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Glyphosate retention in grassland riparian areas is reduced by the invasion of exotic trees

La retención de glifosato en las áreas ribereñas con pastizales se reduce por la invasión de árboles exóticos

Giaccio GCM[1], P Laterra[2], VC Aparicio[3], JL Costa[3]

Abstract. In this study, we examined some aspects regarding the effect of willow trees (*Salix fragilis* L.) invasion of grassland riparian environments in the Argentinean Pampas on the runoff reduction, sedimentation and glyphosate retention in the riparian vegetation strip (RVS). To assess the influence of willows on the filtering mechanisms, we performed runoff simulation experiments in plots of 1.5 x 2.5 m, in coastal environments characterized by the presence of willows or the lack of trees. Despite the short length of the experimental plots, the retention of glyphosate in the controls, with no trees, was higher and reached almost 74%. Nevertheless, sediment retention did not differ significantly between the tree areas and the grassy controls. The runoff reduction in plots with willows was of 63%. The presence of willow trees significantly altered the measured biophysical properties, such as soil moisture and aboveground biomass, compared to areas without trees. Analysis of partial correlations for environments with and without trees showed that the reduction in runoff volume increased significantly with the soil sand content and the groundwater table depth, while it decreased with bulk density, soil moisture and the riparian slope. Sediment retention increased significantly with aboveground biomass, litter and root biomass; and decreased with the riparian slope. In turn, glyphosate retention increased significantly with sediment retention and decreased with the riparian slope and litter biomass. The mechanisms involving the effect of willows could not be well explained. Due to the increased intensification of agriculture, treeless RVS are important to reduce glyphosate concentration in streams and their sinks. Nevertheless, the presence of trees is also important in the context of agroecosystems and agricultural landscapes, as they contribute to reduce the runoff flow.

Keywords: Riparian vegetation retention; Surface runoff; Sediment retention; Glyphosate retention; Ecosystem services.

Resumen. En este estudio se analizaron algunos aspectos relacionados al efecto de la invasión de sauces (*Salix fragilis* L.) en ambientes ribereños con vegetación herbácea, de las Pampas de Argentina, sobre la reducción del flujo de escorrentía y la retención de sedimentos y glifosato en las franjas de vegetación ribereñas. A fin de evaluar la influencia de los sauces sobre los mecanismos de filtrado, se realizaron experimentos de simulación de escurrimiento superficial en parcelas de 1,5 por 2,5 m en ambientes caracterizados por presencia vs ausencia de sauces. A pesar de la escasa longitud de las parcelas experimentales, la retención de glifosato en las parcelas control, -sin árboles-, alcanzó casi al 74%. Sin embargo, la retención de sedimentos no difirió significativamente entre las áreas con y sin árboles. Por su parte, la reducción del volumen de escorrentía en los sitios con árboles alcanzó el 63%. La presencia de árboles solo modificó significativamente las propiedades biofísicas humedad del suelo y biomasa aérea, comparadas con áreas sin árboles. Los análisis de correlaciones parciales para ambientes con y sin árboles, mostraron que la reducción en volumen de escorrentía aumentó significativamente con el contenido de arena del suelo y la profundidad al nivel freático, y disminuyó con la densidad aparente, la humedad del suelo y la pendiente de la franja ribereña. Sin embargo, la retención de sedimentos aumentó significativamente con la biomasa aérea, de mantillo y de raíces y disminuyó con la pendiente de la franja ribereña. A su vez, la retención de glifosato aumentó significativamente con la retención de sedimentos y disminuyó con de la pendiente de la franja ribereña y la biomasa de mantillo. No obstante, los mecanismos que involucran el efecto de los sauces no pudieron ser bien explicados. Si bien surge la importancia de los ambientes sin árboles por su función de filtrado de glifosato frente a la creciente intensificación de la agricultura, en el contexto de agroecosistemas y paisajes agrícolas la presencia de árboles, contribuye a la reducción del flujo de escorrentía.

