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Land-use and topography shape soil and groundwater salinity in central Argentina

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ABSTRACT

Being one of the oldest and most serious environmental problems, soil and groundwater salinization poses critical challenges for the managing of agricultural and natural areas. Together with climate, topography and land-use are main controls dictating salt accumulation patterns at different spatial scales. In this paper, we quantified the response of salt accumulation to the interactive effects of topography (lowland-upland gradients) and vegetation (annual crops, tree plantations, native grasslands) across a sub-humid sedimentary landscape with shallow groundwater in the Inland Pampas of Argentina. We measured salt stocks from the surface down to the water-table through soil coring and their horizontal distribution through electrical-resistivity imaging in eleven fields occupied by annual crops, eucalyptus plantations and grasslands, encompassing water-table depth gradients of 1–6 m below the surface. Land-use and topography exerted strong influences on salinity and explained together 82% and 66% of the spatial variability of groundwater salinity and soil salt accumulation (0–2 m of depth), respectively. As a single explanatory variable, land-use overwhelmed topography dictating salinity patterns. Tree plantations stored 7–8 times more salts than croplands and grasslands throughout the unsaturated soil profile in areas with shallow water-tables (<3.5-m depth). As groundwater became shallower, its salinity and that of the unsaturated soil above it increased, although the slope of this relationship was significantly higher in tree plantations. Soil salinity profiles and electrical-resistivity imaging showed maximum salinization around the water-table in tree plantations, indicating that groundwater absorption and solute exclusion by tree roots may be the dominant salinization mechanism. Our study highlights the strong influence of land-use on salinization patterns, which can be even stronger than the more widely recognized controls of climate and topography, and proposes some guidelines for a better use of vegetation to manage hydrology in salt-affected areas. A poor comprehension of this influence, as well as its underlying mechanisms, may lead to incorrect diagnosis of salinization and the implementation of ineffective management actions.

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1. Introduction

Soil and water salinization are some of the oldest and most serious environmental problems in the world, affecting more than 830 million hectares in more than 100 countries (Martinez-Beltran and Manzur, 2005). Globally, 10% of the land surface is salt-affected and ∼1.5 million hectares of productive lands are lost every year because of salinity problems (Ghassemi et al., 1995). Climate change may further increase the area at risk of salinization in some regions due to increased aridity (Schofield and Kirby, 2003). Salinization reduces agricultural outputs by billions of dollars each year, with remediation efforts being difficult and expensive. In addition, salinization may also damage rural infrastructure, water supplies and local economies. Because of all this, understanding what causes salinization is important for predicting salinity problems and managing them.

Among several influencing variables, climate and topography are the main factors controlling salinization at global and regional scales (Schofield and Kirby, 2003; Nosetto et al., 2008). Although salinization takes place in all climatic regions, it is more likely to occur in drier areas where potential evapotranspiration exceeds rainfall. Under these conditions, solutes entering the ecosystem via atmospheric deposition and rock weathering are less likely to be

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leached and tend to accumulate in soils and sediments. Topography influences salinization patterns directly through its effect on groundwater depth (Salama et al., 1999) and indirectly through the redistribution of water below- and above-ground across the landscape. As groundwater becomes shallower, capillary upflow, bringing groundwater and solutes toward the root zone and soil surface, increases, as does the risk of salinization (Shah et al., 2011). Although the topographic influence on salinity has long been recognized, its interaction with land-use on salt redistribution in the landscape has not been studied in as much detail.

Land-use change is one of the most important anthropogenic causes of salinization. Vegetation, through its different transpirative capacity and rooting depth, strongly affects the partition between transpiration, deep drainage and runoff. Consequently, land-use changes have the potential to disrupt the water balance of a given territory and trigger salinization, especially when herbaceous-woody transitions are involved (Jobbágy et al., 2008). Australia offers the most vivid example of the impact of land-use change on salinization. In the west and southeast of the continent, the replacement of vast areas of woodlands by herbaceous species decreased evapotranspiration and increased deep drainage, a flux that was very small under native vegetation (George et al., 1997). This process raised the water-table and moved deeply stored salts to the surface, degrading large areas of formerly productive lands (Pierce et al., 1993). Through a different mechanism, afforestation in native grasslands has been also linked to salinization in the plains of Argentina, the Carpathian basin and Western Siberia (Nosetto et al., 2007). In these areas, the establishment of tree plantations enhances groundwater discharge from shallow water-tables because of the higher transpirative capacity of trees compared to grasses. As result of groundwater consumption by trees, solutes excluded by roots accumulate in soils and aquifers to harmful levels (Jobbágy and Jackson, 2004).

In many plains with sub-humid climates, like the Pampas, the steppes of western Siberia, the Great Plains of western Canada or the Carpathian basin, salinization is a key issue, affecting the productivity and availability of agricultural lands (Szabolcs, 1989). In these landscapes, the natural liquid evacuation of water excesses is precluded by the lack of well-defined regional drainage networks and extremely low regional topographic gradients. Consequently, water excess leads to shallow water-table levels that favor local evapotranspirative discharge and salt accumulation in the lowest landscape positions. Drainage engineering operations are possible in these cases, but they are expensive and nearly always pose difficulties disposing of saline effluents. In this context, increased evaporation of water excesses is the most feasible, particularly biodrainage with plant species of high transpirative capacity to lower water-table levels (Stirzaker et al., 1999; Mahmood et al., 2001). The establishment of tree plantations with this objective has been successful in some places (Heuperman et al., 2002) and it is seen as a promising choice for the Pampas (Alconada Magliano et al., 2009). However, salt accumulation in the root zone and groundwater triggered by net groundwater consumption by the trees seems unavoidable (Stirzaker et al., 1999). Strong salinization with grassland afforestation has been documented in different shallow groundwater areas around the world (e.g. Khanzada et al., 1998; Jobbágy and Jackson, 2004; Nosetto et al., 2007). However, it is less clear how these processes may change across the typical topographic gradients and their associated shifts in water-table depths that characterize most of the eolian sedimentary landscapes of the Pampas.

The plains of central Argentina, known as the Pampas, host some of the most fertile and productive agricultural landscapes of the world. However, because of the flat topography and sub-humid climate, groundwater there is usually very shallow and can threaten rural economies through periodic flooding and salinization (Taboada et al., 2009; Viglizzo et al., 2009; Aragón et al., 2010). The region, historically dominated by native grasslands, was gradually transformed to a mixture of native grasslands, annual crops, and pastures beginning in the late 19th century (Hall et al., 1992). However, since the 1980s, and especially in the last decade, the remaining grasslands and pastures have been almost completely converted into croplands, with soybean being the most profitable and dominant crop today. Because of the lower evapotranspiration and shallower rooting systems of annual crops compared to pastures (e.g. Nosetto et al., 2012), this widespread land-use change has been linked to an increase of water-table levels, flooding events and salinization problems, as suggested by historical water-table records, land-use patterns and hydrological modeling (Contreras et al., 2008; Viglizzo et al., 2009). Such flooding events, which may involve up to 30% of the landscape (Aragón et al., 2010), have a strong impact on rural economies because they can deteriorate rural infrastructure, decrease available cropping area, and may trigger salinization processes of low reversibility (Taboada et al., 2009).

Geophysical surveying, and particularly the electrical resistivity method, is a fast and cost-effective way for deriving spatially distributed information on ground electrical conductivity (Robinson et al., 2008). Together with mineral composition, salt and water content influence the electrical conductivity of soils and sediments. However, below the water-table level, water content remains constant because all soil pores are filled with water and consequently, changes in ground electrical conductivity will be mainly dictated by salt contents. Therefore, the electrical resistivity approach has the potential to characterize the spatial and temporal variability of groundwater salinity. This technique has been extensively used for commercial water and mineral prospecting purposes. However, in spite of its clear potential, its use in ecohydrological studies is relatively new (Jackson et al., 2005; Jayawickreme et al., 2011).

