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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.



## 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