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# Higher water-table levels and flooding risk under grain vs. livestock production systems in the subhumid plains of the Pampas

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ABSTRACT

Although the strong influence of vegetation shaping the hydrological cycle is increasingly recognized, the effects of land-use changes in very flat regions (i.e., hyperplains, regional slope <0.1%) are less understood in spite of their potentially large magnitude. In hyperplains with sub-humid climates, long-lasting flooding episodes associated to water-table raises are a distinctive ecohydrological feature and a critical environmental concern. We evaluated the hydrological impacts caused by the replacement of livestock systems, dominated by perennial alfalfa pastures, by grain production systems, dominated by annual crops, that have been taking place in the Pampas (Argentina). For this purpose, we combined remote sensing estimates of vegetation transpiration and surface water coverage with long-term (1970–2009) hydrological modeling (HYDRUS 1D), and water-table depth and soil moisture measurements. The NDVI derived from MODIS imagery was 15% higher in dairy systems than in grain production ones, suggesting higher transpiration capacity in the former (852 vs. 724 mm $y^{-1}$). Even higher contrasts were found among individual cover types, with perennial pastures having the highest NDVI and transpiration potential rates (0.66 and 1075 mm $y^{-1}$), followed by double winter/summer crops (0.55 and 778 mm $y^{-1}$) and single summer crop (0.45 and 679 mm $y^{-1}$). Significantly deeper long-term average water-table levels in dairy system compared to single and double cropping (4 m, 1.5 m and 2.1 m, respectively) were suggested by the hydrological modeling and confirmed by field observations at nine paired sites (pasture vs. cropland, $p < 0.05$) and two transects. At two additional paired sites, continuous water-table depth monitoring with pressure transducers, provided insights about the mechanisms behind these contrasts, which included enhanced groundwater recharge in the cropland and direct groundwater discharge by the pasture. Soil profiles, being notably drier under pastures (316 vs. 552 mm stored at 0–3 m depth, $p < 0.05$), prevented the recharge episodes experienced by agricultural plots after an extraordinary rainy period. Our study highlights the key role of land-use on the hydrology of subhumid hyperplains, supporting the linkage of groundwater level raises and flood frequency and severity increases with the expansion of grain production systems in the Pampas. Given the spatial connectivity imposed by the hydrologic system and the strong association observed between the plot water balance and regional flooding, it is highly relevant to improve the quantification of the hydrological responsibility and interdependence of land use decision across plots and farms. This further step should support territorial policies that optimize the hydrological services of the region.

## 1. Introduction

There is growing evidence about the strong imprint that vegetation has on hydrology and, as a result, about the effect that profound land-use changes can have on the water services of ecosystems. Some of the most striking examples come from the deforestation of woody watersheds, where increased flash floods and erosion are among the most harmful consequences (Bradshaw

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et al., 2007), or the establishment of tree plantations in non-woody watersheds, where decreased water yield has been an issue of concern (Farley et al., 2005). In very flat sedimentary landscapes (i.e., hyperplains, regional slope <0.1%), however, in which river networks are absent or poorly developed, and vertical water fluxes dominate over horizontal ones, the hydrological outcomes of vegetation changes are less evident and are usually mediated by the groundwater system (Usunoff, 2009). Hyperplains, and particularly those with sub-humid climates, tend to display long-lasting flooding episodes associated to water-table raises that are a distinctive ecohydrological feature and a critical environmental concern for their inhabitants (Aragón et al., 2010; Lóczy, 2010). Understanding the role of vegetation and land-use regulating these highly dynamic hydrological systems becomes increasingly important in the context of growing climate variability and competing ecosystem service awareness.

Hyperplains cover a large area of the planet and particularly those with sub-humid climate play an important role as global food sources (Imhoff et al., 2004; Fan et al., 2013). However, the flat topography and low river density of these landscapes combined with a subhumid climate define a fragile hydrological equilibrium where dry years lead to deep water-tables and droughts, while water excesses easily turn into flooding episodes (Viglizzo and Frank, 2006; Aragón et al., 2010) which rather than displaying high frequency and short duration (i.e., flash floods), show slow initiation and even slower retraction times (i.e., slow floods). The hyperplains of the Pampas and Chaco in Argentina, central Canada, eastern Hungary, northern Caspian basin, western Siberia, and northeastern China among others, are all areas that share this particular topographic/climatic setting (Jobbágy et al., 2008). Under poor river networks and low topographic gradients, flood retraction is mostly driven by direct evaporation from sporadic lagoons and water bodies, soil evaporation and transpirative discharge by vegetation when water-tables are shallow enough to be reached by root systems (Aragón et al., 2010; Florio et al., 2014). Vegetation thus plays a key role on the hydrology of these landscapes, as it can affect not only groundwater recharge rates (Kim and Jackson, 2012), as in most landscapes, but discharge rates as well (Nosetto et al., 2007).

The Argentinean Pampas is a characteristic hyperplain with subhumid climate where recurrent floods and drought episodes have historically threatened the agricultural production and social welfare (Viglizzo and Frank, 2006). The Pampas, extending across 600,000 km$^2$ of temperate Argentina, is one of the most important food-producing regions of the world (Hall et al., 1992). The region was originally dominated by native grasslands, and since the late 19th century, a livestock industry started growing, based firstly on natural grasslands and incorporating alfalfa pastures later. With the arrival of European immigrants in the 1880's and the development of the railroad network, a grain cropping culture started expanding in the Pampas which coexisted with the livestock industry under a grain crop-pasture rotation system (Hall et al., 1992). In the last two decades, however, a widespread replacement of livestock systems by grain production systems is taking place, motivated principally by the combination of a low profitability of beef industry and high grain price (Viglizzo et al., 2009). Extensive livestock activities (cow-calf operation) moved to other regions that have marginal suitability for cropping, while more intensive livestock activities (dairy and steer fattening) could still be found in the Pampas but in a much lesser extent than in previous decades.

The expansion of grain production systems over mixed livestock-grain systems involved an extensive replacement of perennial pastures, dominated by alfalfa, by annual crops (Paruelo et al., 2006). For instance, the area of perennial pastures declined from 4.6 million ha in 2001 to 2.6 million ha in 2005 in Buenos Aires province (INDEC, www.indec.gov.ar). By contrast, the area covered by annual crops increased by 30% in the same province, from 8.5 million ha for the period 1996–2000 to 11 million ha in 2011–2012, being soybean (50%), wheat (20%) and maize (15%) the dominant crops (MAGPyA, http://www.minagri.gob.ar). Alfalfa pastures have strong structural and functional contrasts compared to annual crops which include deeper root systems and steadier leaf areas (Ridley et al., 2001; Keating et al., 2002). While the lower leaf area of annual crops may result in higher soil evaporation rates (Nosetto et al., 2012), studies show that the higher transpirative capacity of alfalfa pastures compensates for these differences, generating higher evapotranspiration rates that can exceed by 30% those of annual crops (Ridley et al., 2001; Keating et al., 2002). In addition, alfalfa shows higher tolerance to salinity than some crops (e.g., maize and wheat, Bresler et al., 1982).