In this paper we explored how land-use and topography interact to shape salinization patterns in the Inland Pampas of Argentina. Our specific aims were to quantify the response of soil and groundwater salinity to water-table depth gradients and to contrasting vegetation types associated with different land uses. In this context, we also evaluated the potential of two-dimensional electrical resistivity imaging to assess groundwater salinity and its correlation to topography and vegetation. The Inland sub-region of the Pampas, with well-developed local topographic gradients associated with past eolian activity, offers an excellent scope to explore the interaction of land-use and topography on salinization. We evaluated this interaction by assessing soil and groundwater salinities in eleven fields under different land-use covers, i.e. crops, eucalyptus plantations and grasslands, across a water-table depth range 1–6 m. We sampled soils and groundwater more intensively in two of the study fields, including soil/groundwater sampling pits at different topographic positions combined with electrical-resistivity imaging across topographic gradients and across a tree plantation-cropland edge.

2. Materials and methods

2.1. Study region

We performed our study at "El Consuelo" farm (9300 ha; latitude −34°12′, longitude −64°18′), close to the town of Vicuña Mackenna (Córdoba province, Argentina). The region is typical of the eolian sedimentary landscapes of the Inland Pampa and was originally occupied by native grasslands (Soriano et al., 1991). Currently, most of the study area is devoted to the rainfed production of soybean (*Glycine max* L.), wheat (*Triticum aestivum* L.), maize (*Zea mays* L.) and sunflower (*Helianthus annus* L.). Between 2006 and 2010, average yields of soybean and maize, the two dominant crops, were 2.3 and 6 Mg ha^{-1}, respectively (MAGPyA, http://www.minagri.gob.ar). Remnant patches of native grasslands are very scarce and they are mostly devoted to cattle grazing. Eucalyptus plantations are currently a relatively minor vegetation cover, but patches <20 Ha in size can be found across the region today. Large-scale afforestation is increasing rapidly in some areas of the Pampas and is expected to continue its expansion in the coming decades (Wright et al., 2000).

The climate of the study region is sub-humid temperate, with a mean annual temperature of 16.5 °C. Mean temperatures for the coldest (July) and warmest (January) months are 9.7 and 24 °C, respectively. Average wind speed approaches 15 km h^{-1} and presents a constant hazard of soil erosion (Hall et al., 1992). Rainfall averages 740 mm year^{-1} for the last century (1910–2007) and 850 mm year^{-1} for the last 20 years (1991–2010) and is concentrated in summer and autumn (67%). Mean annual FAO reference evapotranspiration approaches 1200 mm year^{-1} (1960–1990, CRU database, New et al., 2002). Predominant soils of the study area are Entic Haplustolls that do not present any significant restriction to crop growth. They have a sandy texture and are well drained and deep (>150 cm). Sand content usually exceeds 70% and the soil organic matter in the top horizon is <1.5% (INTA-SAGyP, 1990).

The regional drainage network is poor because of a very flat landscape with a slight topographic gradient (slope <0.05%) that develops along ~500 km in the W–E direction (Degioanni et al., 2002; Jobbágy et al., 2008). This flat topography constrains surface drainage and together with a sub-humid climate determines the presence of shallow water-tables across most of the landscape. However, at local scales of <500 m distance, the water-table depth is dictated by topographic gradients associated with the dune landforms and it can vary from 0 to 7 m.

At the local level, groundwater fluxes and surface runoff from high to local closed depressions without drainage outlet, hereafter bottomlands, promote the presence of shallow water-tables (<2 m) and in some cases the formation of surface water. These depressions usually operate as solute sinks and as evaporative discharge areas (Cisneros et al., 1997; Degioanni et al., 2002). Soils typically do not show salinity problems except in some bottomlands, where very shallow water-tables (<1 m) promote groundwater discharge through direct soil evaporation, which drives increased salt concentration (Taboada et al., 2009). If wet periods extend for several years, the water-covered area expands at the expense of land suitable for cropping, as does the salinity-affected area (Lavado and Taboada, 1988; Hall et al., 1992). The establishment of tree plantations in those areas with shallow water-tables (2–3 m of depth) has also proved to lead to salinization because of net groundwater discharge and solute exclusion by tree roots (Jobbágy and Jackson, 2004).

2.2. Sampling fields

The interaction between land-use and topography shaping salinization patterns was explored at 11 fields of the 9300-ha "El Consuelo" farm occupied by crops (5 fields) and eucalyptus plantations (5 fields). Some of these fields were more intensively sampled with 3 to 6 sampling positions along topographic gradients, while other fields were sampled more modestly in 1 or 2 positions (Table 1). In addition, and as a baseline reference, we sampled soil and groundwater in four topographic positions in a native grassland field. Soil and groundwater sampling was performed between August 2008 and October 2011.

Cropland fields were between 100 ha and 400 ha in size and, at the time of sampling, had soybean (4 sampling positions) or maize (7 sampling positions) crops or were fallow with no vegetation cover (8 sampling positions). A typical crop rotation in the region encompasses a 3-year-long cycle including a sequence of wheat/soybean (late sowing) double-crop in year one, maize in year two, and then soybean in the final year (early sowing). This crop rotation has been applied over the 10 year period preceding sampling. No-tillage management is widespread in the region and was applied to all the cropland fields where our study was performed. Weeds were controlled with herbicides, particularly glyphosate. Selected fields showed well-developed topographic gradients and did not include extremely high dune crests. Eucalypt plantations (*E. camaldulensis*) were established between 1970 and 1972 and were 36–40 years of age at the time of our measurements. Plantations size varied between 1 ha and 25 ha. The trees had never been harvested, fertilized, or irrigated, and current tree density approached ~450 trees ha^{-1} and tree height ~30 m. No understory was present. The grassland field was 5 ha in size and it had a typical botanical composition of the grasslands of the area, with *Paspalum* sp., *Bromus* sp. and *Stipa* sp. as the dominant species (Soriano et al., 1991).

2.3. Soil and groundwater sampling

Soil samples for electrical conductivity analysis were collected by cores every 0.50 m of depth and extended down up to the water-table level. Water-table depth was manually measured at each sampling position after at least 2 h of borehole construction to allow the equilibration of the water-table level. Water-table depth at sampling positions varied between 1 and 4.8 m in croplands fields, between 2.2 and 5.6 in eucalypts fields and between 2.7 and 5.5 m in the grassland field. Sampling points were located >40 m from fences to avoid edge effects. In tree plantations, sampling points were >1 m from tree stems. Soil samples were taken with a hand-auger (10-cm outside diameter). Full samples from each half meter depth interval were immediately mixed, sub-sampled and stored in plastic bags. Soil samples were oven-dried for 72 h (45 °C) and sieved (1 mm). Soil electrical conductivity was determined in a 1:2 soil–water extract shaken for ~12 h. Measurements were made in a 50 ml beaker with a conductivity meter automatically corrected for temperature (Orion model 115). In order to estimate the amount of salt accumulated in soil and sediments, we calculated the total dissolved solids (TDS) from electrical conductivity measurements according to Bresler et al. (1982). Accumulated salts per square meter was estimated based on previously established bulk density estimations (Nosetto et al., 2009).

Groundwater samples were manually collected at each sampling position from observation wells, which penetrated into the saturated zone ~0.4 m. In the laboratory, groundwater samples were syringe-filtered (0.45 μm) and kept at 4–6 °C until analysis. Along with the soil extracts, electrical conductivity of groundwater samples was determined with a conductivity meter automatically corrected for temperature (Orion model 115).

We evaluated the land-use and topographic effects on salinization using general linear models. We also performed linear regressions between water-table depth (explanatory variable) and groundwater electrical conductivity and salts stored in the first 2 m of the soil profile (dependent variables) for the different vegetation covers. Although water-table depth may have implicitly captured vegetation effects (e.g. Heuperman, 1999; Jobbágy and Jackson, 2004), they should be minimal on our sites given the high hydraulic conductivity of their sandy sediments (>80%), which would favor a rapid equilibrium of any hydraulic gradients developed between forested and agricultural sites (Jobbágy and Jackson, 2004). This assumption is supported by observations of absolute water-table levels at two pairs of sites showing no water-table depression under the plantation.