Palabras clave: Retención vegetación ribereña; Escorrentía superficial; Retención de sedimentos; Retención de glifosato; Servicios ecosistémicos.

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[1] Chacra Experimental Integrada Barrow. INTA. CC 50. (B7500) Tres Arroyos. Argentina.
[2] Facultad de Ciencias Agrarias, UNMDP - EEA INTA Balcarce. CONICET. CC 276. (B7620) Balcarce. Argentina.
[3] EEA INTA Balcarce. CC 276. (7620) Balcarce. Argentina.
Address correspondence to: Ing. Agr. (M.Sc.) Gustavo Carlos Maria Giaccio, Fax / Phone 054-2983-431081, *e-mail:* giaccio.gustavo@inta.gob.ar
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INTRODUCTION

The term riparian derives from the repairs Latin word for stream bank. The riparian ecosystems are dynamic environments, characterized by high energy regimes, marked heterogeneity of habitats, diversity of ecological processes and multidimensional gradients. They occupy the transition zone between terrestrial and aquatic ecosystems, and include the riparian vegetation strips (RVS) (Naiman et al., 2005). Some functions of the RVS are: runoff water flow reduction (Arora et al., 2010; Schoumans et al., 2014); sediment retention (Syversen, 2005; Gumiere et al., 2011; Schoumans et al., 2014), and glyphosate retention (Syversen, 2003; Syversen & Bechmann, 2004). Their holding capacity depends mainly on the soil characteristics (Syversen & Bechmann, 2004; Syversen, 2005), although the influence of vegetation on these processes is still not well known.

In general, the importance of tree species in riparian areas has been studied in comparison to areas modified by human impact, like deforestation, intensive agriculture, overgrazing, urban development (Naiman et al., 2005). To a less extent, the role of trees has been compared to the role of herbaceous vegetation (Lyons et al., 2000). According to Lyons et al. (2000), riparian vegetation can be classified as “woody” and “grassy”. Woody vegetation includes trees and shrubs whose canopies provide at least 75% of coverage and have a height of 2 meters or more. Grassy vegetation comprises grass and herbaceous species that do not exceed 2 meters in height and produce more than 75% of the ground coverage.

In the RVS of the Austral Pampas, the native natural grassland is composed mainly of species of the family Poaceae and Cyperaceae (Soriano et al., 1991; Leon, 1992). Although it retains most of its original features, it has been widely invaded by exotic species like *Festuca arundinacea Schreb.* Currently, a large proportion of the river banks and streams is modified by the presence of well-developed forested strips of the naturalized specie *Salix fragilis L.* (Villamil, 2008) which are associated with a more open herbaceous layer (Giaccio, 2011). Several authors recommend trees as an effective measure to reduce pesticide drift and prevent their entry into aquatic environments (FOCUS, 2007; Reichenberger et al., 2007). Furthermore, the presence of trees is considered as a biodiversity hotspot for terrestrial and aquatic organisms (Richardson et al., 2010; Suurkuukka et al., 2014). The potential impacts of invasive species are widely recognized throughout the world, although their quantitative assessments are rare (Jäger et al., 2007; Pyšek & Richardson, 2010). For example, in Australia naturalized willows are recognized for altering the vegetation structure and functioning of streams (Catford et al., 2013). Willow trees develop a strong root system that structures the riparian soils, and can also reduce surface runoff and retain sediment particles by the large pieces of fallen wood in the ground (Lyons et al., 2000). Preliminary studies on the Southern Pampas show that the presence of *Salix fragilis* increases the infiltration rates in soils (Giaccio et al., 2010). Thus, it can be assumed that glyphosate retention would also increase, as it is a process that depends mainly on the infiltration processes (Syversen & Bechmann, 2004; Arora et al., 2010). Some studies document specific cases where grassy riparian areas provide equal or higher benefits than those with woody riparian areas. Basically, this has been pointed out in places where the banks and slopes are low, and the herbaceous vegetation may show superior performance in preventing erosion than the woody vegetation (Lyons et al., 2000).