In this paper, we evaluated the hydrological impacts caused by the replacement of mixed livestock-grain production systems by systems exclusively devoted to grain production across a range of nested spatial scales in the Inland Pampas region of central Argentina, focusing on the water-table dynamics and flooding. We hypothesized that the replacement of mixed systems, dominated by alfalfa pastures, by grain production systems leads to shallower water-tables and increases the risk of flooding. The shallower rooting system and lower leaf area of annual crops compared to alfalfa pastures, together with the presence of fallow periods with no vegetation cover, will reduce transpiration rates and increase soil moisture, which would translate into increased aquifer recharge. In addition, the reduced transpirative capacity, rooting depth and tolerance to salinity of annual crops (e.g., maize and wheat), will constrain direct groundwater discharge in comparison with alfalfa pastures. Consequently, shallower water-tables and higher soil moisture levels under annual crops will reduce the capacity of the system to buffer water excesses, increasing the frequency of flooding episodes in the long term.

## 2. Materials and methods

### 2.1. Study region and study sites

We performed our study at the vicinity of the town of Trenque Lauquen (Buenos Aires province, Argentina), located in the core of the Flat Inland Pampa. The region was covered by eolian sediments that were shaped during the last glaciations (Iriondo, 1999). The vast majority of soils developed from fine sand and silty sediments deposited during the late Quaternary (E1 and E3 formations, according to Tricart, 1973). In most cases, soil profiles were fully developed from one of the two materials (E1 or E3) resulting in Entic and Typic Hapludolls. It is also common to find the contact between these two materials within the top meter of soil profiles, often in the form of a Paleo B horizon (thapto-argilic or thapto-natric Hapludolls). Generally, it is difficult to differentiate the two units because of their similarities in terms of mineralogy and grain size; however, in the Paleo B cases, where the E3 material suffered illuviation and erosion before the deposition of E1 materials the differentiation becomes clearer (INTA, 1989).

The landscape is a very flat plain with a regional slope <0.05% where sediments deposited by SW–NE winds favored the formation of sand dunes ridges perpendicular to this orientation (Jobbágy et al., 2008). Due to this configuration of the landscape, soil depth is variable, being deeper than a meter in most of the landscape (~92%), but reduced to ~50–60 cm in local depressions located between dunes ridges (INTA, 1989).

The region was originally occupied by native grasslands (Soriano et al., 1991) that were subject to extensive cattle grazing until the beginning of the twentieth century when the onset of cultivation took place. Since that time, the rotation of rainfed annual crops (mostly maize, sunflower and wheat) with perennial alfalfa pastures was widespread, with both types of covers occupying similar areas in mixed livestock-cropping farms. In the last two decades, however, technological and market changes have favored the expansion of annual crop cultivation (including a growing fraction soybean) which displaced livestock production to other regions rapidly reducing the area under pastures (Viglizzo et al., 2009).

The climate of the study region is sub-humid and temperate, with a mean annual temperature of 15.7 °C and a rainfall average of 950 mm $y^{-1}$ (1970–2009). Mean annual FAO reference evapotranspiration is 1174 mm $y^{-1}$ (1970–2009). The last large flooding episode in the plain took place in 2001, when the water-covered area increased from 3% to 28% (Aragón et al., 2010). After that flooding peak, the water covered area retracted up to the initial levels, which persisted until the initiation of this study. The subhumid climate and the extremely flat topography determine shallow water-tables (<5 m of depth) and the presence of permanent lagoons and wetlands throughout the landscape (Aragón et al., 2010).

We performed this study by using complementary methodologies and across different spatial scales. We quantified, through MODIS satellite images, the potential transpiration at the farm and plot scales and, through classification of Landsat satellite images, we characterized the flooded area of the region and its relationship with water-table levels. Complementary, we used a hydrological model to simulate long-term water balance components and water-table depth in dairy, single summer cropping, and double winter/summer cropping systems. The field work involved water-table depth measurements and soil sampling for moisture analysis in crop and pasture plots.

### 2.2. Remote sensing

We used the normalized difference vegetation index (NDVI) derived from MODIS imagery to quantify the consumption of water by the vegetation. A close association between satellite-derived vegetation indexes and plant transpiration has been documented in different, dry to subhumid regions of the world (Running and Nemani, 1988; Contreras et al., 2011). In this paper, we characterized the seasonal dynamic of the NDVI at the farm and plot scales.

At the farm scale, we selected nine large areas (200–500 ha in size) exclusively devoted to dairy ($n = 3$) and grain production ($n = 6$). With this analysis, we aimed to integrate all the typical land covers that coexist in each one of these productive systems. At the plot level, we selected 39 positions that were completely occupied by a single vegetation type. Selected plots were 30–100 ha in size and corresponded to alfalfa pastures ($n = 19$), single summer cropping (maize and soybean, $n = 12$), and double winter–summer cropping (wheat/soybean, $n = 8$) covers. For the period 2008–2012, we used the MOD13Q1 product (collection 5), which represents a 16-days NDVI composite with a pixel size of 250 m.

### 2.3. Hydrological modeling

To evaluate the effects of the productive system on water fluxes and water-table dynamic in the long term, we used the hydrological model HYDRUS 1D (Šimůnek et al., 2005). This model simulates the transport of water based on the Richard's equation and incorporates a sink term to account for water uptake by vegetation. With these modeling exercises, we did not aim to reproduce the actual field conditions but to understand the effect of the typical sequence of crops of each productive system on water-table dynamics. Given this purpose and considering the local variability in terms of soil types and landforms imposed by the sand dunes landscape, we defined a flow domain of 20 m of depth encompassing a single sandy loam soil layer, which is the dominant soil texture in the region covering almost half of the area according to soil maps (INTA, 1989). Although in local depressions, the thickness of this homogenous layer is lower and soils may have higher clay content and natric horizons in some cases, these exceptional situations represent a low fraction of the landscape (~10%). By contrast, high topographic positions with a thick homogenous top layer are the dominant landform, covering 56% of the area (INTA, 1989; INTA-SAGyP, 1990). While the selection of a single representative soil profile and a unique landscape position is a simplification of the study problem that do not take into account the spatial variability in terms of geology, geomorphology and soils of the study region and prevents exact quantitative regional estimates, it also offers useful insights about the integrated effects of land-cover on the hydrological system through extended times and complements the other observational approaches used in this work. However, it should be aware that the hydrological effects of the land-use changes that we simulated here may differ from situations with different soil, geological and geomorphologic conditions (e.g., depressions with natric subsoils; soils with thapto horizons), so that, the results obtained in this section would not be extrapolated to those situations. It also worth noting that these local depressions are not usually cultivated because of the poor soil conditions and they are usually devoted to cattle grazing based on natural grasslands.

