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Reciprocal influence of crops and shallow ground water in sandy landscapes of the Inland Pampas

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ABSTRACT

In regions with shallow water tables, ground water may have a positive (water supply) or negative (waterlogging or salinization) impact on crops. Reciprocally, crops can influence ground water, altering water table depth and chemical composition. We quantified these reciprocal influences along natural gradients of groundwater depth in flat sedimentary landscapes of the Inland Pampas occupied by wheat, soybean, and maize during two growing seasons (2006/2007 and 2007/2008). We correlated crop yield and groundwater depth maps at the field level and made direct plant, soil and groundwater observations at the stand level across topographic gradients. Water table level largely accounted for spatial crop yield variation, explaining 20–75% of their variance. An optimum groundwater depth range, where crop yields were highest, was observed for all three crop species analyzed (1.40–2.45 m for maize, 1.20–2.20 m for soybean, and 0.70–1.65 m for wheat). The areas within these optimum bands had yields that were 3.7, 3 and 1.8 times larger than those where the water table was below 4 m for wheat, maize, and soybean, respectively. As groundwater levels become shallower than these depth bands, crop yields declined sharply ($\sim$0.05 kg m^{-2} on average for every 10 cm increase in water table level), suggesting negative effects of waterlogging, root anoxia and/or salinity. Groundwater levels below these depth bands were associated with gradually declining yields, likely driven by poorer groundwater supply.

Crops influenced groundwater levels through their control of recharge and discharge fluxes. The presence of active crops prevented recharge events (sharp water table level rises) observed during rainy periods in fall and spring. Crops consumed ground water generating increasing discharge as the water table depth decreased. This consumption led to rising soil and groundwater salinization towards shallower water table positions as the growing season progressed. The electrical conductivity of ground water for maize at maturity doubled the pre-sowing values ($\sim$2.2 dS m^{-1} vs. $\sim$1.1 dS m^{-1}, $p < 0.01$,) when ground water was above 2-m depth, whereas negligible changes were observed when groundwater depth exceeded 3.5 m. In flat humid landscapes, such as the Inland Pampas, crops and shallow ground water may be closely connected and influence each other through different mechanisms, posing both opportunities and risks for agricultural systems. Understanding these complex interactions could help raise and stabilize yields and provide keys to regulate the labile hydrology of these plains.

1. Introduction

In regions with shallow water tables, crops and ground water can interact through several mechanisms. Depending on the prevailing water table depth, ground water may be either unavailable to crops, a valuable water source, or a stress factor because of waterlogging or salinity (Kahlown et al., 2005; Ayars et al., 2006). Reciprocally, crops can influence ground water, altering water table depth and chemical composition (Jobbágy and Jackson, 2004). Here we quantify these reciprocal influences along natural gradients of groundwater depth in flat sedimentary landscapes of the Pampas occupied by annual crops.

When water tables lie near the bottom of the rooting zone of crops, ground water may act as a valuable water source through

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capillary movement from the saturated zone up to the root absorption zone (Ayars et al., 2006). Under dry climates direct groundwater consumption by crops may reduce or completely eliminate irrigation requirements (Pratharpar and Qureshi, 1998), whereas under more humid climates it can increase and stabilize the yields of rain-fed crops. Above a certain water table depth, however, the positive influence of ground water on yield changes to the negative effects of waterlogging (Reicosky et al., 1985). Anoxic conditions in this case reduce root activity, nutrient availability, and plant germination and establishment (McKevlin et al., 1998). Water tables near the surface can also reduce crop production when waterlogging impedes machinery transit, interrupting sowing operations. In flat sedimentary plains, high water table levels increase flooding and significantly reduce the amount of land available for cultivation (Viglizzo and Frank, 2006).

The relevance of groundwater effects on crops depends on the balance of precipitation inputs and atmospheric demand through the growing season, groundwater salinity, soil water transport characteristics and crop attributes. Positive effects of groundwater supply are likely to be greater during drier than wetter years. In contrast, negative effects (waterlogging) should be larger in relatively wet years. Increasing groundwater salinity reduces the benefits of groundwater supply and aggravates the consequences of waterlogging (Hutmacher et al., 1996). Through its influence on hydraulic conductivity, soil texture influences the rates at which ground water can flow from the saturated zone to roots (Hillel, 1998). Among crop attributes, root growth and distribution and tolerance to waterlogging and salinity are of key importance in regulating groundwater influences. Crops able to generate deep root systems in a shorter time will have better chances of reaching ground water under deep water table conditions. Crops tolerant to waterlogging will be more likely to grow with shallow water table conditions (Kahlown et al., 2005). Crop tolerance to salinity will cause great contrasts in groundwater consumption when its salt content is high (Ayars et al., 2006; Nosetto et al., 2008).

Although both positive and negative groundwater effects on crop performance are typically recognized, their simultaneous occurrence under field conditions has not to our knowledge been documented previously. However, humid plains with poor regional drainage networks, such as the Pampas (Argentina), provide the opportunity to evaluate both positive and negative effects of ground water directly in the field. This arises because of the combination of a positive water balance and a poor surface drainage network, resulting in shallow water tables across the landscape (Nosetto et al., 2007). Although shallow ground water can represent a highly valuable resource in this important food producing region, it may also entail a serious risk for agricultural systems when ground water reaches levels detrimental to vegetation. This particular setting concurrently offers a big challenge to land managers and agronomists trying to minimize waterlogging risks and maximize water benefits, as well as a valuable opportunity to scientists trying to understand the reciprocal influences between ecosystems and ground water (Jackson et al., 2000; Jobbágy and Jackson, 2007).

Groundwater influences on crop performance can be accompanied by reciprocal effects of crops on groundwater level, flow and chemical composition. Vegetation indirectly influences groundwater recharge through evapotranspiration and water drainage. Moreover, vegetation influences ground water by direct uptake from the water table or the capillary fringe above it (Nosetto et al., 2007). Substantial groundwater consumption by vegetation may lower the water table, triggering lateral groundwater flows from the surrounding environment and/or deeper aquifers (Heuperman, 1999; Jobbágy and Jackson, 2004). The chemistry of the ground water can also be affected by vegetation. Through groundwater absorption and solute exclusion by roots, plants may increase groundwater salinity up to levels that restrict groundwater uptake by vegetation or cause toxicity, if no mechanism to remove solutes exists (Jobbágy and Jackson, 2004).

In this paper we explore the reciprocal influences of crops and shallow ground water through two full growing seasons in an aeolian sedimentary landscape representative of the Inland Pampas of Argentina. The Pampas, extending across 600.000 km^2 of temperate Argentina, is one of the most important temperate cropping regions of the world. About ~60% of its area is suitable for rain-fed agriculture (Hall et al., 1992) with ~21 million hectares being currently devoted to the production of soybean, wheat, and maize, among other grains (SAGPyA, http://www.sagpya.mecon.gov.ar). Our specific aims are to (1) characterize groundwater effects on crop production across natural gradients in water table depth dictated by topography, and (2) evaluate crop effects on groundwater depth and salinity based on periodic observations (monitoring wells and soil salinity measurements) across topographic transects. To accomplish these aims, we combined crop yield and groundwater depth mapping with stand-level observations of groundwater depth and soil salinity under three crops: wheat, soybeans, and maize.