Additionally, we grouped sampling points in low and high topographic positions and analyzed the groundwater salinity and total salt stored in the whole soil profile, from surface to water-table,

Table 1
Description of study fields and sampling positions.

Field	Sampling position	Vegetation cover	Vegetation stage	Landscape position	Water-table depth (m)
1	1	Tree plantation	n.a.	Mid-slope	3.7
	2	Tree plantation	n.a.	Hill top	5.5
	3	Tree plantation	n.a.	Mid-slope	3.2
2	1	Tree plantation	n.a.	Hill top	5.3
	2	Tree plantation	n.a.	Bottomland	2.2
	3	Tree plantation	n.a.	Footslope	2.8
3	1	Tree plantation	n.a.	Mid-slope	4.4
4	1	Tree plantation	n.a.	Hill top	5.5
	2	Tree plantation	n.a.	Mid-slope	3.5
	3	Tree plantation	n.a.	Mid-slope	3.8
	4	Tree plantation	n.a.	Mid-slope	3.5
	5	Tree plantation	n.a.	Mid-slope	3.1
	6	Tree plantation	n.a.	Mid-slope	2.9
5	1	Tree plantation	n.a.	Mid-slope	3.5
	2	Tree plantation	n.a.	Bottomland	2.3
	3	Tree plantation	n.a.	Hill top	5.6
	4	Tree plantation	n.a.	Mid-slope	3.2
	5	Tree plantation	n.a.	Mid-slope	2.8
6	1	Cropland	Fallow	Footslope	2.8
	2	Cropland	Fallow	Bottomland	2.3
	3	Cropland	Fallow	Mid-slope	3.4
	4	Cropland	Fallow	Mid-slope	3.8
	5	Cropland	Fallow	Hill top	4.8
	6	Cropland	Fallow	Hill top	4.8
7	1	Cropland	Soybean reproductive	Bottomland	1.7
	2	Cropland	Soybean reproductive	Mid-slope	2.5
	3	Cropland	Soybean reproductive	Hill top	3.7
	4	Cropland	Soybean reproductive	Mid-slope	3.6
	5	Cropland	Maize early vegetative	Mid-slope	4.1
	6	Cropland	Maize early vegetative	Mid-slope	4.0
8	1	Cropland	Maize early vegetative	Bottomland	1.5
	2	Cropland	Maize early vegetative	Mid-slope	2.6
	3	Cropland	Maize early vegetative	Hill top	3.8
9	1	Cropland	Maize reproductive	Mid-slope	2.9
	2	Cropland	Maize reproductive	Bottomland	1.7
10	1	Cropland	Fallow	Mid-slope	3.5
	2	Cropland	Fallow	Bottomland	1.0
11	1	Grassland	n.a.	Mid-slope	3.1
	2	Grassland	n.a.	Mid-slope	4.3
	3	Grassland	n.a.	Hill top	5.6
	4	Grassland	n.a.	Footslope	2.7

through two-way ANOVA with topographic position and land-use as main effects.

2.4. Geoelectrical surveying

To obtain a better spatial description of groundwater salinity and the influence of land-use and topography on it, we performed electrical-resistivity imaging (ERI) in two fields occupied by crops and eucalyptus plantation. We carried out seven ERI measurements that extended along a 108-m-long transect. Along each transect, ground level variation was registered with a hose level every 15 m. Three or four boreholes were made at each transect to measure water-table depth, to sample soil and groundwater, and to measure soil temperature to correct conductivity measurements for temperature effects. We extrapolated water-table depth for the whole transect based on the relationship between water-table depth and surface elevation.

Two resistivity datasets were collected in February and November 2009 along a transect with a 1.3 m topographic gradient (hill top–bottomland) in a cropland field where water-table depth ranged from 1.5 to 4 m. Another two transects, surveyed on the same dates, were located in a eucalyptus plantation; one transect spanned a topographic gradient of 1.6 m (hill top–mid-slope) while the other was located in a flat footslope area. In the first of the previous eucalypts transects, water-table level varied between 4.1 and 5.6 m of depth; in the second one, water-table level was shallower and varied between 2.7 and 3.3 m of depth. In order to evaluate the effect of land-use on groundwater salinity, we located a resistivity transect in a flat mid-slope area (topographic gradient = 0.4 m) across a cropland-plantation edge, where water-table depth varied between 3 and 4 m. Three electrical-resistivity measurements were carried out on this transect in February 2009, November 2009 and February 2010. The samplings performed in February 2009 and February 2010 were preceded by humid conditions, with 181 and 260 mm of rainfall accumulated in the previous eight weeks in each of these years, respectively. The sampling of November 2009 was performed under much drier conditions, with 15 mm of rainfall accumulated in the previous eight weeks.

Resistivity imaging was performed with a multielectrode resistivity unit (Syscal Junior, Iris Instruments). Electrodes were installed in a straight line with 1.5-m separation distances between them, allowing an imaging depth of 12–15 m. Standard electrode-pairing methods (Wenner, Dipole-Dipole; Loke, 2000) were used to capture the optimal two-dimensional distribution of

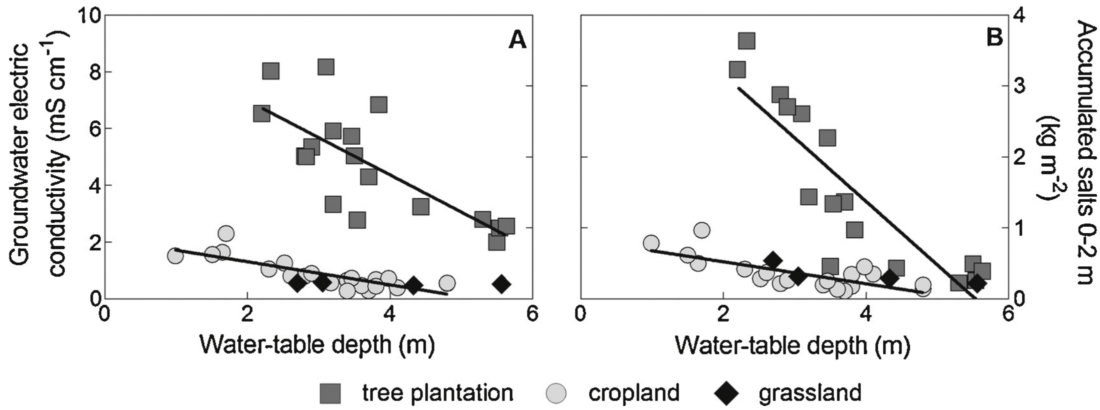

Fig. 1. Relationships between water-table depth (m) and groundwater electrical conductivity (mS cm^{-2}) (A) and accumulated salts in the first 2 m of the soil profile (kg m^{-2}) (B) in tree plantations, croplands and grasslands. Significant linear relationships were adjusted in tree plantations (r^2 = 0.57 and r^2 = 0.76 in panels A and B, respectively, p < 0.01) and croplands (r^2 = 0.67 and r^2 = 0.55 in panels A and B, respectively, p < 0.01) but not in grasslands (p > 0.1).

ground conductivity. The field data collected were inverted with commercially available RES2DINV software, which also allows for integration of topographic information in the inversion (Loke, 2009) to obtain estimates of bulk ground electrical conductivity distribution along each transect.

3. Results

Land-use and topography exerted strong influences on soil and groundwater salinities (Fig. 1). In combination, both effects explained 82 and 66% of the spatial variability of groundwater salinity and soil salt accumulation (0–2 m of depth), respectively. As a single explanatory variable, land-use had a stronger influence than topography on salinity patterns, explaining 70 and 38% of the aforementioned variables. Water-table depth, dictated by topographic gradients, was a poor explanatory variable when all land-use types were pooled together, but its influence was clear when land-use types were analyzed separately (Fig. 1). As groundwater became shallower, its salinity and that of the unsaturated soil above it increased, although the slopes of these relationships were significantly higher in tree plantations (p < 0.01, n = 39, Fig. 1). For every meter increase in water-table level, the groundwater conductivity and the accumulation of salts in the first 2 m of the soil profile of tree plantations increased 1300 uS cm^{-1} and 900 gr m^{-2}, respectively (p < 0.01). In contrast, these rates of change in croplands were significantly lower and approached 400 uS cm^{-1} and 140 g m^{-2} for groundwater and soil, respectively (p < 0.01). As groundwater became deeper, differences in the amount of salts stored in the first 2 m of the soil profile between croplands and plantations decreased, tending to disappear where groundwater was >5 m deep (Fig. 1B). The single grassland field that we sampled showed low groundwater and soil salinities and no significant relationship with the water-table level (p > 0.10, n = 4), matching the conditions observed under croplands (Fig. 1).