Hydraulic properties (van Genuchten, 1980) were determined with the pedotransfer functions available in the Rosetta software (Schaap et al., 2001) and defined for the sandy loam textural class, which was confirmed by particle size distribution analysis on soil samples of study sites and is the dominant class of the study region, covering ~47% of landscape (INTA, 1989; INTA-SAGyP, 1990). Daily values of precipitation, potential transpiration and potential evaporation were defined as upper boundary conditions, and a zero flux condition was defined for the lower boundary. Water was allowed to build up in the soil surface up to a maximum height of 10 cm and beyond this limit, water excesses were removed from the system. By defining these conditions, we aimed to represent the closed basin nature that characterizes the study region, where water excesses may lead to seepage flooding and where the regional evacuation of these water excesses may only become relatively relevant during extreme flooding episodes (Aragón et al., 2010). Horizontal water fluxes were not simulated. Simulation period extended for 40 years (1970–2009). The water-table at the beginning of the simulation period was set at 5 m depth, and the results from the first four years of simulation (1970–1973) were excluded from the analysis.

Three different productive systems were simulated in HYDRUS: dairy, continuous single summer cropping and continuous double winter/summer cropping systems. The dairy system was represented by a 6-year crop rotation that involved four years of alfalfa pasture and two years of single summer crops. The different vegetation types were represented in HYDRUS by changing the maximum rooting depth, potential transpiration, and potential evaporation. For summer and winter crops, we considered that maximum rooting depth increased linearly at a rate of 0.18 cm per degree-day from sowing to a maximum value of 2 m (Dardanelli et al., 2008). In this calculation, we used a base temperature (above which degree-days are counted) of 8 °C and 0 °C for summer and winter crop, respectively (Dardanelli et al., 2008). For alfalfa, we considered that maximum rooting depth increased linearly during the first two years following sowing up to a maximum depth of 3.5 m and then it remained constant. We defined maximum rooting depth and root growth rate of alfalfa conservatively and based on direct observations of alfalfa roots distribution in soil profiles and previous works (Borg and Grimes, 1986; Collino et al., 2005). Root distributions were assumed to decline linearly from the surface to the maximum rooting depth in all vegetation types. The same Feddes et al. (1978) function was used as root water uptake model for all crops.

Potential transpiration and potential evaporation were determined as the product between the reference evapotranspiration (ETo) and the basal crop coefficient (Kcb) and evaporation coefficient (Ke), respectively (Allen et al., 1998). Penman–Monteith potential evapotranspiration was estimated using temperature, humidity, wind speed and solar radiation data, which together with rainfall data were registered at the city of Trenque Lauquen (~18 km from study fields) (Allen et al., 1998). Kcb values were obtained scaling NDVI values from MODIS imagery between minimum and maximum Kcb values of 0 and 1.15, respectively (Allen et al., 1998; Nosetto et al., 2012). Ke values were computed as the difference between the maximum value of 1.15 and the Kcb. This value was later corrected according to the vegetation cover fraction which was derived from the NDVI data (Carlson et al., 1995; Allen et al., 1998). Potential transpiration and potential evaporation values are transformed to actual values in HYDRUS by affecting them by a stress factor controlled by soil moisture levels.

### 2.4. Water-table depth survey

The effects of the productive system on the water-table levels were assessed with three complementary approaches. Firstly, we performed two cropland-pasture-cropland transects where we measured the water-table depth in May 2013. In one case, we measured the water-table depth at seven positions along a 1 km-long transect and in the other, at four positions along a 0.5 km-long transect. Measurements were performed following a period of 25 days without rainfall in order to avoid any short term level gradient caused by recharge contrasts.

Secondly, we measured the water-table depth at nine paired sites (perennial pasture-annual crop, sites A–I) in November 2010. Sampling points were located ~40 m away from fences. A dry period with 34 mm of accumulated rainfall in the previous month preceded this sampling event and no rainfall was recorded in the previous week. In both sampling approaches, the sampled plots were occupied by pastures or annual crops for at least two years preceding sampling.

Thirdly, we obtained continuous records of water-table depth (30-min intervals between June 2011 and May 2013) in one additional site (site J) with paired alfalfa and cropland plots. These contiguous plots were cultivated in a pasture-crop rotation, where three or four years of perennial alfalfa pastures were followed by two years of annual crops. Water table depth monitoring in the pasture encompassed its second and third year of life, whereas in the agricultural plot, it included the initial fallow period that followed the elimination of the three-year-old pasture with herbicides. During the monitoring period, this cropland plot was occupied by maize (October 2011–February 2012), oats (March 2012–October 2012) and maize again (December 2012–April 2013). After a short fallow period, alfalfa was sown again in May 2013. Monitoring wells were located at 80 m away from the pasture-cropland edge. We registered water-table levels at high vertical (1.4 mm) resolution using automated pressure transducers with built-in dataloggers (HOBO water level logger; Onset Computer Corporation, Bourne, Massachusetts, USA).

In order to evaluate the possibility of direct groundwater discharge by vegetation, we also registered water-table levels at 30-min intervals in two additional paired plots (site K, alfalfa pasture and maize) where the water-table was shallower (~3 m). Monitoring extended during 24 days in December 2011 with maize transitioning from advanced vegetative stage to silking and the alfalfa pasture having an age of 20 months. At this site, where diurnal water-table fluctuations were observed in the pasture but not in the cropland, we estimated daily groundwater use by the pasture through the diurnal water-table fluctuations approach proposed by Engel et al. (2005). We used the estimate of specific yield under fluctuating conditions proposed by Loheide et al. (2005) for sandy loam soils (SY = 0.17). Given that local topographic variations (e.g., dunes ridges vs. depressions) may generate differences in water-table depth not associated with the vegetation cover, we measured at all paired sites and transects the ground elevation differences between sampling positions in order to correct water-table depth measurements and to describe the hydraulic gradients.

### 2.5. Soil moisture measurements

We sampled soils for moisture analysis at sites A–C during October 2011. Perennial pastures were dominated by alfalfa (*Medicago sativa*) which was accompanied by white clover (*Trifolium repem*) and bromegrass (*Bromus unioloides*). Agricultural plots were devoted to the cultivation of summer crops (soybean, maize and sunflower) and in some cases they were also cultivated with winter crops (wheat and barley). Both paired plots at each site were located on the same topographic position and shared the same soil type.