2. Materials and methods

2.1. Study site

The study sites were located at "El Consuelo" farm (Fig. 1, 9300 ha; latitude −34°12', longitude −64°18'), close to the town of Vicuña Mackenna (Córdoba province, Argentina). The area is typical of the aeolian sedimentary landscapes of the Inland Pampa and was originally occupied by native grasslands (Soriano et al., 1991). Currently, most of this region is dominated by annual crops, followed in importance by pastures and native grasslands. The climate is temperate, with a mean annual temperature of 16.5 °C. Average wind speed approaches 15 km h^{-1} and presents a constant hazard of erosion (Hall et al., 1992). Mean annual rainfall is ~740 mm $year^{-1}$ for the last century (1910–2007) and ~920 mm $year^{-1}$ for the last 15 years (1992–2007) and is concentrated in summer and autumn (67%). Mean annual Penman-Monteith potential evapotranspiration approaches ~1200 mm $year^{-1}$ (1960–1990, CRU database, New et al., 2002).

An interesting feature of rainfall patterns in this area is its variability, with coefficients of variation for mean monthly rainfall usually exceeding 70%. This pattern, together with the seasonal variation of water availability combined with soil properties, creates two important production risks. First, rainfall deficits during September to October can decrease potential yield by delaying when summer crops are sown (Hall et al., 1992). Second, rainfall deficits in the middle of the summer can decrease growth during critical crop stages such as flowering or grain-filling (Calvino et al., 2003). The presence of shallow ground water could very likely reduce the second hazard. The first hazard can also be ameliorated if water table levels are shallow enough to convey capillary moisture to the establishing plants.

Predominant soils are deep (>150 cm), sandy, well drained Entic Haplustolls, which do not present any significant restriction to crop growth. Soil organic matter in the top layer is <1.5% and sand content usually exceeds 70% (INTA-SAGyP, 1990). The regional surface run-off network is poor because of a very flat regional landscape with a slight topographic gradient (average slope ~0.15%) that develops in the W-E direction (Fuschini Mejía, 1994; Degioanni et al., 2006). This topographic configuration that constrains liquid evacuation pathways of water excess, combined with a humid climate, determines the presence of shallow water tables and the long-term accumulation of solutes derived from atmospheric depositions and rock weathering in the landscape

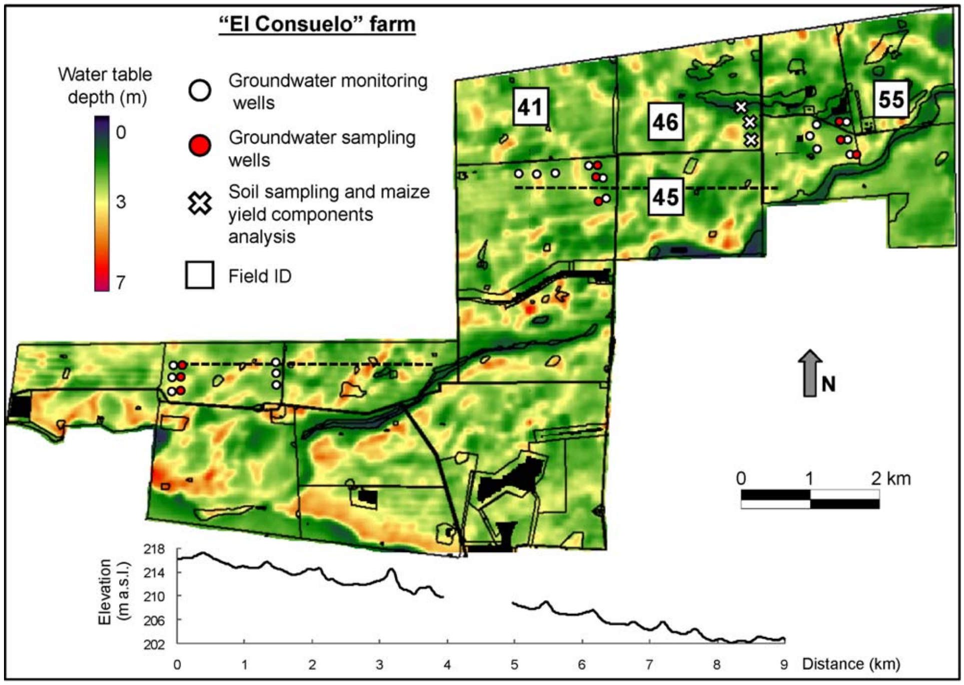

Fig. 1. Setting of the study system. The limits and fields of "El Consuelo" farm overlay a groundwater depth map (January 2008). Eighteen groundwater monitoring wells, distributed in six three-point-transects, were located across the W-E regional topographic gradient. Nine new boreholes were made in September 2007 for additional groundwater sampling. Groundwater depth vs. crop yield analyses were performed at fields #41, #45, #46 and #55. Detailed maize yield component analysis and soil sampling were carried out at three positions within field #46 during the 2007/2008 growing season. At the bottom, two W-E transects (dashed lines in the map) of surface elevation (m a.s.l.) show the regional W-E topographic gradient and the patch-level variation.

(Degioanni et al., 2002). Locally, groundwater depth variation (typically 0–7 m) is dictated by the local topographic gradients associated with the dune landforms. Higher groundwater levels are observed during autumn–winter, when precipitation exceeds potential evapotranspiration (INTA – SAGyRR, 1987; Degioanni et al., 2002). At the local level, piezometric gradients generate groundwater fluxes from high to low topographic positions, promoting the formation of surface water bodies that operate as water and solute sinks from the local surrounding (Degioanni et al., 2002) through focalized evaporative discharge (Cisneros et al., 1997; Degioanni et al., 2002). If wet periods extend for several years, the water-covered area expands at the expense of land suitable for cropping (Lavado and Taboada, 1988; Hall et al., 1992). Regional discharge, which brings a high solute load in the Pampas, does not take place in our study region but approx. 100 km eastward, what implies that salty groundwater bodies occur only in local discharge foci in bottomland positions.

2.2. Sampling fields

Reciprocal groundwater – crop influences were explored at four fields of "El Consuelo" farm cultivated with soybean, maize and wheat in the 2006/2007 and 2007/2008 growing seasons (Table 1 and Fig. 1). The growing seasons analyzed had contrasting rainfall patterns. From May 2006 to April 2007, the site received 780 mm of rain, approaching average annual values. During this period, the growing season of summer crops (November–March) was particularly humid, receiving 685 mm (27% above the historic mean). The ratio between precipitation (Pp) and crop evapotranspiration (ETc) calculated according to Penman-Monteith with typical Kc factors (Allen et al., 1998; Della Maggiora et al., 2000) approached 1.5 and 1.27 for maize and soybean, respectively. By contrast, the growing season of the wheat crop (June–November) was particularly dry, receiving only 147 mm (44% below the historic mean; Pp:ETc = 0.31).

In 2007/2008, annual rainfall was 670 mm and the growing season of summer crops received 421 mm (22% below the historic mean). The Pp:ETc ratio approached 0.96 and 0.60 for soybean and maize, respectively. In the wheat growing season, rainfall was 256 mm, approaching the historic mean and yielding a Pp:ETc ratio of 0.85.

A typical crop rotation in the region encompasses a 3-year-long cycle including a sequence of wheat/soybean (late sowing) double crop – maize – soybean (early sowing). This crop rotation has been applied in the farm for the last 8 years. No-tillage management is widespread in the region and was applied to all the fields of the farm where our study was performed. Weeds were controlled with herbicides, particularly glyphosate. Fields were weed-free managed throughout the whole study period. Selected fields showed well-developed groundwater depth gradients and do not include extremely high dune crests.