In low topographic positions, with water-tables <3.5-m depth, tree plantations stored 8 times more salts than croplands throughout the unsaturated soil profile (from surface to the water-table level), and the groundwater was 5 times saltier (p < 0.05, Fig. 2). In high topographic positions, with water-tables >3.5-m depth, the accumulation of salts in eucalypts soils was smaller, yet still 4 times higher than in croplands. Groundwater salinity was 7 times higher in eucalypts than in croplands at fields with water-tables between 3.5 and 5.5 m of depth, suggesting significant groundwater consumption by trees at these high topographic positions. The soil and groundwater of the grassland field showed salinity levels that were similar to those of croplands (Fig. 2, p > 0.1).

Soil profiles of eucalypts in low topographic positions showed increasing salinity with depth, with maximum values observed around the water-table level (Fig. 3), what suggests that groundwater absorption and solutes exclusion by tree roots is the dominant salinization mechanism (Jobbágy and Jackson, 2007). The position of maximum salinities in the soil profile was closely associated with the water-table depth in both tree plantations (r^2 = 0.78, p < 0.01) and crops (r^2 = 0.91, p < 0.01). However, whereas in plantations salinity peaks were found 1 m above the water-table level, in croplands maximum salinities were observed just 30 cm above it. Between 2 and 2.5 m of depth, soil electrical conductivity of lowlands eucalypts was one order of magnitude higher than in croplands (Fig. 3). Soil electrical conductivity was low (<200 uS cm^{-1}) throughout the whole profile in croplands and in the grassland field (data not shown), in both lowland and highland positions. In high topographic positions, eucalypt soils showed lower electrical conductivity than in lowlands, but tripled the conductivity of croplands between 2 and 5 m of depth (291 and 100 uS cm^{-1} for eucalypts and croplands, respectively, Fig. 3). In the top soil (0–50 cm), tree plantations stored 50 g more salts per m^2 than croplands (137 vs. 86 g m^{-2}, p < 0.01, n = 35).

The electrical-resistivity imaging (ERI) showed a close match with direct measurements of the electrical conductivity of

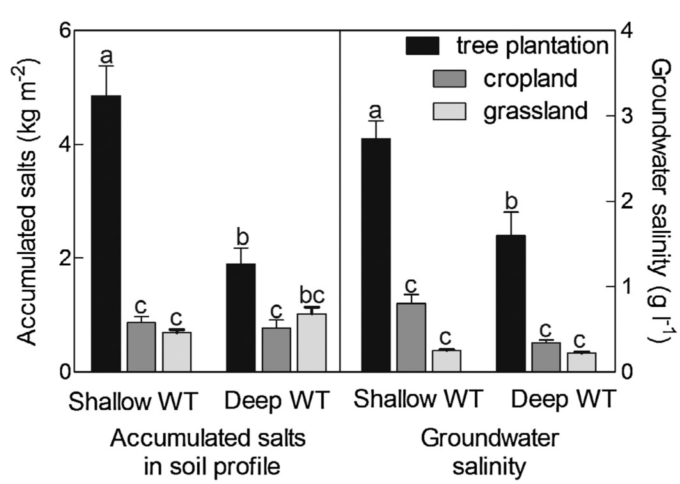

Fig. 2. Storage of salts in soils and groundwater in tree plantations, croplands and grasslands. The amounts of salts accumulated in the soil profile (kg m^{-2}) from the surface down to the water-table and groundwater salinity (g l^{-1}) in tree plantations, crops and grasslands in areas with shallow (<3.5 m) and deep water-table levels (>3.5 m) are presented. Electrical conductivity measurements were transformed to total dissolved solids according to Bresler et al. (1982).

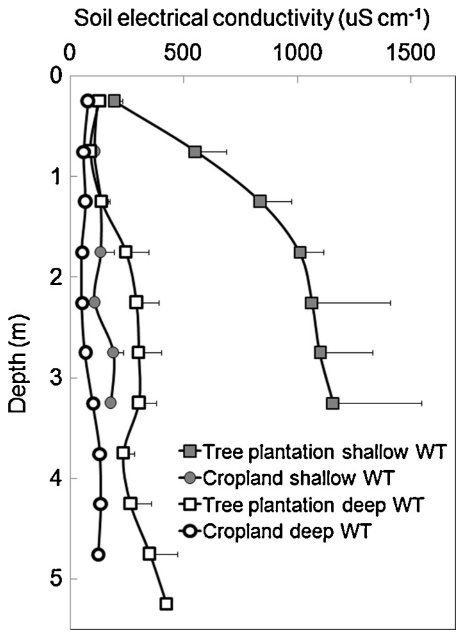

Fig. 3. Vertical profiles of soil salinity in tree plantations and croplands. Soil electrical conductivity profiles (uS cm^{-1}) in tree plantations and cropland in areas with shallow (<3.5 m) and deep water-table levels (>3.5 m) are shown. Mean values + S.E. are shown.

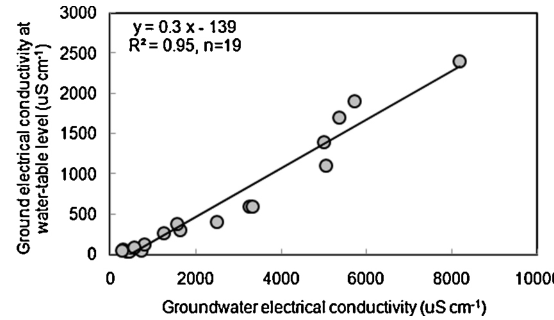

Fig. 4. Relationship between groundwater electrical conductivity (uS cm^{-1}) and ground electrical conductivity (uS cm^{-1}) at the water-table level. The electrical conductivity of groundwater samples was determined with a conductivity meter automatically corrected for temperature (Orion model 115). Ground electrical conductivity was determined with a multielectrode resistivity unit (Syscal Junior, Iris Instruments) after numerical inversion with RES2DINV software. Points correspond to tree plantations (n = 8) and croplands (n = 11) positions.

groundwater at the water-table level (Fig. 4), highlighting the usefulness of this tool to assess salinity in the saturated zone. Ground electrical conductivity (G-EC) estimated with the ERI technique for the top 50 cm of the saturated zone was linearly correlated with the electrical conductivity of groundwater samples taken at the water-table level (GW-EC) (r^2 = 0.95, p < 0.01, n = 19). As expected, given that the ERI technique is sampling a ground volume that is not fully occupied by groundwater but by solids as well (66% of solids according to sand/clay/silt composition, Saxton et al., 1986) which are substantially less conductive, the ground electrical conductivities values derived from ERI were on average 80% lower than the ones directly measured in the groundwater samples. Based on this tight relationship we were able to estimate GW-EC based on our G-EC measurements (Fig. 4).

The two two-dimensional electrical-resistivity transects in the cropland field collected in February (Fig. 5A) and November 2009 (Fig. 5B) along a topographic gradient showed increasing salinity at the water-table level toward the lowland, reaching maximum values at the footslope and recovering slightly in the bottomland. Both seasonal transects showed similar patterns, with hill top areas (water-table at 4 m of depth) showing GW-EC < 625 uS cm^{-1}. In the footslope (water-table at 1.8–2 m of depth), GW-EC in the water-table zone increased to ~2115 uS cm^{-1}. At this position maximum GW-EC values were observed at greater depth into the saturated zone, approximately 1 m below the water-table, where they approached ~2780 uS cm^{-1}. In the bottomland (water-table at 1.5 m of depth), GW-EC declined to ~1700 uS cm^{-1} and ~1450 uS cm^{-1} in February (Fig. 5A) and November (Fig. 5B), respectively.