Sediment production of a basin is the net result of erosion and deposition within the basin (Jain & Das, 2010). The amount of sediments generated is a function of anthropogenic and physical factors including agriculture, slope, location and rain intensity (Kusimi et al., 2014). Sediments are generated by detachment of soil particles, which can then be carried in suspension by runoff into watercourses (Ta et al., 2013). They play an important functional role in river ecosystems, providing a substrate for biological and chemical processes. Excessive amounts of sediment can cause a wide range of impacts, to the point that they have been recognized as a major cause of environmental degradation of watercourses. When sediments are deposited in beds streams they produce flow alterations, depth reductions (Grabowski et al., 2011) and a decrease in light penetration, affecting primary production of vegetation and harming aquatic organisms in all trophic levels (Naiman et al., 2005).

Glyphosate is the most used pesticide in Argentina, mainly due to the proliferation of GM crops coupled with no-till management and chemical weed control. An estimated 78.5% of the agricultural area (i.e., 27 million hectares) is cultivated under no-till (Aapresid, 2012) with a discharge of 200 million liters of glyphosate per year (CASAFE, 2013). Although glyphosate is considered to have a low leaching potential (Borggaard & Gimsing, 2008), some studies have found high vertical mobility (Veiga et al., 2001) and residues have been detected in groundwater (Kjaer et al., 2011). Sasal et al. (2010) reported concentrations of glyphosate in water runoff above the limit of detection. Aparicio et al. (2013) also reported high concentrations of glyphosate in surface water, suspended sediments and bottom sediments of streams in the Southeast of Buenos Aires Province.

Glyphosate´s physicochemical characteristics are very different to those of most herbicides: it has a high water solubility, a low value of octanol/water partition coefficient (K_{ow}), a high ratio of organic carbon partition (K_{oc}) and high abiotic solid phase/water partition (K_d), being the abiotic solid phases: soil, sediment and suspended particles (Mayer et al., 2006). These values indicate that this compound is mostly found adsorbed (Carriquiriborde, 2010). In the soil matrix, glyphosate is mainly adsorbed to iron and aluminium oxides and clays, leading to the formation of surface complexes (Welten, 2000).

The content and type of clay, and the cation exchange capacity (CIC) are important soil parameters to assess its adsorption (De Santana et al., 2006). Since glyphosate is bound to soil particles through the phosphoric acid group, the addition of inorganic phosphate may release adsorbed glyphosate from the soil particles through specific site competition (Franz et al., 1997; Pechlaner, 2002). This competition occurs only when the levels of phosphorus and pH values in the soil are very high (Prata et al., 2003). Accordingly, Simonsen et al. (2008) found that phosphate fertilization significantly increases the risk of glyphosate washed from the soil into water bodies.

As noted by Lyons et al. (2000), there are few studies that document relative retention efficiency of different pollutants in riparian environments with or without trees. In this context, the aims of this study were: i) to evaluate the ability of grassy strips to retain sediments and glyphosate from agricultural origin, and ii) to evaluate the effects of exotic trees on the retention capacity in strips of riparian vegetation of the Austral Pampa. It is hypothesized that the presence of tree layers increases the filtering capacity of the surface runoff (increasing of sediment and glyphosate retention transported in water) in alluvial soils of riparian environments dominated by grasslands.

MATERIALS AND METHODS

Description of the studied area. The Pampas Ecoregion is the most important grassland ecosystem of Argentina, comprising a surface of approximately 540000 km^2. They have a relatively flat terrain, with a gentle slope towards the Atlantic Ocean, with soils suitable for agriculture and livestock. The Southern Pampa is the most southern portion of this ecoregion and it belongs exclusively to the Buenos Aires Province. Their altitudes range from sea level to 1243 m (Soriano et al., 1991). The fluvial system is well defined and the area presents an exoreic basin, with slow course meandering streams, low gradient riverbeds, silty or clay bottom and abundant organic detritus (Ringuelet, 1962).