2.3. Groundwater monitoring wells

Eighteen monitoring wells, distributed in six three-point transects, were established in three representative fields of the farm (Fig. 1). The distribution of transects encompassed the regional west–east gradient with average elevation ranging from 221 m above sea level (westernmost transect) to 205 m (easternmost transect) (Fig. 1). All transects were located in such a way that each of them traversed the patch topographic variation of the wind-shaped landscape and extended from typical crests to topographic depressions. Elevation differences between crests and depressions averaged ~2 m. Extreme topographic situations were avoided in the selection of the well positions. The length of the transects ranged from 150 to 700 m.

Boreholes (10-cm outside diameter) were augered at each position of these transects. PVC pipes (10-cm outside diameter), extending ~0.5 m below the water table and 1.5–2 m above the ground surface, were closely fitted inside each borehole. The upper pipe opening was capped with a PVC cap. In the lower 0.5 m section of the pipe, 20 holes (2 mm diameter) were made with an electric drill. To avoid rain water moving down the pipe wall, the PVC pipe at the ground level was covered first with a thin polyethylene film (250 μm) and then with soil. The polyethylene film was stuck to the exterior wall of the pipe with adhesive tape. Groundwater depth, determined from the top of the upper pipe opening, was manually measured every ~15 days during crop growing seasons and ~30 days during fallow periods. The absolute elevation of the top of each pipe was determined with a differential GPS (Trimble 4600 LS, Trimble Navigation Ltd., Sunnyvale, CA, USA; horizontal static accuracy = 5 mm; vertical static accuracy = 10 mm) and, by subtracting the groundwater depth, we obtained the absolute groundwater elevation.

In addition to groundwater depth measurements, ground water was sampled every 1–2 months during the 2006/2007 growing season (sowing to post-harvesting) for electrical conductivity (EC) analysis. Samples were taken after removing 5 times the volume contained in the well. Water samples were syringe-filtered (0.45 μm) and kept at 4–6 °C until analysis. EC measurements were made in 50 ml beakers with a conductivity meter automatically corrected for temperature (Orion model 115; Orion Research, Mass. MA, USA) In September 2007, six and three months after soybean and maize harvest, respectively, nine new boreholes (three in fields after 2006/2007 early soybean and six after 2006/2007 maize, Table 1) were made for additional groundwater sampling.

2.4. Groundwater depth mapping

In order to map the groundwater depth at the farm level we generated a fine resolution elevation map (FR E-map). The southernmost part of the farm, corresponding to a different geomorphic unit (terraces of the Quinto River), was excluded from the analysis. Surface elevation was mapped with a horizontal resolution of ~20 m using a differential GPS (Trimble 4600 LS, horizontal kinematic accuracy = 1 cm; vertical kinematic accuracy = 2 cm) mounted on a vehicle. Point vector data of surface elevation were rasterized and interpolated using the Inverse Distance Weighted procedure in order to generate the FR E-map (O'Sullivan and Unwin, 2003) (Fig. 2). In order to highlight the regional topographic gradient and to remove the patch topographic variation associated with the wind-shaped landforms (see bottom of Fig. 1), a smoothed topographic surface or coarse resolution elevation map (CR E-map) was generated (Fig. 2). We derived this CR E-map from the FR E-map using a spatial filter based on a 1 km × 1 km averaging kernel. Then, to remove the regional topographic gradient and highlight the patch elevation differences associated with the local aeolian landforms, we generated a map of altimetric residuals (ER-map = FR E-map − CR E-map) (Fig. 2).

We used linear regression models of groundwater absolute elevation vs. coarse resolution (1 km × 1 km averaged) absolute surface elevation ($r^2 > 0.99$, $p < 0.001$, $n = 18$) to generate a groundwater absolute elevation map (GWE-map) for the whole farm (Fig. 2). Regressions were performed using groundwater elevation data from the 18 monitoring wells and from several time periods according to the growing season of each crop in order to adjust their effective GWE-maps. For instance, for the maize 2006/2007 growing season, the regression was performed with the average groundwater elevation for the period November 2006–March 2007. Finally, by subtracting the groundwater elevation map (GWE-map) from the fine resolution elevation map (FR E-map), we developed a model that was capable of reconstructing and mapping water table depths from the surface for all pixels (WTD-map, Fig. 2).

We evaluated the accuracy of the groundwater depth mapping approach by repeating the regression procedure with a jackknife method that uses data from 17 monitoring wells to predict levels in the remaining well. A close association was obtained between observed and predicted groundwater depth values ($r^2 = 0.94$, $p < 0.001$, $n = 18$, mean square error < 20 cm).

2.5. Crop yield mapping

Crop yields were recorded with a Greenstar[TM] monitor (John Deere Inc., Moline, Illinois) mounted in harvesting machinery equipped with a differential GPS (Trimble 4600 LS). Yields and the associated ground location were recorded at 2-s intervals, which results in one yield datum per ~34 m^2 (harvester head width = 8.5 m, average velocity = 7 km h^{-1}). Monitors were calibrated following manufacturer's recommendations. Point yield data were rasterized and interpolated using the Inverse Distance Weighted procedure to a final pixel size of 20 m (the same spatial resolution of groundwater depth maps). A 40-m-wide zone on the boundaries of each field was excluded from analyses to avoid potential edge effects.

2.6. Additional field measurements

In order to assess the effects of groundwater depth on crop growth and performance in greater detail, intensive measurements were performed in one maize field during the 2007–2008 growing season. In order to account for the different effects of ground water (GW) on crops, three sampling positions were established for relatively shallow-, intermediate- and deep-ground water, based on the groundwater depth map of November 2007 (Fig. 1). Across these positions water table depth fluctuated between 0.7 and 0.9, 1.6 and 1.8 and 2.70 and 2.95 m, respectively, below the surface during the growing season. These positions were located ~180–200 m apart. To assess groundwater effects on maize yield, three rectangular harvest areas of ~6 m^2 (1.6 m × 3.7 m) were randomly determined per position. Within each position, harvest areas were spaced ~10–15 m apart. Maize cobs were manually harvested and shelled; grains were oven-dried at 45 °C for 72 h.

Table 1
Characteristics of wheat, soybean and maize fields considered in the analysis.

	Wheat		Soybean		Maize	
	2006/2007	2007/2008	2006/2007	2007/2008	2006/2007	2007/2008
Field ID	41	55	55	55	46	45
Area (ha)	330	233	233	233	318	331
Sowing date	June 03–11	June 01–20	October 23–24	December 15–18	November 20–21	September 26–28
Plant density (plants m^{-2})	340	340	32	32	6.5	6.5
Row spacing (cm)	21	21	38	38	53	53
Cultivar	Klein Capricornio	Premium11 DMCronox DM Onix	DM 4870	DM 4870	DK 747 MG	DK 747 MG
Urea fertilizer (g m^{-2})	15	15	–	–	15	15