The electrical-resistivity transects performed in the eucalyptus plantation evidenced the influence of topography on the intensity of soil and groundwater salinization. Resistivity imaging in a highland (hill top–mid-slope) area with eucalyptus (water-table at 5.6 m of depth) showed GW-EC values approaching ~800 uS cm^{-1} that increases to ~2100 uS cm^{-1} where the water-table was at 4.4 m (Fig. 6A). In this transect, a salt bulge was present 5 m

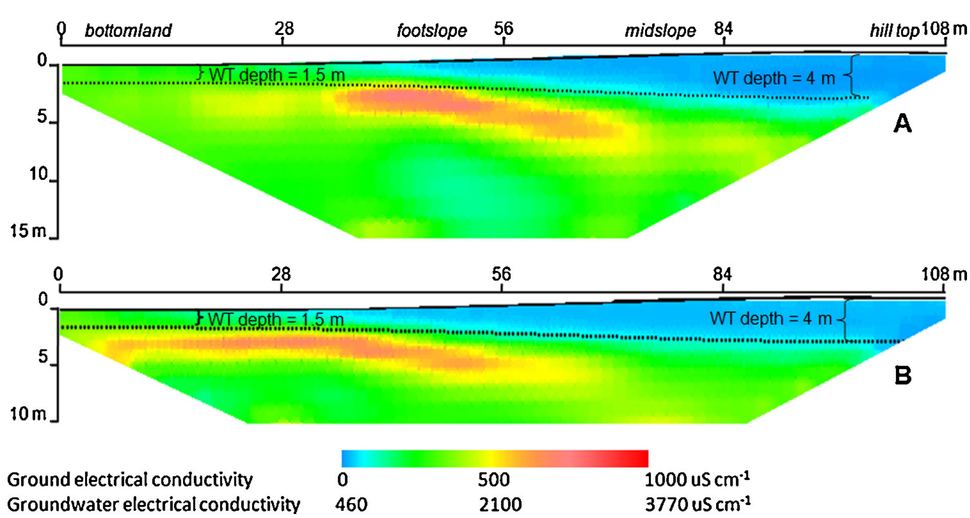

Fig. 5. Two-dimensional ground electrical conductivity transect along a topographic gradient in a cropland site. Transects were performed in February 2009 (A) and November 2009 (B) when the plot was occupied by active soybean and corn crops. Water-table depth varied between 4 and 1.5 m along the transect. Ground conductivity was determined with a multielectrode resistivity unit (Syscal Junior, Iris Instruments) after numerical inversion with RES2DINV software. The water-table level along the transect is indicated with a dotted line. A color scale of groundwater electrical conductivity estimated with the relationship of Fig. 4 is presented at the bottom. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

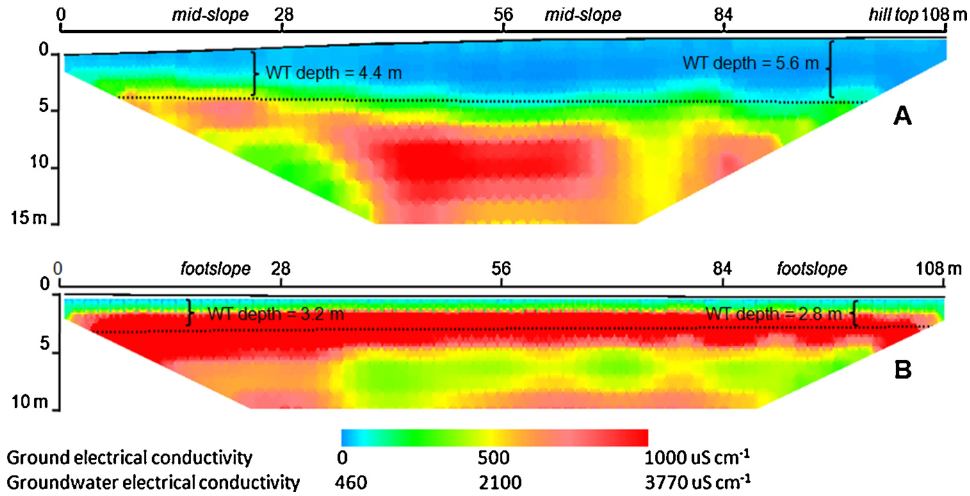

Fig. 6. Two-dimensional ground electrical conductivity transect in a tree plantation site. Transects were performed in February 2009 (A) and November 2009 (B). Water-table depth varied between 5.6 and 4.4 in (A) and between 3.2 and 2.8 in (B). Ground conductivity was determined with a multielectrode resistivity unit (Syscal Junior, Iris Instruments) after numerical inversion with RES2DINV software. The water-table level along the transect is indicated with a dotted line. A color scale of groundwater electrical conductivity estimated with the relationship of Fig. 4 is presented at the bottom. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

below the water-table level (10 m below the soil surface), where GW-EC increased to ~3800 uS cm^{-1}. High GW-EC values, between ~7100 and 10.400 uS cm^{-1}, were observed in another electrical-resistivity transect in a footslope area occupied by eucalyptus and with the water-table at 2.8–3.2 m (Fig. 6B). These high conductivity values were only registered in a well-defined depth range of 1 m centered at the water-table level, likely resulting from the water uptake and solute exclusion process by tree roots. Below this depth range, a zone of lower conductivity was detected, with values approaching ~1600 uS cm^{-1} and extending 5 m below the water-table. Below this fresh zone, GW-EC increased again, as in the previous transect, up to values of ~3100 uS cm^{-1} (Fig. 6B).

The electrical-resistivity transects across the cropland-eucalypt edge highlighted the strong effect of land-use on groundwater salinity (Fig. 7). The presence of fresh groundwater is evident across the cropland zone (50 m, three transects), with GW-EC values at the water-table level <950 uS cm^{-1} (Fig. 7). Toward the plantation core, just beyond the crop-eucalypt edge, GW-EC increased steeply, reaching a maximum value of ~7100 uS cm^{-1} 40 m away from the border (Fig. 7). In the plantation, and below the high salinity zone that was vertically centered at the water-table level, a relatively fresh zone extended down between 9 and 12 m of depth (Fig. 7A) with GW-EC <1780 uS cm^{-1}. Below this fresh zone, GW-EC increased up to 4100 uS cm^{-1} (Fig. 7A).

The vertical and horizontal arrangement of groundwater salinity along the crop-eucalypt transect varied through time, with the most noticeable shift taking place between 8 and 10 m of depth in the plantation (Fig. 7). There, a fresh zone (GW-EC <1780 uS cm^{-1}) that was clearly captured in February 2009 (Fig. 7A), tended to disappear and become saltier (GW-EC >3500 uS cm^{-1}) nine months later in November 2009 (Fig. 7B) under much drier conditions. Eight week accumulated rainfall was 181 and 15 mm before the samplings of February and November 2009, respectively; and as a result, water tables were 0.4 m deeper on average in the second date. In February 2010 sampling was performed under more humid conditions (260 mm of rainfall accumulated in the previous eight weeks and water-table level 0.7 m shallower than in November 2009), yet the 8–10 m-depth zone in the plantation did not show any clear sign of salinization decline.

4. Discussion

Historically, climate and topography have been seen as the most important parameters controlling salinization at the global scale (Schofield and Kirby, 2003). In this paper, we showed that land-use is also a main driver of salinization locally that may override topographic control and, as demonstrated in an earlier study, climatic influences (Nosetto et al., 2008). This key role of vegetation on salinization arises essentially from the contrasting capacities of the different vegetation covers to transpire water. Tree plantations for instance, are able to transpire up 70% more than croplands and native grasslands of the study region because of their higher aerodynamic conductance and deeper roots, among other features (Kelliher et al., 1993; Canadell et al., 1996; Nosetto et al., 2012). If this high water demand of trees is supplied by shallow ground waters, a salinization process will occur, which would not be expected in a salinization framework based only on climatic and topographic influences (Schofield and Kirby, 2003). Tolerance to salinity adds a new and less explored axis to vegetation controls on salinization, with more salt-tolerant plant species likely leading to stronger salinization (Nosetto et al., 2008).