Selection of sampling sites. The factors that were taken into account for the selection of the sampling sites included sampling in a wide geographic range (in this case in the Azul, Tandil and Balcarce departments), accessibility, and comparable slopes and soil textures with contrasting environments of woody vegetation, composed of *S. fragilis* and an herbaceous layer dominated by *F. arundinacea,* and grassy vegetation, mainly composed of *F. arundinacea*.

A Digital Elevation Model of the studied area was used in order to delimit and select the most relevant sub-basins, established by the runoff volume of each site. The image was obtained by the Shuttle Radar Topography Mission (SRTM) (90 m resolution) (http://srtm.csi.cgiar.org) and was analysed using the software Idrisi Andes. From the various selected sites that met the required parameters, four sites with and without trees were chosen randomly. The location of the sub-basins and their respective surfaces are shown in Table 1 and their geographical location is shown in Fig. 1.

Table 1. Sampling sites, location and surface of the selected sub-basins.
Tabla 1. Sitios de muestreo, ubicación y superficie de las sub-cuencas seleccionadas.

Stream	Latitude	Longitude	Surface (ha)
Del Azul	S 36° 50' 50.3"	W 59° 54' 03. 7"	247.05
La Pastora	S 37° 4' 55.63"	W 59° 32' 12.39"	235.30
San Felipe	S 37° 26' 47.3"	W 58° 56' 31.0"	556.90
Napaleofú	S 37° 33' 24.0"	W 58° 47' 32.4"	146.60

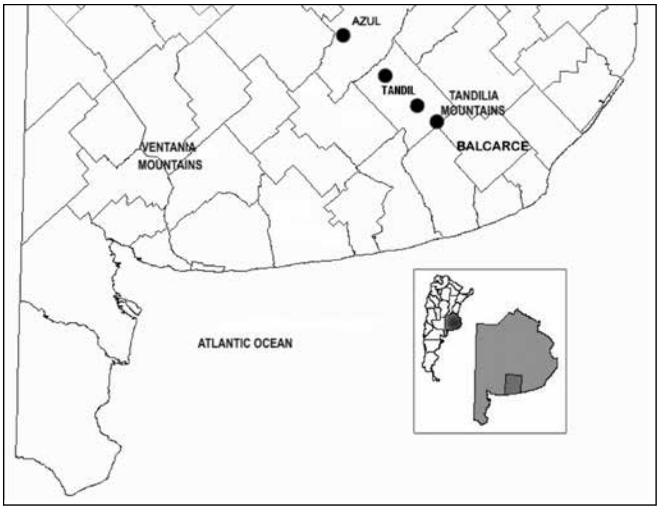

Fig. 1. Location of the sampling sites (black dots) at department scale inside the Austral Pampa.
Fig. 1. Ubicación de los sitios de muestreo (puntos negros) a escala de partido dentro de la Pampa Austral.

Methodology and analysis of samples. Surface runoff simulations were performed by applying water to the runoff plots following a similar procedure to that used by Hook (2003). The runoff volume reduction and the percentage of sediment retention was used as an indicator of the filtering capacity, since the transport capacity of sediments in water is a function of flow velocity (Haan et al., 1994). The experiment was conducted in the spring of 2012. Three rectangular plots were randomly delimitated, with a length of 2.5 metres parallel to the general slope of the RVS, and a width of 1.5 meters perpendicular to the RVS. The device used for the generation of surface runoff consisted of a 150 liter tank, zinc plates and a flow collector (Fig. 2). Water and sediments with the corresponding glyphosate doses were added to the tank (adapted from Syversen & Bechmann, 2004). Under natural conditions, the adjacent soils would saturate simultaneously with the RVS when it starts raining and before surface runoff is generated, thereby the plots were pre-wetted with 150 liters of water (equivalent to 40 mm of rain). A shaker was used to maintain the particles in suspension inside the tank and a pump was used to extract the solution at a determined flow rate. The flow rate was set constantly at 1.11 L/s, which represents 40 mm/h of rain intensity (FAO, 1997). The water used in the tanks had the following characteristics: RAS= 7.65, EC= 0.62 dS/m and pH= 8.0.