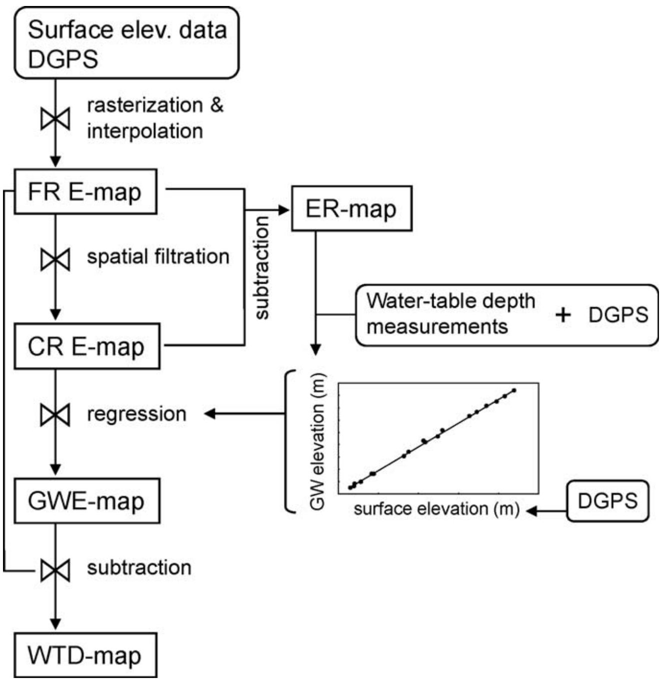

Fig. 2. Approach utilized to map groundwater depth. Differential GPS data were rasterized and interpolated to generate a fine resolution elevation map (FR E-map), which was then smoothed to produce a coarse resolution elevation map (CR E-map). A map of elevation residuals (ER-map) was calculated as the difference between the FR and CR E-maps. Based on linear regressions between the absolute groundwater elevation (measured at 18 monitoring wells) and the absolute elevation of the surface at their positions, combined with the elevation residual determined above, yields a groundwater elevation map (GWE-map). Finally, by subtracting the GWE-map from the FR E-map, we generated a water table depth map (WTD-map).

In addition, soil samples were collected at 20-cm depth intervals for electrical conductivity determination (ECs) at the same three previous positions. Soil sampling extended down to depths of 1.4, 2.0 and 2.4 m for shallow-, intermediate- and deep-ground water positions. Samples, taken at the time of the R3 phase (Ritchie et al., 1993), were located in the centre of the 53-cm inter-row space. Four replicates per position were randomly established. As with harvest areas, within each position, soil sampling points were spaced ~10–15 m apart. Soil samples were oven-dried for 72 h (45 °C) and sieved (1 mm). ECs was determined in a 1:2.5 soil–water extracts previously shaken for ~12 h. Measurements were made in a 50 ml beaker with a conductivity meter automatically corrected for temperature (Orion model 115). Soil textural analysis, based on the hydrometer method (Bouyoucos, 1962), indicated that all positions were characterized by a sandy loam texture in shallow soil layers (<0.50 m depth) and loamy sand in deeper horizons with the sand content reaching ~80%.

We performed a complementary assessment of soil salinity along the groundwater depth transects at the same intensively sampled maize field through an electromagnetic induction technique that characterizes apparent soil electrical conductivity (ECa) in a non-invasive way. We used the electromagnetic instrument (EM38, Geonics Ltd.) in the horizontal dipole mode, which provides an effective measurement depth of ~0.75 m when the instrument is placed on the ground (Sudduth et al., 2001). Thirty measurements were taken every ~10 m along two ~170 m long transects ~35 days after physiological maturity. Groundwater depth varied between 0.5 and 2.2 m along these transects.

2.7. Data analysis

To account for the non-linear positive and negative effects of ground water on crop yields, piecewise regressions with two breakpoints on the explanatory variable (i.e. groundwater depth) were adjusted (Piegorsch and Bailer, 2005) for the crop yield map – groundwater depth map dataset. The first segment of the model (waterlogging band) encompasses the negative waterlogging effects of shallow ground water, where increasing depth to the water table led to increased crop yields. The second segment, bracketed by the two breakpoints, represents the optimum groundwater depth range (optimum band), where crop yields were highest and small water table depth variations had little effect on crop performance. The third and last segment (declining yields band) of the model represents the decline of crop yields as the water table deepens. Linear, power, exponential and logarithmic functions were tested in the first and third segments of the model and a plateau (i.e. a constant) function in the second one. The best explanatory model, resulting from the best combination of the previous functions, was selected based on the Akaike Information Criteria (Akaike, 1974).

The effects of groundwater depth on maize yield components and soil electrical conductivity were analyzed using one-way analysis of variance (ANOVA). In this case, the groundwater depth variable was categorized into shallow- (0.7–0.9 m of groundwater depth), intermediate- (1.6–1.8 m) and deep-groundwater positions (2.7–2.9 m) and, where appropriate, these were compared using Duncan's tests.

3. Results

3.1. Groundwater effects on crops performance

Ground water exerted both positive and negative influences on crop production, as shown by the significant response of crop yields to water table depth (Fig. 3). An optimum groundwater depth range, where crop yields were highest, was observed for all three crop species analyzed. These optimum groundwater depth bands were 1.40–2.45, 1.20–2.20 and 0.70–1.65 m in maize, soybean and wheat, respectively (average depth of inflection points in both growing seasons are considered). When ground water was shallower than these depths, crop yields showed a sharp decline (Fig. 3), suggesting the negative effects of waterlogging, root anoxia and/or salinity. Wheat yield, for instance, decreased ~0.08 kg m^{-2} for every 10 cm increase in groundwater height above this optimum range in the 2007/2008 growing season. The rates of yield decline for maize and soybean approached 0.065 and 0.023 kg m^{-2}, respectively. Where groundwater level was deeper than the optimum band, crop yields also decreased, albeit substantially at lower rate (Fig. 3). In this depth band, for every 10 cm decline in groundwater depth, yields decreased on average 0.018, 0.028 and 0.005 kg m^{-2}, for wheat, maize and soybean, respectively.

The piecewise regression analyses indicated that water table level largely accounted for spatial crop yield variation (r^2 = 0.20–0.75; RMSE = 0.055–0.17 kg m^{-2}; Fig. 3). Interestingly, the association was tighter in the driest growing season (summer, 2007/2008 for maize and soybean, and winter 2006/2007 for wheat), suggesting a larger contribution of ground water to crop water requirements during this period. In the driest growing season, with rainfall 40% below the historic mean, groundwater depth explained 75%, 41% and 50% of the variation in maize, soybean and wheat yields, respectively. Explanatory power decreased to the still considerable 48%, 20% and 38% in the growing season with normal rainfall.