Afforestation has been linked to salinization in several native grassland areas worldwide, where enhanced groundwater consumption (and salt accumulation) by trees is subsidized by lateral groundwater fluxes from the surrounding native grassland matrix (Heuperman, 1999; Jobbágy and Jackson, 2004). We found that soil and groundwater salinization also proceeds when afforestation takes place in a cropland matrix like the Inland Pampas of Argentina, indicating that native grasslands and croplands may share a similar hydrological behavior. Analogous salinization patterns (Figs. 1 and 2) and evapotranspiration estimates (Nosetto et al., 2012) between both covers support this notion. Similarly to what occurs in native grasslands throughout the Pampas, under croplands the water balance is positive (Nosetto et al., 2012) and consequently the surplus rainfall recharges groundwater and keeps soil profiles with low salinity levels (Figs. 3 and 8). By contrast, tree plantations experience a negative water balance which is compensated by shallow groundwater consumption, driving salt accumulation in the ecosystem (Fig. 8). In the long term, the sustained groundwater use by tree plantations could be only maintained by surplus water supplied from the cropland matrix (Fig. 8). This is basically the functioning of biodrainage systems where tree

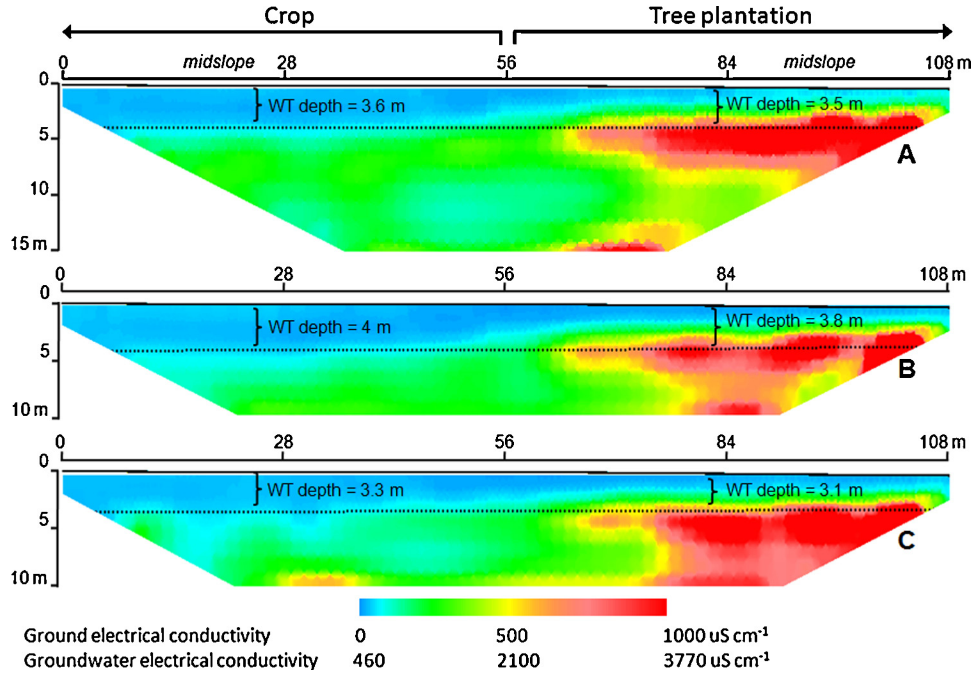

Fig. 7. Two-dimensional ground electrical conductivity transect across a cropland-tree plantation edge in multiple dates. Transects were performed in February 2009 (A), November 2009 (B) and February 2010 (C), when the cropland plot was occupied by active soybean (A) and corn (B and C) crops. Ground conductivity was determined with a multielectrode resistivity unit (Syscal Junior, Iris Instruments) after numerical inversion with RES2DINV software. The water-table level along the transect is indicated with a dotted line. A color scale of groundwater electrical conductivity estimated with the relationship of Fig. 4 is presented at the bottom. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

plantations are spread in the landscape in such a way to maximize the capturing of water excesses from the surrounding herbaceous matrix (Heuperman et al., 2002). However, the intensity and the velocity of the salinization process after afforestation could be reduce by establishing plantations with lower water demand and less negative water balance (Nosetto et al., 2008). For instance, selection of deciduous tree species with high salinity tolerance (e.g. *Quercus* sp.), low planting density, and silvopastoral schemes are all practices that would help to achieve that goal.

Through its influence on water-table depth, topography exerted strong control over the intensity of salinization (and groundwater consumption) triggered by afforestation. Although salinization was stronger with shallow water-table levels, we found that afforestation increased soil and groundwater salinities across the full range of water-table depth explored (2–5.5 m) (Figs. 1A and 8). Even to the maximum depth we sampled (5.5 m), tree plantations quadrupled groundwater salinity of croplands, suggesting significant groundwater consumption by plantations with those water-table depths. However, afforestation-induced salinization did not affect upper soil layers (0–2 m) when the water-table was deep (Figs. 1B and 8), in agreement with salinization patterns observed under oak plantations with groundwater at 5 m of depth (Nosetto et al., 2007). These results give support to “walking plantations” schemes, where plantations, after harvesting, are replaced by shallow-rooted crops or pastures and a new plantation is established on an adjacent site (Heuperman, 1999). Given that salinization takes place deep in the soil profile, the new crop/pasture will find a suitable rooting zone environment.

Afforestation is considered as a valuable biodrainage alternative to evacuate water excesses from the landscape; however the

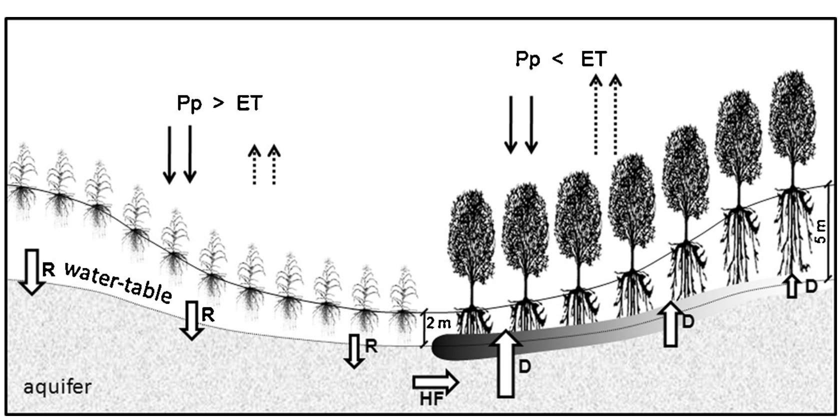

Fig. 8. Diagrammatic representation of main water fluxes and salinization patterns across a toposequence in tree plantations and croplands. In croplands, the water balance is positive (Pp > ET), leading to recharge fluxes (R) that keep soils with low salinity. In tree plantations the water balance is negative (Pp < ET), generating a water deficit that is compensated by groundwater uptake (discharge, D). Groundwater uptake and salt exclusion by tree roots lead to ecosystem salinization (gray shaded zone) which intensifies in areas with shallow water-table. The sustained groundwater use by tree plantations is maintained by horizontal water flow (HF) from the cropland matrix.

accumulation of salts that may accompany this practice threatens its long-term sustainability. Considering that in most of the Pampas there are minimal possibilities for water (and salts) evacuation into rivers or channels because of the very low topographic and piezometric regional gradients and the closed nature of most basins, salinization after afforestation seems inevitable. Our findings provide some guidelines to plan the location of plantations in biodrained landscapes in order to minimize salinization risk and increase the success of the practice. Afforestation in bottomlands and footslopes should be avoided because salinization will proceed at faster rates and to higher levels (Fig. 8) because of the high groundwater uptake by trees. It is interesting to highlight that the transpiration of *Eucalyptus camaldulensis* trees is significantly reduced when they are exposed to surface irrigation or groundwater exceeding 5 dS m^{-2} (Sweeney and Stevens, 1997; Oster et al., 1999), values that were only observed where water-tables were <4-m depth (Fig. 1). In addition, there are fewer possibilities for salt removal from the root zone at these low topographic positions and the risks of waterlogging are higher. By contrast, mid-slope and hill top positions would be more appropriate for tree planting since salinization is weaker and takes place at greater depth in the soil profile (Figs. 1 and 3).