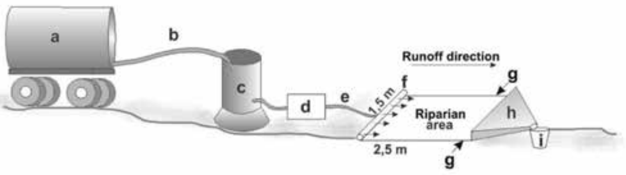

Fig. 2. Device simulation of surface runoff. a: tank with water; b: water supply pipe; c: supply tank with water and added sediments and glyphosate; d: pump with pressure gauge; e: water supply line with added sediment and glyphosate; f: leaky pipe to generate runoff; g: zinc plates to contain runoff; h: flow runoff collector; i: runoff tank.

Fig. 2. Dispositivo simulador de escorrentía superficial donde: a: cisterna con agua; b: tubería de suministro de agua; c: tanque de suministro de agua con agregado de sedimentos, glifosato, fósforo y nitrógeno; d: bomba con medidor de presión; e: tubería de suministro de agua con agregado de sedimentos y solutos; f: caño cribado para generar escorrentía; g: planchas contenedoras de cinc; h: embudo colector del flujo; i: recipiente colector del flujo de escorrentía.

In accordance to Søovik & Syversen (2008), soil collected from an agricultural plot of the studied area was used as a source of suspended solids or sediments. The soil was obtained from the first 3 cm of the A horizon, as this portion of the soil is known to be more susceptible to erosion (Polyakov & Nearing, 2004). The main physicochemical characteristics of the sampled soil were clay: 37.7%; sand: 29.4%; silt: 32.9%; CEC: 23.5; PSI: 4.2 and RAS: 6.7. The soil was disaggregated, dried at 30 °C until constant weight and sieved through a 2 mm mesh. Glyphosate was added to 1000 g of soil to achieve a final concentration of 18 µg/L (Syversen & Bechmann, 2004), and was left to reach the adsorption-desorption equilibrium with the soil particles for 24 hours. Thereafter, the mixture was dissolved in water to reach a final concentration of 5 mg/L in the supply tank. Before starting the experiment a sample of this solution was used to calculate the initial glyphosate concentration. The runoff volume was measured after each run, in order to obtain the value of water reduction that infiltrates in each experiment. Sampling was done by triplicates in each site, and pooled into one 1 L plastic bottle, then stored at 4 °C until arrival at the laboratory where they were kept at -20 °C until analysis. Before analyses, the samples were thawed and filtered through a nylon membrane of 0.45 microns to separate the suspended sediments. The wet weight of the sediments was recorded and then oven dried to obtain the dry weight. The sediment concentration in each sample was calculated as follows (1):

$$\textit{Sediment concentration} = \frac{(\textit{wet weight} - \textit{dry weight})}{\textit{sample volume}} \qquad (1)$$

The efficiency of sediment retention was expressed as (2):

$$\textit{Sediment retention} = \frac{(\textit{initial concentration} - \textit{final concentration})}{\textit{initial concentration}}\ x\ 100 \qquad (2)$$

Glyphosate concentrations were determined in water and sediments samples using liquid chromatography coupled to a tandem mass spectrometer (LC MS/MS) at the EEA INTA Balcarce laboratory. The limits of detection (LD) obtained for soil samples with the present technique was 5 µg/kg for AMPA and glyphosate, and the limits of quantification (LQ) was 10 µg/kg (Aparicio et al., 2013).