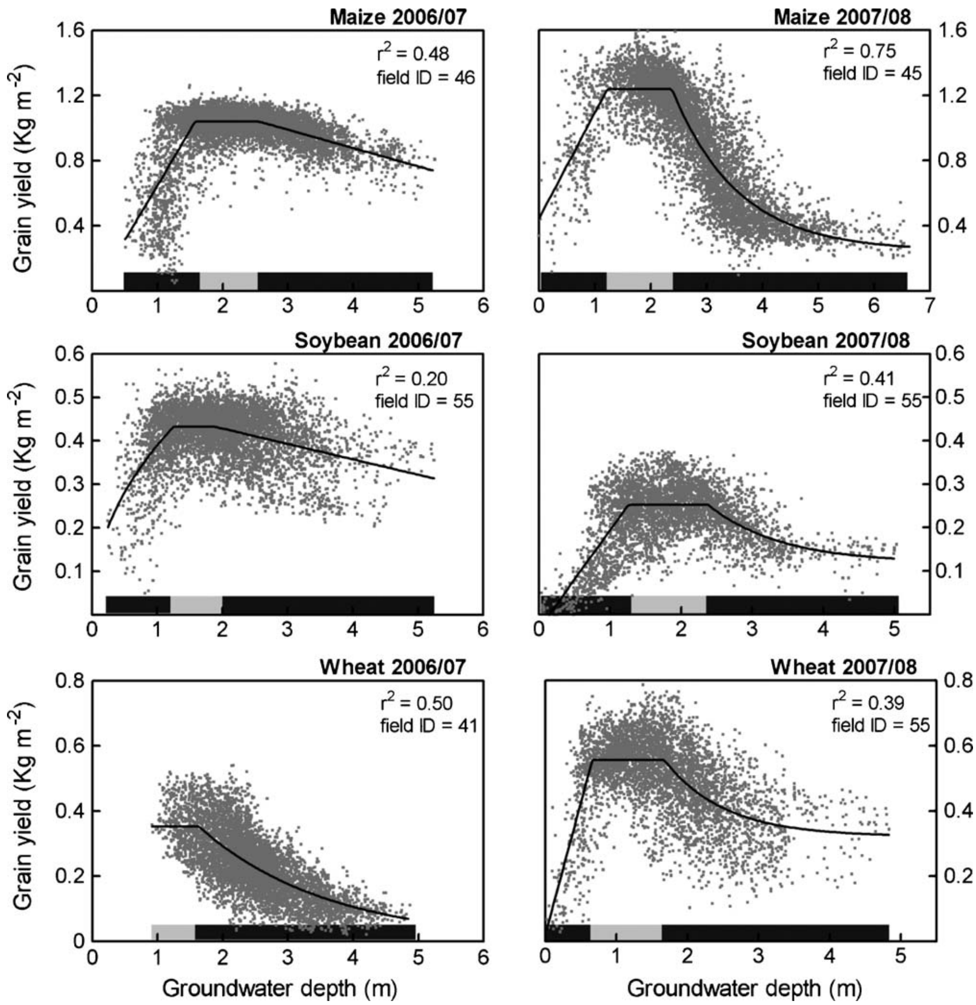

Fig. 3. Relationships of groundwater depth (m) and crop yields (kg m^{-2}) for maize, soybean and wheat in two growing seasons, 2006/2007 and 2007/2008. Groundwater depth values are averages for the whole growing season. Crop yields were mapped with Greenstar^{TM} monitors and groundwater depth was mapped using the procedure described in Fig. 1. Points represent yield measurements and groundwater depth estimates for each sampling unit. Piecewise regressions with two breakpoints were used. The best explanatory models are shown. The gray area on the *x*-axis delineates the three bands of groundwater effects on crops defined by the regression model (waterlogging, optimum and declining yields bands).

Important contrasts emerged between both growing seasons after normalizing crop yields according to the observed maximum of each crop in each growing season (Fig. 4). Normalized yields declined much more steeply as the water table deepened below the optimum band during the driest growing seasons, suggesting a stronger positive groundwater influence during this period. In the driest growing season, crop yields (averaged for all crop species) decreased by ~3% for every 10 cm drop in groundwater depth below the optimum band. This resulted in normalized yield declines of 0.50, 0.31 and 0.53 relative units in areas with ground water at 4–5 m depth compared to ground water at the optimum depth, for maize, soybean and wheat, respectively (Fig. 4). By contrast, in the wettest growing season this decline was only ~1% per 10-cm decrease, resulting in normalized yield declines of 0.19, 0.16 and 0.29 relative yield units. However, neither the width of the optimum groundwater depth band nor the positions of the inflection points showed any significant change between both growing seasons (Fig. 4), suggesting a low plasticity of these parameters to rainfall amounts occurring during the growing season.

The comparison of crop yields between areas with optimum groundwater provision (within the optimum depth band) and with negligible groundwater contribution (water table depth > 4 m) suggests that groundwater contributions had the largest impact on wheat, followed by maize and soybean. This pattern could be partially due to the drier conditions experienced by wheat compared to maize and soybean, as suggested by mean Pp:ETc ratios for both growing seasons of 0.6, 1.05 and 1.12 for wheat, maize and soybean, respectively. During the driest growing season, the areas within the optimum groundwater depth had yields that were 3.7, 3 and 1.8 times larger than those where the water table was below 4 m for wheat, maize, and soybean, respectively (Fig. 4). Assuming that crop yields in areas with a water table below 4 m would be the ones expected in the absence of ground water, we estimated that ~0.14 kg m^{-2} (~60% of total field production) of wheat grains were produced in field #41 during the driest growing season solely because of groundwater availability. Based on this reasoning and assumptions, ground water would have allowed an extra production of ~0.51 and 0.08 kg m^{-2} for maize and soybean in fields #45 and #55 respectively, during the 2007–2008 growing season (~55% and 37% of total field production, respectively). In contrast, during the 2006–2007 growing season, the negative effects of shallow water table led to grain losses of 0.038 and 0.008 kg m^{-2} in maize (3.8% of total field #46 production) and soybean (1.8% of total field #55 production), respectively. In the case of wheat, grain loss approached 0.012 kg m^{-2} in field #55 during the 2007–2008 growing season (2.4% of total field production).

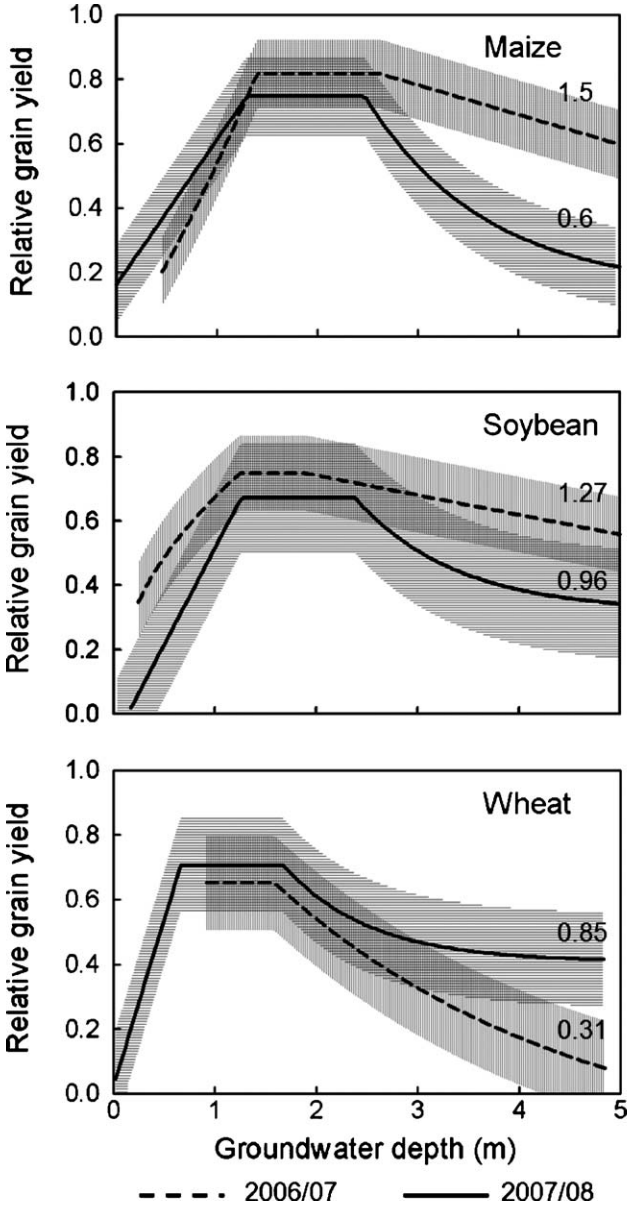

Fig. 4. Normalized crop yield responses of maize, soybean and wheat to groundwater depth. Yields were normalized according to the observed maximum of each crop in each growing season. Lines result from the best explanatory model based on piecewise regressions with two breakpoints. Gray areas represent 75%-prediction intervals and values above them indicate Pp:ETc ratios for the whole growing season of each crop.