A decrease in groundwater salinity was observed in the bottomland of crops with the shallowest water-tables, compared to footslopes where maximum salinity was observed (Fig. 5), suggesting some additional influence of topography on salinity patterns, beyond the effect on water-table levels. This salinity decrease in the bottomland could be expected if anoxic conditions, driven by the shallow water-table, hinder groundwater consumption (and salt accumulation) by crops (Ayars et al., 2006) and/or if runoff water from higher topographic positions enhances groundwater recharge in those low areas. The water-table depths observed in the bottomlands (~1.5 m) would not be shallow enough to negatively affect crop behavior, and in fact, they would be optimum for groundwater consumption by crops (Kahlown et al., 2005; Nosetto et al., 2009). On the other hand, we observed that the absolute elevation of the water-table was significantly higher (~1 m) in the bottomland compared to the highland (data not shown), suggesting that bottomlands are catching runoff water that enhances recharge and raise water-table. This extra input of water in the bottomlands would decrease groundwater consumption by crops and at the same time increase the possibilities for salt leaching from the surface soils.

Our intensive soil and groundwater sampling and geoelectrical measurements provided insights into the mechanism of salinization triggered by tree plantations. Groundwater uptake by tree roots plus solute exclusion and altered groundwater flow within the aquifer produced by the enhanced discharge have been suggested as drivers for this process (Sapanov, 2000; Jobbágy and Jackson, 2007). Solutes excluded by root membranes will tend to accumulate where groundwater encounters roots, typically the upper portion of the aquifer and/or capillary fringe (Jarrel and Virginia, 1990; Heuperman, 1999). We observed a well-defined zone of salinization (1 m-thick) centered on the water-table level and a fresh zone underneath (Figs. 6 and 7), suggesting that groundwater uptake and solute exclusion is a dominant salinization mechanism at our studied sites. In addition, another salty zone was also evidenced at 10–12 m of depth, below the fresh zone, in the tree plantation but not in the cropland, suggesting some perturbation of deeper groundwater fluxes. The enhanced groundwater discharge triggered by the tree plantation may have promoted the intrusion of deeper ground waters with a different chemical composition (e.g. saltier) than the one existing in the upper levels of the aquifer (Jobbágy and Jackson, 2007). Although our results point to solute exclusion as the main salinization driver, the intrusion of saltier ground waters deserves further attention because it can drive salinization on its own (Sapanov, 2000).

Geophysical surveying has been largely used for commercial exploration of mineral and water resources (Robinson et al., 2008). More recently, its use has expanded to agronomic studies where different geophysical surveying methods are used for mapping physical and chemical soil properties (e.g. Fulton et al., 2011; Saey et al., 2011). Despite being fast and relatively inexpensive methods, their application in ecohydrological studies is novel (Jayawickreme et al., 2011). In this work, we identified a strong relationship between ground electrical conductivity at the water-table level estimated from resistivity imaging and the electrical conductivity directly measured in groundwater samples (Fig. 4). This approach allowed us to have a better description of salinization patterns and to gain deeper insight into the underlying mechanisms. Our results here and others recently published (Nosetto et al., 2008; Jayawickreme et al., 2011) highlight the value of geoelectric tools for the description of salinization patterns and the understanding of ecohyrological processes, which may certainly help in a better design of restoration practices of salt-affected areas.

Our study reaffirms the strong influence of land-use on salinization patterns, which can be even stronger than the more widely recognized controls of climate and topography. For instance, the establishment of forests in an area where they were historically absent triggered a salinization process that would not be expected given the existing conditions of climate, topography and vegetation. The intensity of this salinization is highly dependent on topography, with stronger salinization taking place where water-tables are shallower. This strong land-use influence is largely dictated by the different water use patterns of vegetation types. Ignoring this strong influence, as well as its underlying mechanisms, may lead to incorrect prognosis of salinization risks and implementation of ineffective remedial measures where solutions are being sought.

Acknowledgements

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References

Alconada Magliano, M.M., Bussoni, A., Rosa, R., Carrillo Rivera, J.J., 2009. El biodrenaje para el control del exceso hídrico en Pampa Arenosa, Buenos Aires, Argentina. Investigaciones Geográficas, Boletín del Instituto de Geografía, UNAM 68, 50–72.

Aragón, R.M., Jobbágy, E.G., Viglizzo, E.F., 2010. Surface and groundwater dynamics in the sedimentary plains of the Western Pampas (Argentina). Ecohydrology 4, 433–447.

Ayars, J.E., Christen, E.W., Soppe, R.W., Meyer, W.S., 2006. The resource potential of in-situ shallow ground water use in irrigated agriculture: a review. Irrigation Science 24, 147–160.

Bresler, E., McNeal, B.L., Carter, D.L., 1982. Saline and Sodic Soils. Principles-Dynamics-Modeling. Springer-Verlag, Berlin.

Canadell, J., Jackson, R.B., Ehleringer, J.R., Mooney, H.A., Sala, O.E., Schulze, E.D., 1996. Maximum rooting depth of vegetation types at the global scale. Oecologia 108, 583–595.

Cisneros, J.M., Cantero, J.J., Cantero, A., 1997. Relaciones entre la fluctuación del nivel freatico, su salinidad y el balance hídrico, en suelos salino-sódicos del centro de argentina. Revista de la Universidad Nacional de Río Cuarto 17, 23–35.

Contreras, S., Nosetto, M.D., Calderon, S., Jobbágy, E.G., 2008. Impacto de las aguas subterráneas en la producción de agroecosistema: modelización acoplada a