At each sampling site, the following attributes were determined:

-riparian slope, calculated using an optical level;

-aboveground biomass contained in 4 plots of 0.25 m^2 each (without considering the aboveground biomass of the trees because it does not have a direct influence on the retention process);

-litter biomass (detached vegetation from soil and remaining vegetable waste), collected from the same plots;

-root biomass of woody and grassy vegetation (0-20 cm depth);

-soil texture determined by the pipette method according to Robinson (Soil Conservation Service, 1972), bulk density determined by the cylinder method (Blake & Hartge, 1986) and soil moisture.

Statistical analysis. Data were analysed using the co-variance analysis of variance (ANOVA) for a completely randomized design, with 4 repetitions and 2 treatments (presence or absence of trees). The chosen covariates were those that are less dependent on the type of vegetation, i.e. riparian slope, sand, silt, clay and soil moisture. Also, we analysed the relationship between runoff reduction, sediment and glyphosate retention, with the topographical, soil and biological variables using partial correlations of the pooled data (with and without trees). Statistical analyses were performed using Info Stat version 2013 software.

RESULTS AND DISCUSSION

The topographic, biological and soil variables of the sampling sites with or without trees are shown in Table 2. The presence of willow trees significantly altered the soil moisture and the measured aboveground biomass compared to areas without trees.

The values of runoff reduction, sediment and glyphosate retention in areas with and without trees are shown in Figure 3.

Runoff volume reduction. The runoff volume reduction was significantly higher in the environments with trees (Fig. 3). Analysis of partial correlations for environments with and without trees, showed that the reduction in runoff volume increased significantly with sand content of the soil and the groundwater table depth, while it decreased with bulk density, soil moisture and the riparian slope (Table 3).

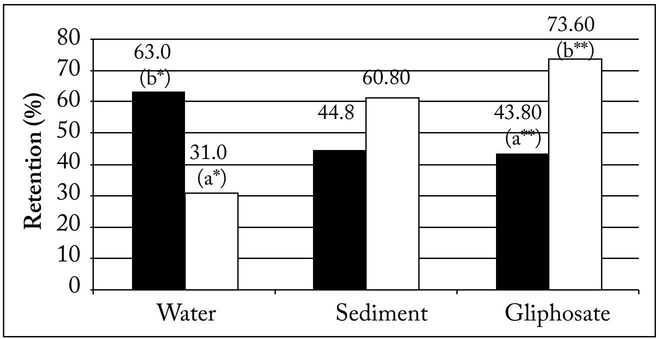

Fig. 3. Average efficiency of surface runoff reduction, sediment retention and glyphosate retention in woody and grassy riparian areas. Black columns represent woody environments and white columns represent grassy areas. Different letters indicate significant differences (*P≤0.05; **P≤0.01)

Fig. 3. Eficiencia media de la reducción del volumen de escorrentía superficial y de la retención de sedimentos y glifosato en áreas ribereñas con y sin árboles. Las columnas negras representan los sitios con árboles y las columnas blancas representan los sitios sin árboles. Letras diferentes indican diferencias significativas (*P≤0,05; **P≤0,01).

These results are consistent with the fact that the groundwater table depth determines the unsaturated soil portion that can store water (Troch & De Troch, 1993), which also explains the influence of soil moisture, conditioned by the sand content. Also as bulk density increases, soil porosity is reduced (Sobieraj et al., 2004), negatively affecting infiltration. The influence of the riparian slope in the runoff reduction is due to a decrease in the water flow rate, thereby increasing infiltration (Naiman & Decamps, 1997). The highest values of runoff retention are attributed to the presence of trees, in accordance with Niemeyer et al. (2014). This behaviour is related to the groundwater depth and sand content of the soil, and the low values of bulk density, moisture content and riparian slope, registered in soils that support trees compared to those without trees, consistent as suggested by Frasier et al. (1998).