Differences in maize yield for the 2007/2008 growing season at three positions along the gradients in groundwater depth were observed for the number of ears per square meter, the number of grains per square meter, the number of grains per row and grain weight (Table 2). In contrast, plant density and the number of rows per ear did not differ with changes in groundwater depth ($p > 0.10$, $n = 3$). Maize plants growing within the optimum depth band (according to our whole field analysis, Figs. 3 and 4), produced the largest number of ears per square meter ($p < 0.05$, $n = 3$) but the lowest number of grains per row on spike ($p < 0.05$, $n = 3$), partially canceling the previous difference. The negative influence of shallow groundwater depths on maize yield (see Fig. 4) was explained by a decrease of grain number and weight (Table 2, $p < 0.05$, $n = 3$).

3.2. *Crop effects on the dynamics of groundwater and soil conductivities in the 2006/2007 season*

Crops strongly influenced groundwater dynamics, as shown through the analysis of changes in groundwater level (Fig. 5). From November 11 to December 15 total rainfall was 102 mm, which led to strong groundwater recharge (positive groundwater level changes) in maize fields – at seedling stage – and negligible in soybean – at advanced vegetative stage – (Fig. 5A). Likely higher evapotranspiration and soil water consumption by more developed soybean compared to late sown maize during this period, as suggested by Pp:ETc ratios of 0.81 and 1.6, respectively, constrained recharge by storing precipitation inputs within the available water volume of the soil profile. The magnitude of recharge in maize fields was affected by groundwater depth, being more intense in shallow water table areas (Fig. 5A, $r^2 = 0.6$, $p < 0.01$, $n = 12$), likely resulting from the thinner unsaturated zone and lower water-holding capacity of these areas.

Although rainfall totalled 119 mm between January 13 and February 10, groundwater levels decreased significantly in both maize (flowering stage) and soybean (grain-filling stage) fields (Fig. 5B), likely as a result of intense evaporative demand during this period in which ETc values totalled 140 and 128 mm. During this period, declines in groundwater depth were stronger towards shallow groundwater positions ($r^2 = 0.90$ and $r^2 = 0.75$ for maize and soybean, respectively, $p < 0.01$), suggesting intensified groundwater discharge (consumption) by crops in these areas.

Between March 3 and 28, a period of declining potential evapotranspiration, rainfall inputs of 72 mm led to stronger recharge in the soybean field that was already harvested than in maize fields that were at the grain-filling stage (Fig. 5C). This pattern likely suggests a total replenishment of soil profile water in the soybean field because of a more positive water balance during this period (Pp:ETc = 3.4) but not in the maize field, which continued to consume water (Pp:ETc = 1.5).

Important shifts in groundwater salinity were observed in space, across groundwater depth gradients, and through time, during the maize growing season (2006/2007). Groundwater electrical conductivity in maize fields showed increasing values towards positions with shallow ground water (Fig. 6). This trend intensified as the growing season progressed, suggesting that maize plants, through groundwater use and solute exclusion, caused groundwater salinization. In shallow groundwater positions above 2-m depth, the electrical conductivity of ground water for maize at maturity was twice the pre-sowing values ($\sim$2.2 dS m^{-1} vs. $\sim$1.1 dS m^{-1}, $p < 0.01$, $n = 4$, Fig. 6). Six months after maize harvest, groundwater quality tended to recover, as

Table 2
Maize yield components at three positions with different groundwater (GW) depths.

Position	Groundwater depth (m)	Plant density (plants m^{-2})	No. ears m^{-2}	No. grains m^{-2}	No. rows per ear	No. grains per row	Grain weight (g 1000 $grains^{-1}$)	Grain yield (kg m^{-2})
Shallow-GW	0.7–0.9	6.38	7.13 b	319.9 b	13.1	34.3 b	205.9 b	0.66 c
Intermediate-GW	1.6–1.8	6.44	9.67 a	442.4 a	13.6	33.7 b	286.3 a	1.27 a
Deep-GW	2.7–2.95	6.68	7.18 b	356.1 ab	13.1	37.6 a	293.9 a	1.05 b

The mean values of three plots (6 m^2) per site are shown. Maize was sown on November 28–30, 2007 and sampled on May 14, 2008, after physiological maturity. Letters show significant differences ($p < 0.05$) among sites (Duncan's test).

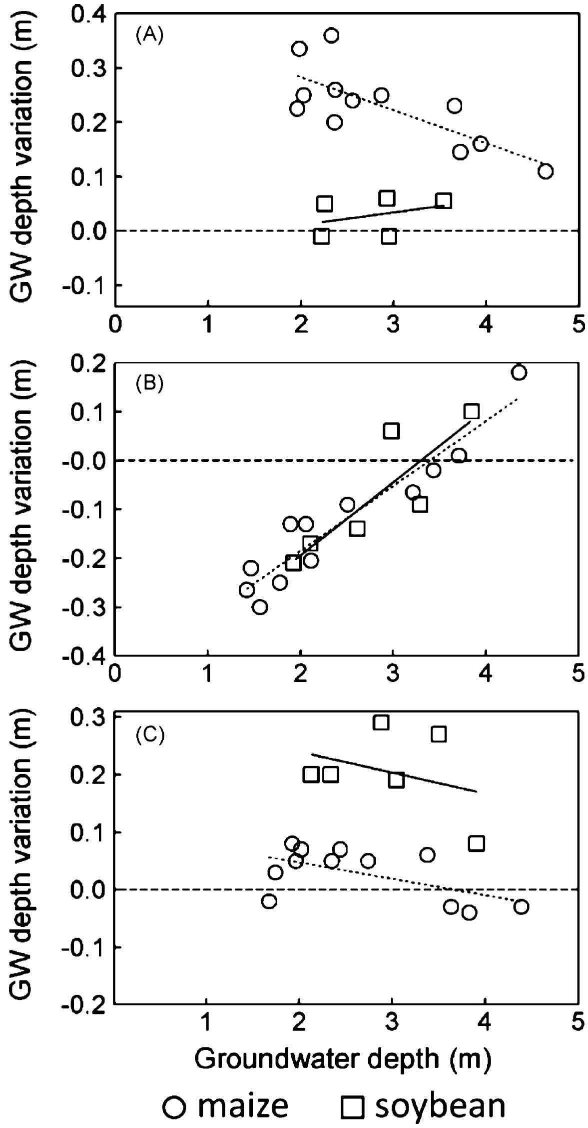

Fig. 5. Groundwater (GW) depth dynamics in maize (circles) and soybean (squares) fields for the 2006–2007 growing season. The relationships between groundwater depth (m) measured at the beginning of the analyzed period and groundwater level change (m) for the periods November 11–December 15 (A), January 13–February 10 (B) and March 10–March 28 (C) are presented. Linear regressions were adjusted between groundwater depth and groundwater depth variation (n = 12 for maize and n = 6 for soybean).

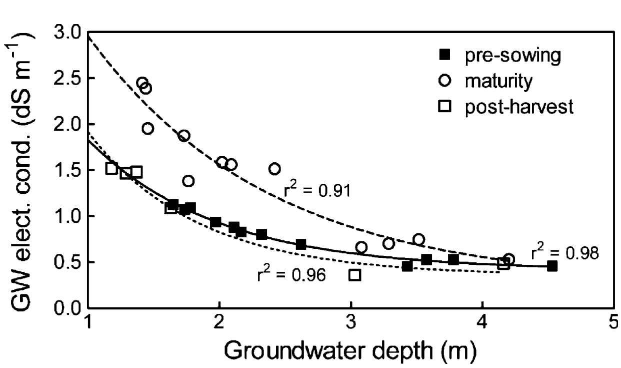

Fig. 6. Groundwater (GW) electrical conductivity (dS m^{-1}) in maize fields and its relation with groundwater depth (m). Groundwater samples were taken before maize sowing (November 11, 2006, n = 12), when maize was close to physiological maturity (April 16, 2007, n = 12), and three months after harvest (September 29, 2007, n = 6). Exponential models were adjusted in the three cases.

suggested by similar groundwater depth vs. groundwater electrical conductivity relationships in both dates ($p > 0.10$, F-test). When groundwater depth exceeded 3.5 m, however, there was little change in the salinity of ground water from sowing to harvest for maize (Fig. 6), likely because groundwater use by maize was negligible.