Soil samples were collected every 0.5 m to a depth of 3 m. At each plot, we randomly located three soil pits. Soil sampling points were spaced ~10–15 m apart and ~40 m away from fences to avoid edge effects. Moisture content was determined gravimetrically 1–2 days after sampling (oven drying method) and then converted to volumetric moisture by multiplying by the bulk density. We estimated bulk density based on the sand and clay contents, determined by the hydrometer method (Bouyoucos, 1962), and the pedotransfer functions developed by Saxton et al. (1986), which are available on-line at http://www.pedosphere.com/resources/bulkdensity

Additionally, in order to characterize the seasonal variation of soil moisture, we sampled soils four times every 3–5 months between June 2011 and June 2012 at site J, where we performed continuous water-table depth monitoring. In this case, soil samples were collected every 0.5 m down to the water-table. The sampling period extended during the second year of the pasture. In the crop plot, the first sampling occurred in the fallow period, prior to maize sowing in October 2011. The subsequent sampling occurred during the maize growing season and the following oat growing season.

### 2.6. Quantification of the flooded area

We characterized the variability of the flooded area and its relationship with water-table levels through classifications of 13 individual Landsat images. We classified the flooded area for the period July 2011–May 2013 by a single-band density slicing. For this purpose, we used the mid-infrared Band 5 from TM and ETM$^+$ sensors on board of Landsat 5 and Landsat 7 satellites, respectively. We located the analyzed area at the center of the Landsat scene 227/82 in order to avoid areas of the scene with missing data caused by the Scan Line Corrector malfunctioning. The analyzed area (20 × 10 km) was located 40 km north–west of the sampling sites and it has similar topographic and climatic characteristics as the study area.

## 3. Results

### 3.1. Evapotranspiration and modeled water-table levels

As whole systems, dairy farms displayed higher transpiration than grain production farms. The annual average NDVI, a surrogate of vegetation productivity and water use by vegetation, was 15%

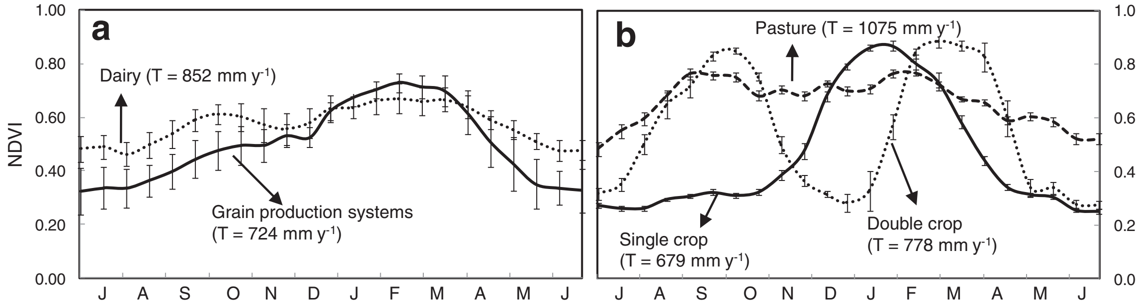

**Fig. 1.** Seasonal dynamic of NDVI derived from MODIS imagery at farm (a) and plot (b) scales, showing the average and standard error for the 2008–2012 period and the annual potential transpiration (T).

higher in dairy systems than in grain production ones (annual mean = 0.57 vs. 0.49, $p < 0.05$, $t$-test) (Fig. 1a). This difference resulted in 128 mm y$^{-1}$(+18%) higher transpiration capacity in dairy systems. Individual cover types showed even higher contrasts than whole systems. The analysis of single plots revealed largest annual average NDVI values for perennial pastures, followed by double crops and then by single crops (annual mean = 0.66, 0.55 and 0.45, respectively) (Fig. 1b).

The modeling exercise suggested that transpiration differences across cropping systems were cancelled by direct soil evaporation contrasts. Long-term (1974–2009) one-dimensional simulations suggested similar evapotranspiration values for dairy rotation and the single (summer) and double (winter/summer) cropping systems, but different partitions between transpiration and evaporation (Table 1). While annual evapotranspiration was just 6% and 4.5% higher in the dairy system than in single and double cropping, respectively, differences increased by 45 and 15% for the transpiration component. By contrast, soil evaporation was 27 and 10% lower in the dairy system than in single and double cropping.

Although similar evapotranspiration rates were suggested by the model for the different systems, they took place under significantly deeper water-table levels in dairy system compared to single and double cropping (Fig. 2a). The mean water-table depth simulated for the period 1974–2009 approached 4 m for the dairy system, but 1.5 and 2.1 m for the single and double cropping systems, respectively. In most of the simulation time (82% of the days), the water-table level was below 4 m of depth in the dairy system and it never reached the soil surface. By contrast in the single cropping system, the water-table level was between 1 and 2.5 m depth half of the time and during 9% of the days the water-table reached the soil surface.

### *3.2. Water-table level observations*

Field observations supported modeling results, showing deeper water table levels under pasture cover. Water-table depth shifted consistently along two cropland-pasture-cropland transects (Fig. 3). The longest transect showed that the pasture sustained a gradient of declining water-table depth from its edge toward its core. Paired measurements at nine sites (crop vs. pasture) also evidenced slightly deeper water-table levels under pastures (Fig. 4) ($p < 0.05$, paired $t$-test), with differences ranging 0.15–0.35 m and averaging 0.2 m for boreholes located 60–100 m apart.

Continuous monitoring at the paired plots of sites J and K showed contrasting water-table level dynamics for croplands and pastures (Fig. 5a) and provided insights about the mechanisms that drive them. At the beginning of the monitoring period (winter 2011, June–August), water-table levels at both monitoring wells had similar behavior, showing a slight water-table rise. This pattern is in agreement with the fact that both plots had similar initial conditions with the alfalfa pasture being 15 months old and the crop plot being briefly in fallow right after an alfalfa pasture was cleared in April 2011. During the first spring months (September–mid October 2011), the pasture showed a water-table decline (−13 cm) that extended until the first rain events, while the water-table rose (+4 cm) in the cropland, suggesting groundwater discharge in the pasture. After a very rainy period (232 mm between November 4–19, 2011, Fig. 5b), the water-table rose 30 cm in the pasture (from 5.1 to 4.8 m) and 110 cm in the cropland (from 5 to 3.9 m), evidencing in this case, higher groundwater recharge in the cropland. During this period, the maximum water-table depth difference between both plots was achieved (90 cm). After water-table level peaked (December 9, 2011), its drop extended until early summer (January 20, 2012) in the pasture but continued until late summer (March 8, 2012) in the cropland. During fall and winter of 2012, water-table showed a steady rose in both plots with level differences ranging 15–25 cm, in agreement with differences in water-table levels observed at the transects and the rest of the paired sites (Figs. 3 and 4). After a very rainy spring (512 mm between October 15 and December 10, 2012), water-tables showed sharp ascents in both plots but still notably higher in the cropland than in the pasture (+100 vs. +60 cm). The following summer (January–March, 2013) was very dry (207 mm, 43% below the average) and water-tables dropped in both plots and depth contrasts approached 20 cm.

