and affects grass productivity in the peripheral areas of meadows, with a more marked influence in the xeric region than in the humid region. In this regard, in general no statistical difference was observed between zones (downslope of forested and non-forested slopes) within each meadow.

However, the results show the heterogeneity between zones and within meadows. The patterns observed in gravimetric soil moisture content, groundwater level and above-ground forage productivity were different comparing both meadows, but we cannot attribute those differences to the different precipitation level.

In the humid meadow, there was a trend towards higher above-ground forage productivity downslope of the forested slope (FG). These results do not agree with the trend of gravimetric soil moisture content, which generally showed no difference between zones.

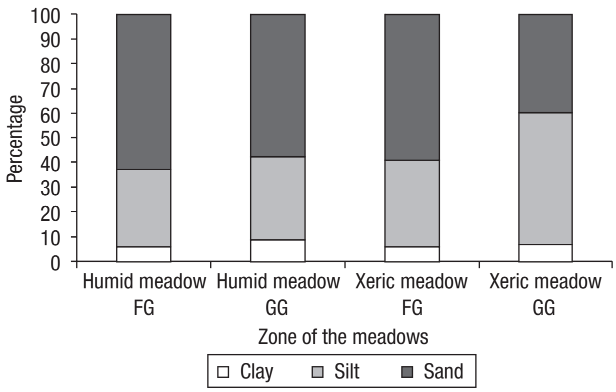

Figure 6. Analysis of soils in meadow grassland downslope of a forested slope (FG) and downslope of a non-forested slope with grassland (GG) in the humid and xeric site.

However, in the FG zone, the PWP was lower than in GG zone, which enabled this soil to hold more water during the dry months compared to the GG zone. Therefore, the higher forage productivity observed downslope of the forested slope, at least in one of the three growing seasons, could be related to the higher water availability in the soil due to its slightly different texture.

In the xeric meadow, there was a trend towards higher above-ground forage productivity downslope of the non-forested slope (GG zone), probably related to the higher soil water availability in that zone. In this case, textural differences between zones were pronounced even before the forest plantation was installed (personal communication from the owners of La Veranada ranch). The huge differences in organic matter content and soil texture, with much higher water retention capacity of soils in the GG zone, could be the cause for the large differences in soil water content throughout the growing season between zones (Fernández and Trillo, 2005).

Although in general, no statistical difference was observed between groundwater level in the two zones within each meadow, a different pattern of groundwater receding was observed depending on the zones. In the humid meadow this occurred later in the FG than in the GG zone, while in the xeric meadow, groundwater receding was later in the GG than in the FG zone. Although there was no statistical difference, this pattern was found to repeat itself over the seasons. This is consistent with the results of gravimetric soil moisture content and above-ground forage productivity. In many shallow groundwater regions, such as meadows, the groundwater table leads to a continuous supply of groundwater to the root zone. In those regions, the role of groundwater in variations of the root zone soil moisture becomes essential (Chen and Hu, 2004).

Patagonian meadows have a wide variety of forms and generally erratic behavior of their channels (Ayesa *et al.*, 1999). Buono *et al.* (2010) studied the annual net primary production in several Patagonian meadows. They also found high variability in their results, and considered that it may stem from climatic and biological features of these azonal ecosystems.

The complexity of the variables determining above-ground forage productivity suggests that the main cause of the differences in trends observed between zones of a meadow or between meadows is not the presence or absence of forest plantations upstream of the peripheral area of meadows, at least considering forested patches as small as those studied. In this regard, Brown *et al.* (2005), with reference to the investigation of Bosch and Hewlett (1982), state that for any impact of vegetation change to be detected, at least 20% of the catchment needs to be modified in its vegetation cover. In both cases studied, the lack of significant differences in the variables measured was probably related to the small percentage of forested catchment.

Although no negative effect could be directly attributed to the presence of plantations, it is possible that, depending on the amount of forested surface, the water fluxes in this section of the meadows could be affected. Scott *et al.* (2004) indicated that the classical forest hydrology literature suggests a linear relationship between the catchment water yield and the percentage of planted or cleared catchments. However, this relationship could change depending on whether the afforestation occurs in places around or away from streams (Scott and Lesch, 1997). Based on the heterogeneity of the meadows, caution must be exercised when planning large-scale afforestation projects.

Conclusions

This study contributes to showing the complex relationships between water dynamics, as affected by several biological and edaphic variables, and forage productivity in Patagonian meadows, which are systems of great productive and ecological importance for this region. No clear direct effect of afforestation on the slopes of meadows on the above-ground forage productivity was observed in either of the meadows studied. Their productivity seems to be more influenced by precipitation during the growing season in conjunction with soil water retention capacity and groundwater level, which were not affected by upslope afforestation, at least during the growing season.

The systems studied revealed high complexity linked to geomorphology and previous history of land use determining primarily soil water retention capacity and consequently, forage productivity. Inclusion of these variables is necessary for comprehensive understanding of the dynamics of these systems. Therefore, the prediction of forage productivity in this type of ecosystem needs to take into account different factors, including the relative influences of the upstream vegetation, geomorphologic and edaphic characteristics, microclimatic conditions, and previous history of land use of the site. The heterogeneity of these environments is shown, determining the need for an individual study for each case.

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