Soil salinity also varied strongly with groundwater depth. Salinity levels in the upper ~0.75 m of the soil, assessed by electromagnetic induction, showed increasing apparent electrical conductivity values as the groundwater depth decreased (Fig. 7A, r^2 = 0.88, $p < 0.01$, n = 30). Soils were non-saline (ECa < 0.1 dS m^{-1}) where groundwater depth was > 1.5 m (Fig. 7A), likely because soil salinization is less intense and/or takes place at greater depth, beyond the penetration range of the electromagnetic instrument (McNeill, 1980). In agreement with electromagnetic measurements, soil chemical profiles showed intense soil salinization immediately above the water table (Fig. 7B). Integrating the upper meter of the profile, the soil electrical conductivity of the shallow-groundwater position was significantly higher, on average, than the conductivity of intermediate- and deep-groundwater positions (4.9, 0.9 and 0.7 dS m^{-1} for shallow-, intermediate- and deep-groundwater positions, respectively; $p < 0.01$). Similarly, when the conductivity of the second meter of depth was integrated, the conductivity of the intermediate-groundwater position was 7 times higher than the deep-groundwater position (3.3 dS m^{-1} vs. 0.4 dS m^{-1}, $p < 0.01$).

4. Discussion

We identified a significant and dual (positive/negative) influence of shallow aquifers on rain-fed crops under real field production conditions in the Inland Pampas. A novel combination of groundwater and crop yield monitoring and mapping techniques allowed us to quantify this influence and relate it to the position of the water tables, providing tools to constrain water supply uncertainty and facilitate risk management in the rain-fed production systems that prevail in the region. Reciprocally, crops influenced the depth and salinity of ground water by altering recharge and discharge fluxes and modifying solute transport and accumulation, highlighting the coupled nature of groundwater–crop interactions in the study region.

4.1. Groundwater effects on crop performance

To effects of ground water on crop productivity shifted according to water table depth and climatic conditions. The analysis of crop yields vs. groundwater depth suggested a well-defined function with common patterns among crops and throughout growing seasons (Figs. 3 and 4). We recognized a first zone in which yield increased from extremely low to maximum values as water table depths increased. This abrupt response is likely driven by the deleterious effects of waterlogging, root anoxia and/or salinity on the studied crops (Reicosky et al., 1985) (Fig. 3). Next, we identified a second zone of maximum yields that remain stable as the water table deepened. Within this ~1-m-thick optimum zone, we speculate that groundwater use by crops is limited only by crop water demand, as opposed to capillary transport rates, thus resulting in yields that are insensitive to water table depth shifts (Kang et al., 2001; Jobbágy and Jackson, 2004; Kahlown et al., 2005). A third zone in which yields decline gradually with water table depth (Fig. 3) suggested that capillary transport rates became increasingly lower than crop water demand rates with depth, creating an asymptotic yield decline towards what may be the expected production under no groundwater contributions (Ragab and Amer, 1986; Raes and Deproost, 2003; Ayars et al., 2006). This sequence of decreasingly negative

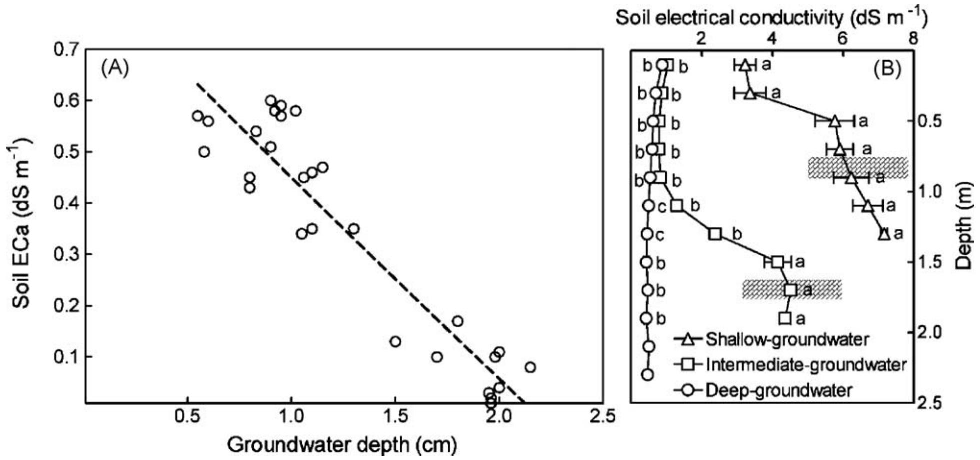

Fig. 7. Soil electrical conductivity (dS m^{-1}) beneath a maize field and its relation to groundwater depth (m). The association between apparent soil electrical conductivity (ECa), measured using an electromagnetic induction soil conductivity meter (n = 30, integration depth ~0.75 m) and groundwater depth is shown in panel A. A linear model was used (r^2 = 0.88, $p < 0.01$). Groundwater depth corresponds to instantaneous values measured at the moment of the conductivity assessment (~35 days after physiological maturity, 2007/2008 growing season). Panel B shows soil electrical conductivity profiles under shallow-, intermediate- and deep-groundwater positions (mean ± S.E., n = 4 per site) during R3 phase (2007/2008 growing season). The shaded areas indicate the range of water level fluctuations through the growing season. Letters show significant differences ($p < 0.05$) among sites (Duncan's test).

(zone 1), highly positive (zone 2), decreasingly positive (zone 3) effects of groundwater on crops as water table depths increase is, to our knowledge, not explicitly incorporated into crop models, making their predictions unreliable under shallow water table conditions. Attempts to represent the positive effects in models (zone 2 and 3) have been made (Liu et al., 1998), yet the inclusion of negative effects (zone 1) and the representation of water table depth shifts in the models are still pending aspects.

Although the yield vs. groundwater depth relationships are robust and consistent across seasons, crop species and fields, measurement errors as well as natural variability may introduce spurious variability that should be considered. In the first case, errors in the measurements of crop yield, terrain elevation and their respective geographic location could have introduced artificial variability in both axes of the analysis (Fig. 3). In addition, our groundwater depth mapping routine could have introduced additional variation into the x-axis (Fig. 3) if additional factors not captured by the analysis, such as shifts in the hydrological properties of deeper sediment layers, had played a significant role. Finally, crop yield may have responded to other sources of heterogeneity such as variable pressures of weeds, pests, and diseases; variability or lack of precision in sowing, fertilization and herbicide applications events, soil fertility/salinity patchiness and/or groundwater salinity variation. Of all of these error sources, those that could show some correlation with topography, such as temperature, soil texture, and run-off, are of special concern for our study. In the case of temperature, the occurrence of early or late frost affecting only lowlands and confounding the effects that we attributed to waterlogging can be discarded in the case of soybean and maize, since temperatures throughout the two growing seasons of these crops never reached less than 6 °C, making bottomland frosts unlikely. In the case of soil texture, high crests have higher sand content than the rest of the landscape, which may confound the effects that we attributed to the lack of access to ground water, curtailing yields, with those of low water-holding capacity. Notably, however, if texture would have driven these effects we would have seen a non-linear effect of topography with small yield drops towards intermediate-depth water tables and steep ones in the extreme of the water table depth gradient, which corresponds to the highest crests. To the contrary, we observed a linear yield drop that had its initiation well below the highest crests. Finally, run-on/off patterns may play a role dictating crop yields and groundwater dynamics as well. This effect cannot be discarded in bottomland positions but is likely unimportant in most of the groundwater depth span, which corresponds to slope positions.