Diurnal water-table fluctuations were observed in an alfalfa plot during December 2011 but not in the adjacent maize plot, evidencing direct groundwater discharge by the pasture with the water table at 3.4–3.6 m of depth (Fig. 6). During the 24-days monitoring period, the average water-table fluctuation in the pasture approached 1.3 cm and fluctuations >1 cm were observed in 63% of the days. By considering the specific yield of sandy loam

**Table 1**
Annual transpiration, evaporation and evapotranspiration simulated with HYDRUS 1D for dairy, single summer and double winter/summer cropping systems.

| | Transpiration (mm y$^{-1}$) | | | Evaporation (mm y$^{-1}$) | | | Evapotranspiration (mm y$^{-1}$) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Mean | Max | Min | Mean | Max | Min | Mean | Max | Min |
| Dairy system | 595 | 873 | 319 | 348 | 455 | 243 | 943 | 1251 | 576 |
| Single summer cropping | 409 | 546 | 16 | 479 | 782 | 319 | 888 | 1030 | 737 |
| Double winter/summer cropping | 516 | 643 | 159 | 388 | 640 | 278 | 904 | 1046 | 661 |

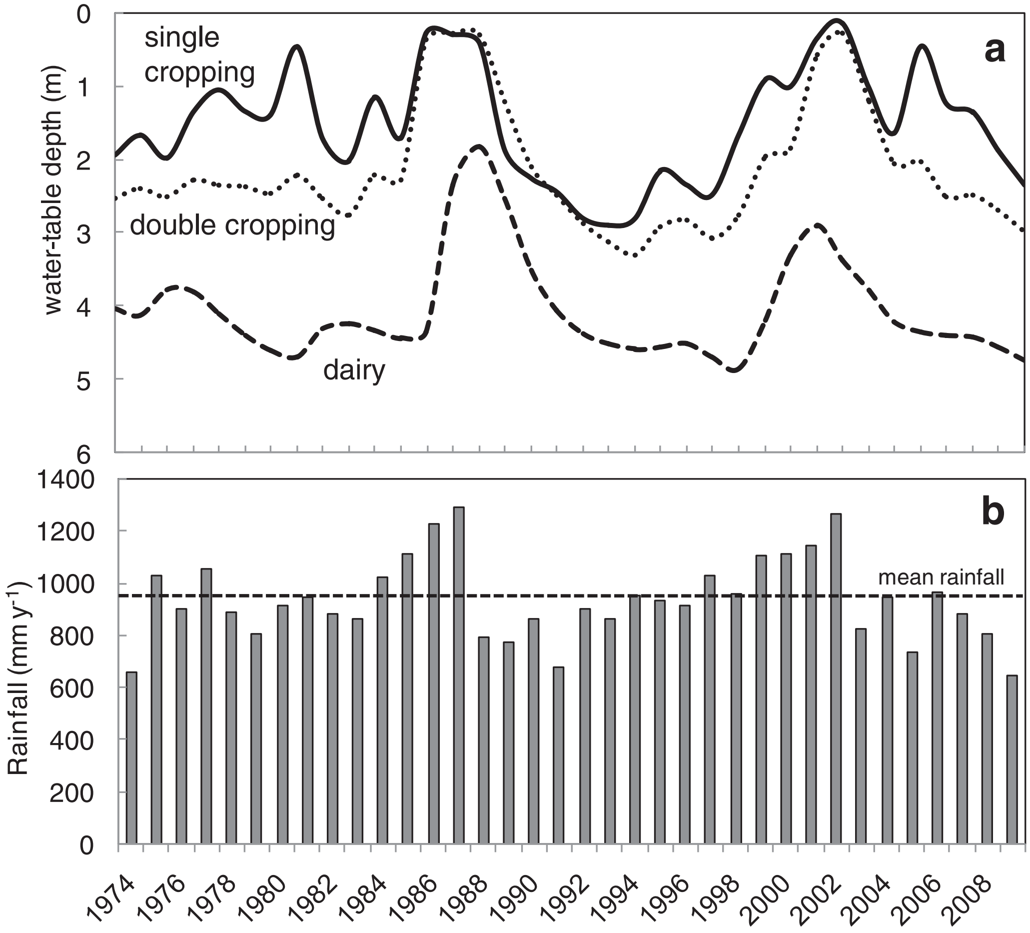

**Fig. 2.** Water-table depth dynamics simulated with HYDRUS 1D (a) for dairy, single summer cropping and double winter/summer cropping productive systems and annual accumulated rainfall (b).

sediments (SY = 0.17, Loheide et al., 2005), we estimated from these diurnal level fluctuations that groundwater uptake by the pasture approached 3.2 mm $d^{-1}$. Taking into account the reference evapotranspiration, the pasture would have obtained about half of its water demand from groundwater during this period. It is important to note that the high salinity of groundwater (electrical conductivity = 7.6 dS $m^{-1}$) did not prevent its consumption by the alfalfa pasture.

### 3.3. Soil moisture observations

Repeated soil moisture measurements between June 2011 and June 2012 at the two pasture and cropland plots of site J showed similar initial conditions but divergent temporal trajectories (Fig. 7). In the first sampling (June 2011), soil moisture profiles showed no significant differences between 2 and 4 m depth (Fig. 7a) and similar water-table depths (~5.3 m, Fig. 5a). However, the cropland soil stored more water (204 vs. 250 mm) in the upper soil at 0–2 m (Fig. 7b), likely responding to rainfall inputs (160 mm) occurred when the plot remains under fallow, after the pasture was eliminated. In the second sampling date in October 2011, soil moisture differences between both plots were evident throughout the whole soil profile (Fig. 7a). Compared to the previous sampling, the first two meters of the pasture soil dried (−54 mm), and no significant changes were observed at greater depths. By contrast, the cropland soil gained water throughout the whole soil profile (+180 mm, Fig. 7c), suggesting water replenishment of the soil profile not only by rainfall (140 mm between both sampling dates) but by capillary groundwater upflux in the lower profile as well. The storage of soil water was ~200 mm and ~300 mm higher in the cropland than in the pasture down to 2 and to 4 m of depth, respectively (Fig. 7b and c). Complementary measurements at three additional paired sites (sites A–C), performed during the same period (October 2011) confirmed the previous pattern, showing that cropland soils stored ~236 mm more water down to 3 m of depth compared to their adjacent pastures ($p < 0.05$, paired *t*-test).

In March 2012, after a very rainy period (720 mm since previous sampling), the water content of the pasture increased in the top meter of the profile and below 3.5 m of depth, responding to rainfall inputs and to a ~40 cm water table level rise, respectively (Fig. 7a), with a dry zone remaining between 1.5 and 3 m of depth. In the cropland, a uniform moisture increase took place throughout the whole profile. The last sampling, on June 2012, was also preceded by a rainy period (287 mm, since previous sampling) that caused a further water-table level rise of ~50 cm. At this time, while the cropland showed a uniform high moisture content from the surface down to the capillary front, the pasture still maintained a dry zone between 2 and 3 m of depth.