Furthermore, according to Blackburn et al. (1992) and Spaeth et al. (1996), infiltration is related to several types of plant communities, indicating that texture is a less significant factor than vegetation. Marelli & Arce (1995) and Pachecoy et al. (1996) obtained low values of hydraulic conductivity on degraded soils with continuous cropping, intermediate values for annual arable crops with different tillage systems and the higher values in soils with forest.

Sediment retention. Regarding the sediment retention, no significant difference was found between environments with or without trees (Fig. 3). However, the analysis of partial correlations showed that the sediment retention increased significantly with aboveground biomass, litter and root biomass; and decreased with the riparian slope (Table 4).

The reduction of the amount of sediments that are transported by surface runoff is related to biomass, litter and aboveground biomass, which cause a reduction in the runoff velocity, by increasing the surface roughness and imposing friction forces (Robinson et al., 1996; Schmitt et al., 1999; Dosskey, 2001). Also, the reduction in flow velocity results in a lower transmission capacity, which favours the deposition

Table 2. Analysis of multiple comparisons among the soil topographic, biophysical and chemical variables, with or without trees. Standard error values are shown in parenthesis. In each row, values followed by different letters indicate significant differences between environments (with or without trees) (P≤0.05).

Tabla 2. Análisis de comparaciones múltiples entre variables topográficas, biofísicas y químicas de los suelos, con o sin árboles. Los valores de error estándar se muestran entre paréntesis. En cada fila, los valores seguidos por letras diferentes indican diferencias significativas entre los ambientes (con o sin árboles) (P≤0,05).

	Riparian Slope (%)	Depth Water Table (m)	Sand (%)	Organic Matter (%)	Electrical Conductivity (dS/m)	Bulk Density (g/cm)	Soil Moisture (%)	Aboveground Biomass of grassy layer (kg/m^2)	Litter Biomass (kg/m^2)	Root Biomass (kg/m^3)
Presence of trees	14.88 (4.78) (a)	0.43 (0.05) (a)	51.68 (5.19) (a)	4.38 (0.51) (a)	0.59 (0.07) (a)	1.22 (0.00) (a)	30.53 (1.15) (a)	0.50 (0.10) (a)	0.34 (0.12) (a)	181.46 (78.42) (a)
Absence of trees	14.62 (4.66) (a)	0.48 (0.04) (a)	48.90 (6,19) (a)	4.83 (0.54) (a)	0.41 (0.04) (a)	1.38 (0.00) (a)	47.35 (2.25) (b)	0.76 (0.06) (b)	0.19 (0.04) (a)	42.91 (26.16) (a)

Table 3. Partial correlation analysis of runoff reduction with the topographic, biophysical and chemical properties of soil with and without trees, with their significance levels.
Tabla 3. Análisis de correlaciones parciales entre reducción del flujo de escorrentía y variables topográficas, biofísicas y químicas de los suelos con y sin árboles, con sus niveles de significancia.

	Riparian Slope	Water Table Depth	Sand	Organic Matter	Electrical Conductivity	Bulk Density	Soil Moisture	Aboveground Biomass	Litter Biomass	Root Biomass
Runoff volume reduction	-0.44	0.92	0.70	0.76	-0.65	-0.88	-0.74	0.39	0.61	0.48
P value	0.05*	0.04*	0.05*	0.14	0.34	0.04*	0.05*	0.16	0.38	0.52

Table 4. Partial correlation analysis for sediment retention among topographic, biophysical and chemical variables of soil with and without trees, with their significance levels.
Tabla 4. Análisis de correlaciones parciales entre retención de sedimentos y variables topográficas, biofísicas y químicas de los suelos con y sin árboles, con sus niveles de significancia.