Although a small proportion of the fields studied was negatively affected by waterlogging during the study period (i.e. the surface affected by high water table levels), economic losses could be very sensitive to slight water table rises, given the sharp yield-groundwater depth function that we observed (Fig. 3) (Cavazza and Rossi Pisa, 1988; Kahlown et al., 2005). In the last growing season of 2007/2008, ~16% of the farm studied experienced negative effects from waterlogging; however, a water table rise of 50 cm would propagate negative effects to almost half of the farm. The balance of positive and negative groundwater effects on crops may shift towards the latter in wetter areas of the Pampas (~1000 mm year^{-1}) with higher groundwater levels and lower climatic water deficits (Viglizzo et al., 2009). Through time, the significant positive trend in annual precipitation (~2 mm year^{-1} for the last 96 years) may have the same effect, posing thus a serious risk for agricultural systems of the flat Inland Pampas. Continuous, regional monitoring of groundwater levels could help greatly to minimize any harmful effects of this trend through mitigation strategies, which could certainly include management of evapotranspiration through land use changes.

The effect of shallow ground water that we observed locally across the groundwater depth gradient at El Consuelo farm seems to be mirrored regionally by grain yield records from surrounding counties with and without accessible ground water. We analyzed grain yield data obtained from the records of the Secretaría de Agricultura Ganadería Pesca y Alimentación (The National Secretary of Agriculture and Fishery, SAGPyA, http://www.sagpya.mecon.gov.ar/) for the period 1998–2008 at the county level (department). Under similar climatic conditions, geomorphology determines the presence of shallow water tables in some of these counties but not in others (Godagnone et al., 2002). The temporal variability of crop yields in the last 10 years was significantly lower in counties with accessible ground water (n = 6) than in the rest (n = 5), with interannual coefficient of variation for maize, soybean, and wheat yields being 16%, compared to 23%. In addition, wheat yields in the last two growing seasons, characterized by marked differences in rainfall amounts, contrasted in these two groups of counties. In counties without groundwater access, wheat yield dropped by half in the driest growing season (1.5 Mg ha^{-1} vs.

3.1 Mg ha^{-1} in 2006/2007 and 2007/2008, respectively), whereas in counties with groundwater access wheat yield was similar (3.4 Mg ha^{-1} vs. 3.7 Mg ha^{-1}, for 2006/2007 and 2007/2008, respectively). This analysis suggests that, at the regional level, ground water plays a key role in supplementing rainfall deficits and stabilizing crop production.

4.2. Crop effects on ground water

Crops exerted a strong control on groundwater dynamics through their influence on recharge and discharge fluxes, as shown in our analysis of groundwater level changes. Through the regulation of soil moisture content and, hence, rainfall drainage towards the water table, crops influence groundwater recharge (Wang et al., 2008), as suggested by the recharge differences observed across fields subject to contrasting crop water demand (Fig. 5A and C). In addition, crops affected groundwater levels through groundwater consumption, with intensifying discharge fluxes as the water table depth decreased (Fig. 5B). This close groundwater–vegetation link suggests a promising avenue to regulate rising ground water, and the resulting waterlogging and flooding episodes, through land use and vegetation management. However, hydrological models, of crucial value to evaluate this possibility, need to improve their representation of vegetation control over recharge and discharge incorporating the relationships that we have introduced (Gulden et al., 2007).

Crops also affected groundwater and soil chemistry (Figs. 6 and 7), increasing salinization and perhaps triggering a long-term negative feedback on crop production. The vertical pattern of soil electrical conductivity, showing increased salinity in the vicinity of the water table, may be explained by the combination of groundwater consumption and solute exclusion by crop roots (Jobbágy and Jackson, 2004). This solute accumulation process may increase salinity up to levels that hinder further groundwater uptake if no mechanism acts to remove accumulated salts (Nosetto et al., 2008). Although some flushing may have occurred during periods of high rainfall and low evapotranspirative demand (Figs. 5 and 7), groundwater salinities > 7 dS m^{-1}, reached in shallow water table areas in our study, may certainly curtail crop production since this salinity in irrigated conditions would reduce maize and soybean potential yields by 60% and 30%, respectively (Carter, 1982). By contrast, wheat, a moderately salt tolerant crop, would produce near-normal yields (Carter, 1982). In addition to salinity shifts, groundwater consumption also led to strong soil and groundwater alkalinization (pH increased from 6.3 to 10.1, data not shown), which may be detrimental for some crop species (e.g. soybean, Prasad and Power, 1997) and exert a negative influence on the bioavailability of critical nutrients like phosphorus (Marschner, 1995).

Independent approaches provided convergent estimates of groundwater consumption by maize at our site, providing some confidence in our conclusions. A chloride mass balance (Thorburn et al., 1995; Nosetto et al., 2007), based on the net gain of chloride at the intermediate groundwater position (experiencing net discharge) compared with the deep groundwater position (experiencing net recharge), and on the concentration of chloride in ground water, suggests a ground water consumption of 210 mm in the intermediate depth position in the maize field during the driest growing season. In this period the water table dropped on average ~0.40 m between early vegetative stages and physiological maturity. Assuming that this drop is driven by the phreatic discharge of vegetation and that lateral groundwater fluxes are negligible, as suggested by low topographic and piezometric gradients in the region, this water table decline suggests an average consumption of 140 mm of ground water (specific yield = 0.35 for loamy sand soil according to Loheide et al., 2005). Considering a typical water-use efficiency of maize for the study region (15 kg ha^{-1} mm^{-1}, Gregoret et al., 2006) and the yield differences observed across the groundwater depth gradient, maize consumed on average 340 mm of ground water, representing 55% of the total crop water consumption. While independent analyses of the chloride balance and groundwater level indicate the amount of net groundwater discharge by the crop (recharge flux–discharge flux), the estimate based on yield increases suggests gross groundwater discharge figures, accounting for total consumption during the growing season. Our estimates matched observations in other regions (Kahlown et al., 2005; Mueller et al., 2005) and highlight the relevance of direct groundwater consumption by crops in shallow water table environments. In the Pampas, field estimates suggest that the contribution of ground water to alfalfa water use may reach up to 340 mm year^{-1} and 40% of the annual water use (Dardanelli and Collino, 2002).

5. Conclusion

Our analysis shows that in flat humid landscapes, such as the Pampas, crops and shallow ground water are closely connected and influence each other. This two-way link, often ignored by crop scientists and land managers, poses both opportunities and risks for agricultural systems. On the one hand, groundwater consumption by crops can improve crop yields and may help to regulate groundwater levels. On the other hand, waterlogging and salt accumulation may threaten crop performance both short- and long-term and reduce the area available for cultivation. A better understanding of the complex interactions between shallow ground water and crops will help to take advantage of such opportunities, while minimizing their associated risks. Facing a rising demand for food products (Pinstrup-Andersen et al., 1999), an intensification of agricultural systems (Hall et al., 1992), and an increasing trend of climatic extremes (Barros et al., 2006), fundamental knowledge of the interaction between groundwater depth and crop productivity should be useful in many agricultural regions of the world.

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