### 3.4. Water-table level and flooding

Groundwater levels and flooded area were closely associated in the study region (Fig. 8a). At the beginning of the study period, when the water tables were at its deepest position, the fraction of the landscape covered by water was at its minimum, reaching only

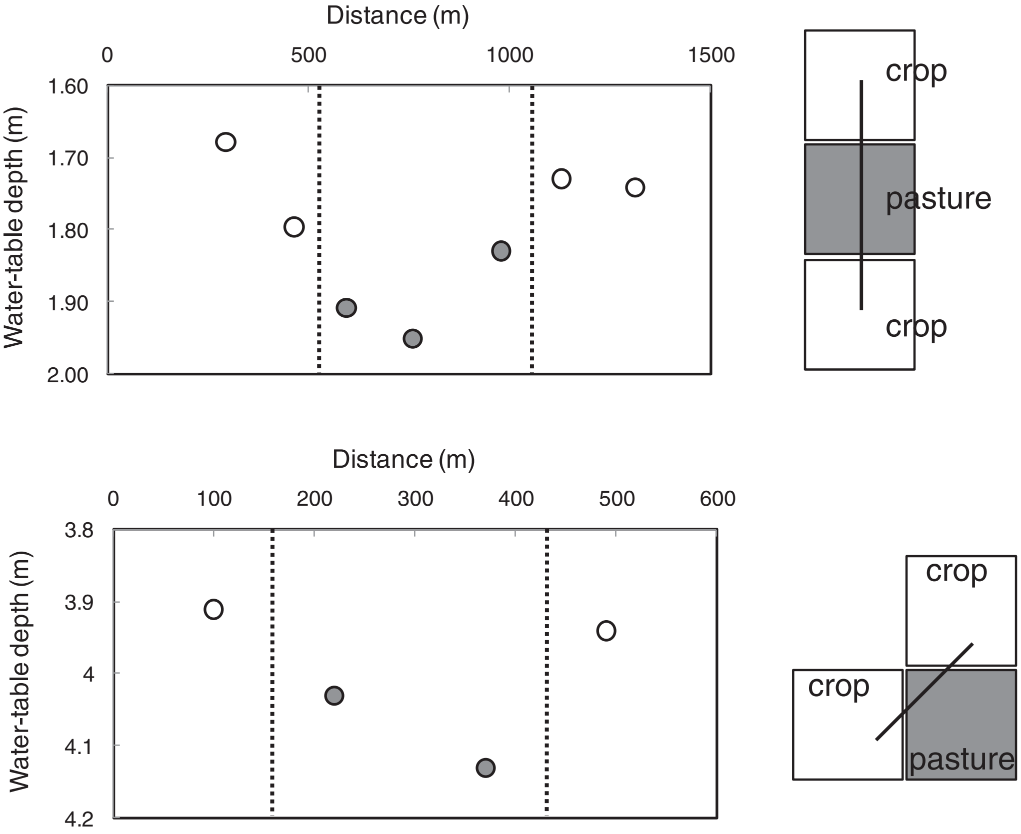

**Fig. 3.** Water-table depth measured in two crop-pasture-crop transects.

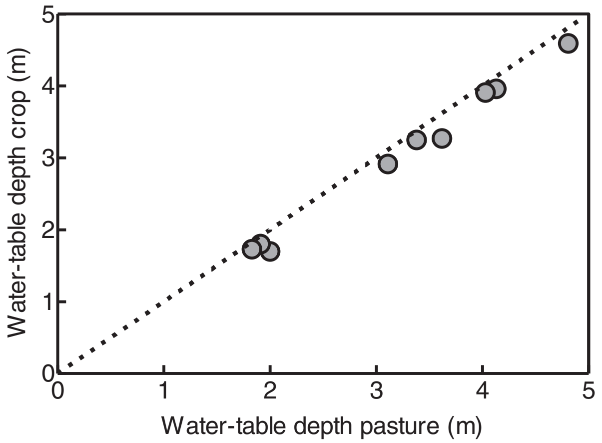

**Fig. 4.** Water-table depth measured at nine paired plots (pasture vs. crops), with the dashed line indicating the 1:1 line.

3% of the area (Fig. 5a). Starting in spring 2011, flooded area expanded steadily, accompanying the water-table level rise, up to a remarkable value of 33.5%, achieved in December 2012. After that flooding peak, the water covered area decreased sharply down to 15% during the dry summer of 2013. A visual comparison of two contrasting times in September 2011 and September 2012, evidenced that flooding progressed with the development of several new water bodies and to a lesser extent through the expansion of permanent water bodies (Fig. 8b). Given the large magnitude of this flooding episode, the new water bodies not only occupied the lowest landscape positions but they extended toward higher topographic areas occupied by annual crops. The relationship between water-table levels and flooded area showed an interesting hysteresis (Fig. 8a), with water-table levels following a lagged dynamics with regard to flooded area.

## 4. Discussion

The expansion of grain production over pasture-based livestock production in the Pampas over the last decades has been linked to the increasing frequency and severity of floods (Viglizzo et al., 2009). Our study provides several lines of evidence supporting this possibility. The replacement of perennial alfalfa pastures by annual crops affected both groundwater recharge and discharge fluxes. These changes stem from the combination of shallower rooting depth and lower annual transpiration capacity of annual crops compared to pastures (Fig. 1). These contrasts affect groundwater recharge through their influence on soil moisture contents (Fig. 7). Higher soil moisture under crops constrained the capacity of soils to hold exceptionally high rainfall inputs like those seen during the study period, favoring recharge (Fig. 5). In the case of groundwater discharge, shallower roots, lower annual transpiration capacity and, very likely, lower tolerance to salinity as well, explain why crops like corn or soybean displayed lower consumption rates than alfalfa pastures (Bresler et al., 1982; Nosetto et al., 2009) (Fig. 6). Alfalfa plants seem to use groundwater and keep high transpiration fluxes during dry periods, explaining the lower interannual variability of transpiration displayed by dairy systems compared to grain cropping systems (Table 1).