	Riparian Slope	Water Table Depth	Sand	Bulk Density	Soil Moisture	Aboveground Biomass	Litter Biomass	Root Biomass
Sediment Retention	-0.88	0.44	0.79	0.78	-0.81	0.90	0.89	0.98
P value	0.02*	0.56	0.21	0.22	0.19	0.01*	0.03*	0.04*

of sediments, whereas the root biomass increases porosity, favouring infiltration and soil structure (Thorne, 1990). This in turn impacts on sediment deposition (Wilson et al., 2005). The riparian slope reduces the water flow rate (Naiman & Decamps, 1997), allowing sediment deposition.

Overall, the sediment retention value registered by the RVS was of 52.8%. An extensive literature review of work performed under different experimental conditions -mainly with different lengths of plots and water flows- registered values of 76% (Arora et al., 2010). The observed trend of increased retention of sediments in the grassy areas is consistent with that reported by Dillaha et al. (1989), where they found that the riparian strips of grassy vegetation can trap more than 50% of the sediment transported by runoff when the depth of the water flow is less than 5 cm. However, despite the higher values of sediments retention obtained in the treeless sites, in two sites ("La Pastora" and "San Felipe") the opposite occurred (i.e., greater sediment retention occurred at sites with trees). This behaviour is related to the higher values of aboveground biomass found in these sites.

Glyphosate retention. Glyphosate retention was significantly higher in the treeless environments (Fig. 3). In turn, analysis of partial correlations for environments with and without trees showed that glyphosate retention increased significantly with sediment retention and decreased with the riparian slope and litter biomass (Table 5).

The relationship between glyphosate retention and sediment retention is confirmed by studies showing glyphosate´s high affinity for clay particles (Syversen & Bechmann, 2004; Carriquiriborde, 2010; Aparicio et al., 2013). It should be noted that the sediment used in this assay had 37.7% clay.

Table 5. Partial correlation analysis for glyphosate retention among topographic, biophysical and chemical variables of soil with and without trees, with their significance levels.
Tabla 5. Análisis de correlaciones parciales entre retención de glifosato y variables topográficas, biofísicas y químicas de los suelos con y sin árboles, con sus niveles de significancia.

	Riparian Slope	Water Table Depth	Sand	Organic Matter	Electrical Conductivity	Bulk Density	Soil Moisture	Aboveground Biomass	Litter Biomass	Root Biomass
Glyphosate Retention	-0.84	0.13	0.51	0.36	-0.58	-0.55	-0.94	0.86	0.93	0.87
P value	0.05*	0.87	0.48	0.14	0,13	0.08	0.05*	0.14	0.05*	0.13

Glyphosate has a higher affinity to adsorb to clay particles than to be retained by litter biomass (Gevao & Jones, 2002). The high affinity of glyphosate to soil particles explains the non-influence of the other studied variables, which are mostly associated with infiltration (soil moisture, sand and bulk density). The glyphosate retention value obtained in the RVS was 58.7%. An extensive literature review of work performed under different experimental conditions, mainly with different lengths of plots and water flows, report values of 61% (Syversen, 2003) and 24-70% (Syversen & Bechmann, 2004).

CONCLUSIONS

The results represent the first descriptions of two contrasting environments, with and without trees, of RVS of the Pampa Austral and their relationship with physicochemical properties of the soil, topography and vegetation, relevant to the reduction of surface runoff, sediment and glyphosate retention. It was shown that glyphosate retention was higher in the riparian communities that are not invaded by tree species, while sediment retention was not associated with the presence or absence of trees. In this case, the reduced flow of runoff water was greater in riparian communities invaded by *S. fragilis*. It should be noted that none of the glyphosate retention mechanisms explored in this work (runoff reduction, sediment retention and biophysical properties of the soil) considers it possible to explain the influence of *S. fragilis*. Therefore, we consider it necessary to explore other alternative mechanisms that were not subject to this work, such as the effect of surface roughness of the ground on the reduction in runoff flow rate. We also consider the need for additional studies to quantify other possible mechanisms.

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