través del código VegNap. XXIII Reunión Argentina de Ecología, San Luis, Argentina.
Degioanni, A., Cisneros, J., Cantero, A., Camarasa, A., 2002. Las inundaciones en la Provincia de Córdoba (Argentina) y las tecnologías de información geográfica: Ejemplos de Aplicación. Serie Geográfica 10, 143–163.
Fulton, A., Schwankl, L., Lynn, K., Lampinen, B., Edstrom, J., Prichard, T., 2011. Using EM and VERIS technology to assess land suitability for orchard and vineyard development. Irrigation Science 29, 497–512.
George, R.J., McFarlane, D.J., Nulsen, R.A., 1997. Salinity threatens the viability of agriculture and ecosystems in Western Australia. Hydrogeology Journal 5, 6–21.
Ghassemi, F.A., Jakeman, A.J., Nix, H.A., 1995. Salinization of Land and Water Resources. University of New South Wales Press, Canberra, Australia.
Hall, A.J., Rebella, C.M., Ghersa, C., Culot, J., 1992. Field crop systems of the Pampas. In: Pearson, C.J. (Ed.), Ecosystems of the World, Field Crop Ecosystems. Elsevier, Amsterdam, pp. 413–450.
Heuperman, A., 1999. Hydraulic gradient reversal by trees in shallow water table areas and repercussions for the sustainability of tree-growing systems. Agricultural Water Management 39, 153–167.
Heuperman, A.F., Kapoor, A.S., Denecke, H.W., 2002. Biodrainage. Principles, experiences and applications. In: International Programme for Technology and Research in Irrigation and Drainage. Food and Agriculture Organization of the United Nations, Rome, pp. 79.
INTA-SAGyP, 1990. Atlas de suelos de la República Argentina. Instituto Nacional de Tecnología Agropecuaria - Secretaría de Agricultura, Ganadería y Pesca, Buenos Aires.
Jackson, R.B., Jobbágy, E.G., Avissar, R., Roy, S.B., Barret, D., Cook, C.W., Farley, K.A., Le Maitre, D.C., McCarl, B.A., Murray, B.C., 2005. Trading water for carbon with biological carbon sequestration. Science 310, 1944–1947.
Jarrel, W.M., Virginia, R.A., 1990. Response of mesquite to nitrate and salinity in a simulated phreatic environment: water use, dry matter and mineral nutrient accumulation. Plant Soil 125, 185–196.
Jayawickreme, D.H., Santoni, C., Kim, J.H., Jobbágy, E.G., Jackson, R.B., 2011. Changes in hydrology and salinity accompanying a century of agricultural conversion in Argentina. Ecological Applications 21, 2367–2379.
Jobbágy, E.G., Jackson, R.B., 2004. Groundwater use and salinization with grassland afforestation. Global Change Biology 10, 1299–1312.
Jobbágy, E.G., Jackson, R.B., 2007. Groundwater and soil chemical changes under phreatophytic tree plantations. Journal of Geophysical Research 112, G02013, http://dx.doi.org/10.1029/02006JG000246.
Jobbágy, E.G., Nosetto, M.D., Santoni, C., Baldi, G., 2008. El desafío ecohidrológico de las transiciones entre sistemas leñosos y herbáceos en la llanura Chaco-Pampeana. Ecología Austral 18, 305–322.
Kahlown, M.A., Ashraf, M., Zia-ul-Haq, 2005. Effect of shallow groundwater table on crop water requirements and crop yields. Agricultural Water Management 76, 24–35.
Kelliher, F.M., Leuning, R., Schulze, E.D., 1993. Evaporation and canopy characteristics of coniferous forests and grasslands. Oecologia 95, 153–163.
Khanzada, A.N., Morris, J.D., Ansari, R., Slavich, P.G., Collopy, J.J., 1998. Groundwater uptake and sustainability of Acacia and Prosopis plantations in Southern Pakistan. Agricultural Water Management 36, 121–139.
Lavado, R.S., Taboada, M.A., 1988. Water, salt and sodium dynamics in a natraquoll in Argentina. CATENA 15, 577–594.
Loke, M.H., 2000. Electrical imaging surveys for environmental and engineering studies. A practical guide to 2-D and 3-D surveys, 59. http://www.georentals.co.uk/Lokenote.pdf
Loke, M.H., 2009. Manual for RES2DINV. http://www.geoelectrical.com/downloads.pdf
Mahmood, K., Morris, J., Collopy, J., Slavich, P., 2001. Groundwater uptake and sustainability of farm plantations on saline sites in Punjab province, Pakistan. Agricultural Water Management 48, 1–20.
Martinez-Beltran, J., Manzur, C.L., 2005. Overview of salinity problems in the world and FAO strategies to address the problem. In: Proceedings of the international salinity forum, Riverside, California, pp. 311–313.
New, M., Lister, D., Hulme, M., Makin, I., 2002. A high-resolution data set of surface climate over global land areas. Climate Research 21, 1–25.
Nosetto, M.D., Jobbágy, E.G., Brizuela, A.B., Jackson, R.B., 2012. The hydrologic consequences of land cover change in central Argentina. Agriculture, Ecosystems and Environment 154, 2–11.
Nosetto, M.D., Jobbágy, E.G., Jackson, R.B., Sznaider, G., 2009. Reciprocal influence between crops and shallow ground water in sandy landscapes of the Inland Pampas. Field Crop Research 113, 138–148.
Nosetto, M.D., Jobbágy, E.G., Toth, T., Di Bella, C.M., 2007. The effects of tree establishment on water and salts dynamics in naturally salt-affected grasslands. Oecologia 152, 695–705.
Nosetto, M.D., Jobbágy, E.G., Toth, T., Jackson, R.B., 2008. Regional patterns and controls of ecosystem salinization with grassland afforestation along a rainfall gradient. Global Biogeochemical Cycles 22, GB2015, http://dx.doi.org/10.1029/2007GB003000.
Oster, J.D., Macedo, T.F., Davis, D., Fulton, A., 1999. Developing Sustainable Reuse and Disposal of Saline Drain Water on Eucalyptus. University of California, Riverside, USA, pp. 112.
Pierce, L.L., Walker, J., Dowling, T.I., McVicar, T.R., Hatton, T.J., Running, S.W., Coughlan, J.C., 1993. Ecohydrological changes in the Murray-Darling basin. III. A simulation of regional hydrological changes. Journal of Applied Ecology 30, 283–294.
Robinson, D.A., Binley, A., Crook, N., Day-Lewis, F.D., Ferré, T.P.A., Grauch, V.J.S., Knight, R., Knoll, M., Lakshmi, V., Miller, R., Nyquist, J., Pellerin, L., Singha, K., Slater, L., 2008. Advancing process-based watershed hydrological research using near-surface geophysics: a vision for, and review of, electrical and magnetic geophysical methods. Hydrological Processes 22, 3604–3635.
Saey, T., Van Meirvenne, M., De Smedt, P., Cockx, L., Meerschman, E., Islam, M.M., Meeuws, F., 2011. Mapping depth-to-clay using fitted multiple depth response curves of a proximal EMI sensor. Geoderma 162, 151–158.
Salama, R.B., Otto, C.J., Fitzpatrick, R.W., 1999. Contributions of groundwater conditions to soil and water salinization. Hydrogeology Journal 7, 46–64.
Sapanov, M.K., 2000. Water uptake by trees on different soils in the Northern Caspian region. Eurasian Soil Science 33, 1157–1165.
Saxton, K.E., Rawl, W.J., Romberger, J.S., Papendick, R.I., 1986. Estimating generalized soil-water characteristics from texture. Soil Science Society of America Journal 50, 1031–1036.
Schofield, R.V., Kirby, M.J., 2003. Application of salinization indicators and initial development of potential global soil salinization scenario under climatic change. Global Biogeochemical Cycles 17, 1078, doi:1010.1029/2002GB001935.
Shah, S.H.H., Vervoort, R.W., Suweis, S., Guswa, A.J., Rinaldo, A.S.E.A.T.M., van der Zee, 2011. Stochastic modeling of salt accumulation in the root zone due to capillary flux from brackish groundwater. Water Resources Research 47, W09506.
Soriano, A., Leon, R.J.C., Sala, O.E., Lavado, R.S., Deregibus, V.A., Cahuepe, M., Scaglia, O.A., Velázquez, C.A., Lemcoff, J.H., 1991. Río de la Plata Grasslands. In: Coupland, R.T. (Ed.), Natural Grasslands: Introduction and Western Hemisphere. Ecosystems of the World 8A. Elsevier, Amsterdam, pp. 367–407.
Stirzaker, R.J., Cook, F.J., Knight, J.H., 1999. Where to plant trees on cropping land for control of dryland salinity: some approximate solutions. Agricultural Water Management 39, 115–133.
Sweeney, S.M., Stevens, R.M., 1997. Growth and water use of eucalypt trees irrigated with saline drainage water. Irrigation Science 17, 173–181.
Szabolcs, I., 1989. Salt-Affected Soils. CRC Press, Florida.
Taboada, M.A., Damiano, F., Lavado, R.S., 2009. Inundaciones en la Región Pampeana. Consecuencias sobre los suelos. In: Taboada, M.A., Lavado, R.S. (Eds.), Alteraciones de la fertilidad de los suelos: el halomorfismo, la acidez, el hidromorfismo y las inundaciones. Universidad de Buenos Aires, Buenos Aires, pp. 103–127.
Viglizzo, E.F., Jobbágy, E.G., Carreño, L.V., Frank, F.C., Aragón, R.M., De Oro, L., Salvador, V.S., 2009. The dynamics of cultivation and floods in arable lands of central Argentina. Hydrology and Earth System Sciences 13, 491–502.
Wright, J.A., DiNicola, A., Gaitan, E., 2000. Latin American forest plantations—opportunities for carbon sequestration, economic development and financial returns. Journal of Forestry 98, 20–23.