Although both field data and hydrological modeling showed deeper water-table levels in alfalfa pastures than in annual cropping, the water-table level contrasts suggested by modeling were notably higher than the observed ones (Figs. 2–4). This disagreement may arise from two issues. On the one hand, most of the cropland plots that we sampled were occupied by alfalfa pastures between two and three years before sampling, carrying a

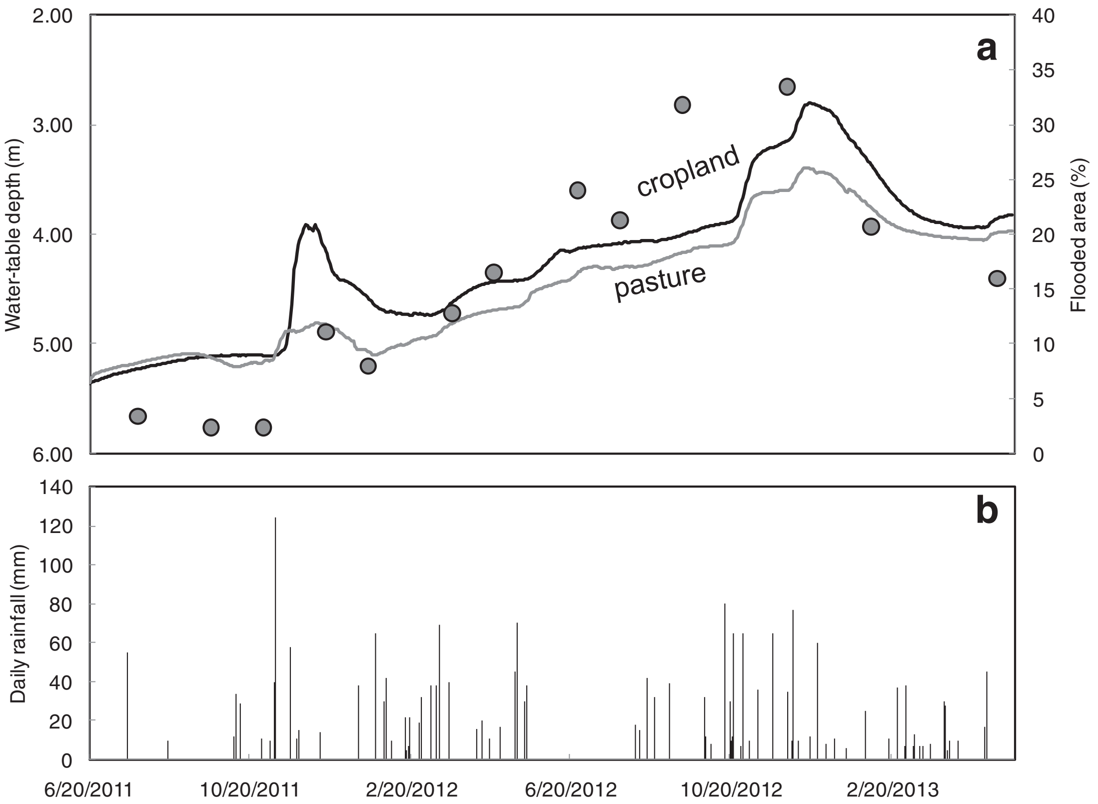

**Fig. 5.** Continuous water-table depth monitoring at two paired plots (pasture vs. cropland) (a) and daily rainfall (b), showing with gray circles (panel a) the flooded area (right *y*-axis) computed from Landsat images.

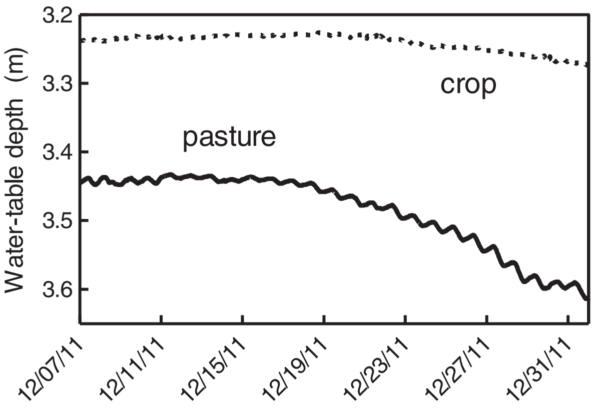

**Fig. 6.** Continuous water-table depth monitoring at two paired plots (pasture vs. cropland) showing direct groundwater discharge in the pasture but not in the maize crop.

"memory" of their effect in the current water balance of the phreatic aquifer. In the simulations, cropland plots were permanently occupied by single or double crop. On the other hand and probably more importantly, the modeling exercises were performed considering a closed system, with no horizontal water fluxes, which would tend to equalize hydraulic gradients and dampen differences between vegetation covers. Although at the regional level groundwater and surface horizontal water fluxes are negligible, in very flat landscapes like the Pampas (Jobbágy et al., 2008; Usunoff, 2009), they may become relevant at more local scales, when piezometric differences between adjacent plots with different land covers arise at short distance (<1000 m) (Jobbágy and Jackson, 2007). It is also important to note that our modeling exercises considered a homogeneous soil profile and they did not take into account the vertical nor horizontal variability in soil hydraulic properties which may also generate discrepancies with field observations. A logical further step would involve a spatially explicit hydrological modeling that takes into account this variability and horizontal water flows.

The Inland Pampa behaves as a closed drainage basin most of the time, except for periods of exceptionally high flooding (Aragón et al., 2010). In this flat region, vertical water fluxes prevail and water outputs follow almost exclusively an evaporative pathway. As a consequence, changing vegetation covers with different transpiration capacity (e.g., perennial pastures vs. annual crops) would not necessarily modify the long-term evapotranspirative water flux (Table 1), but its partition between transpiration, direct soil evaporation and pond evaporation, which may entail different hydrological and productive implications. For instance, the replacement of dairy systems by grain production systems would likely increase the fraction of rainfall inputs that is evacuated as soil evaporation and pond evaporation (Viglizzo et al., 2009), which compensate the lower transpirative capacity of annual crops. In addition, a different long-term equilibrium with shallower water-table levels and higher surface water coverage (Figs. 2 and 8) is likely reached when grain cropping systems displace dairy systems. This new state may further decrease the productive capacity of the region (Viglizzo et al., 2009) and may back feed on local and regional climate modifying rainfall patterns (Sörensson et al., 2010).

In the last three decades, there has been several multiyear periods of exceptionally high rainfall that have triggered water-table levels raises, and the development of flooding episodes (Viglizzo et al., 2009; Aragón et al., 2010). It is interesting to highlight, however, that besides these flooding episodes, it is possible to identify a clear and significant trend of rise in water-table levels during this period, that is not supported by the rainfall

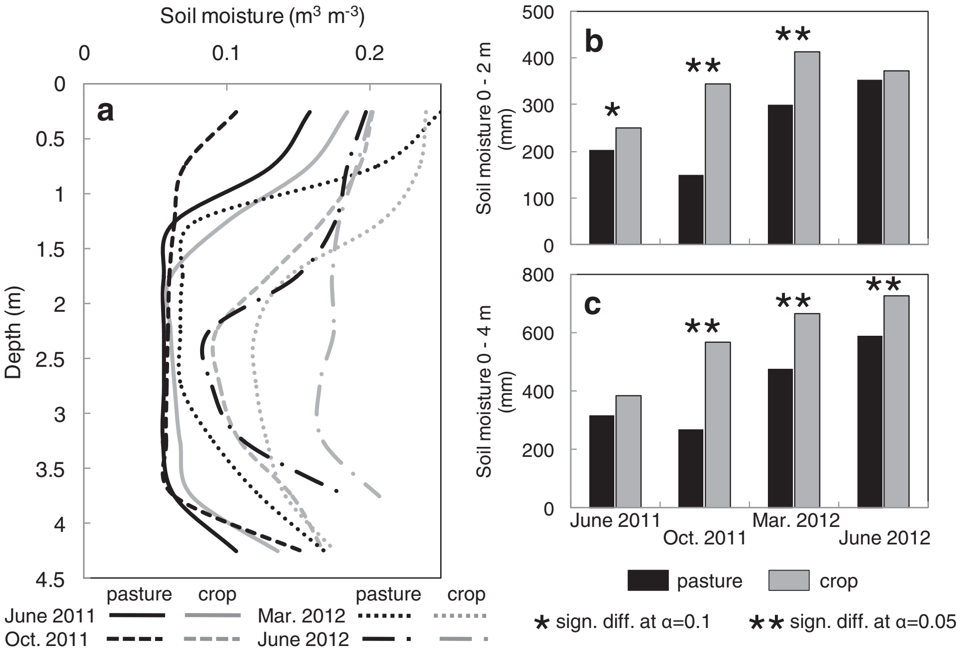

**Fig. 7.** Soil moisture profiles (a) and accumulated soil water down to 2 m (b) and 4 m (c) at two paired plots (pasture vs. cropland).

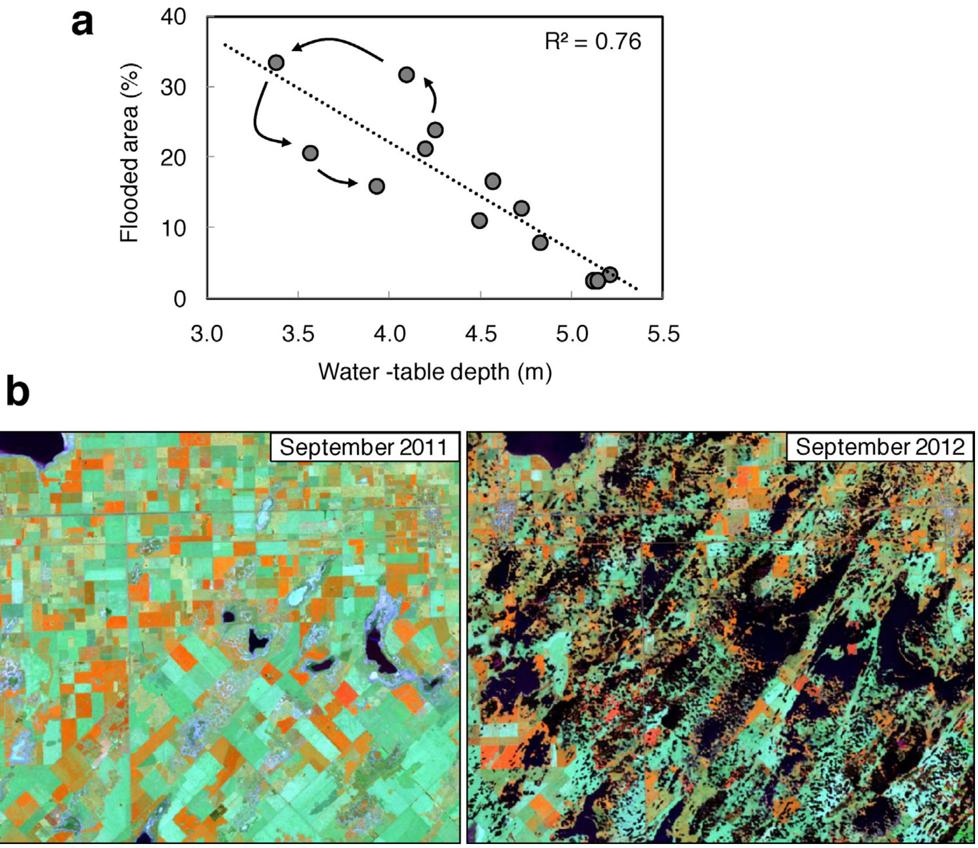

**Fig. 8.** Relationship between water-table depth and flooded area (a) and Landsat images showing the flooded area in two contrasting dates (b) during the study period.

pattern (Ballesteros, 2014). For instance, if we compare the water-table levels during non-flooding periods of the 2000s vs. the 1980s, levels appeared to be 0.6 m shallower on average (Ballesteros, 2014), while the annual average rainfall was 132 mm lower. While it is largely recognized that climate is the main driver of the hydrological cycle (Dingman, 1993), based on the results described in this paper, we can speculate that this upward trend in water-table levels responds to a new ecohydrological equilibrium triggered by the widespread replacement of livestock farms by grain production systems. This new context, that clearly poses higher risks of flooding than a few decades ago, raises the need to consider the ecosystems of the Inland Pampa not only as suppliers of grains for export, but also as providers of a wide range of ecological services, among which water regulation is of key importance for local societies.

As evidenced from the strong relationship between water-table levels and flooded area (Fig. 8), the region displays a close connection between the water balance at the plot scale and the hydrology of whole landscapes. Plot water balances are likely controlling the magnitude of flooding episodes and creating horizontal connectivity effects in which the consequences of the land use decisions made by one farmer could affect many others. Given this picture, it becomes critical to identify different land-users that may alternatively affect and benefit from water regulation services (i.e., affectors and enjoyers according to Scheffer et al., 2000). For instance, both livestock and grain production systems affect the water regulation service, but while livestock systems tend to improve regulation, grain production seems to deteriorate it (Fig. 2). At the same time, livestock farms, particularly those devoted to milk production, are the main beneficiaries of the water regulation service because they depend more critically on flood prevention to bring in and out products and inputs on a daily basis (Mercau et al., 2013). This situation clearly illustrates an asymmetry between different land-users, and raises the need for an accurate assessment of the hydrological responsibilities of each affector. Based on this assessment, it will be possible to define rules or schemes that optimize the hydrological services of the region and develop policies that promote the implementation of these schemes.

## 5. Conclusions

This study highlighted the strong influence of land-use on the hydrology of the Inland Pampa of Argentina. Our complementary approaches evidenced that the replacement of pasture-based livestock systems by grain production decreased transpiration rates and increased soil moisture content, and by doing this, it raised water-table levels and flooding risks. While flooding is an inherent ecohydrological feature of subhumid hyperplains like the Pampas, land-use changes may increase its magnitude and frequency, exacerbating its negative effects on agricultural production, infrastructure and general human wellbeing. This new picture in which humans, by deciding the type of agricultural production performed in the territory, play a key hydrological role opposes the historical view where climate and topography/lithology are considered the main controls of flooding episodes (Dingman, 1993). By contrast to an abiotic view of flooding that has supported the development of hydraulic infrastructure solutions, often ineffective in extremely flat territories (Jobbágy, 2011), a perspective in which land-use is viewed as an hydrological management tool offers a promising pathway.

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