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Interactive effects of water-table depth, rainfall variation, and sowing date on maize production in the Western Pampas

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ABSTRACT

Shallow water-tables strongly influence agro-ecosystems and pose difficult management challenges to farmers trying to minimize their negative effects on crops and maximize their benefits. In this paper, we evaluated how the water-table depth interacts with rainfall and sowing date to shape maize performance in the Western Pampas of Argentina. For this purpose, we analyzed the influence of water-table depth on the yields of 44 maize plots sown in early and late dates along eight growing seasons (2004–2012) that we rated as dry or wet. In addition, we characterized the influence of the water-table depth on intercepted radiation and crop water status by analyzing MODIS and Landsat images, respectively. The four conditions we evaluated (early sown-dry growing season, early-wet, late-dry, late-wet) showed similar yield response curves to water-table depth, with an optimum depth range (1.5–2.5 m) where yields were highest and stable (∼11.6 Mg ha^{-1} on average). With water-table above this range, yields declined in all conditions at similar rates ($p > 0.1$), as well as the crop water status, as suggested by the Crop Water Stress Index, evidencing the negative effects of waterlogging. Water-tables deeper than the optimum range also caused declines of yield, intercepted radiation and crop water status, being these declines remarkably higher in early maize during dry seasons, evidencing a greater reliance of this condition on groundwater supply. Yield in areas with deep water-tables (>4 m) was significantly reduced to between a quarter and a half of yields observed in areas with optimum water-tables. Rainfall occurred around flowering had a strong impact on maize yield in areas with deep water-tables, but not in areas with optimum depth, where yields showed high temporal stability and independence from rainfall in that period. Our study confirmed the strong influence of water-table on rainfed maize and provides several guidelines to help farmers to take better decisions oriented to minimize hydrological risks and maximize the benefits of shallow water-tables.

1. Introduction

With shallow water-tables water flow to the root zone may play an important role in meeting crop water needs (Yang et al., 2007). Lysimeters studies suggest that groundwater could contribute up to 50–70% of water used by rainfed crops (Yang et al., 2007). However, depending on the prevailing water-table depth, groundwater may not be available for crops when it is too deep to reach roots by capillary upflow, be a valuable source of water to allow yield stability when it is at optimum depths, or become a stress agent causing waterlogging and root anoxia when it is too shallow (Nosetto et al., 2009; Kahlown et al., 2005). The sign and intensity of these influences will not only depend on water-table depths but also on the crop attributes, among which its potential exposure to water stress, particularly during the most critical period for yield generation.

In most of the Argentinean Pampas, a shallow phreatic groundwater influences the functioning of agro-ecosystems (Aragón et al., 2010). The presence of this shallow water-table results from the combination of a positive water balance and a poor surface drainage network which constrain the evacuation of water excess through streams and rivers, favoring their storage in the landscape and their evacuation through evapotranspiration (Degioanni et al., 2002). These characteristics are not unique to the Pampas, since they are also manifested in other regions of the world such as the Great Hungarian Plain, the steppes of Western Siberia and the great plains of Western Canada, among others (Jobbágy and Nosetto, 2008). Shallow groundwater exerts a strong influence on vegetation that can

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result in productivity enhancement if it becomes a water source during rainfall deficit periods (Nosetto et al., 2009), or can hamper crop performance when it is very shallow and becomes a waterlogging and anoxia agent and/or a vector for salt transport into the root zone (Ayars et al., 2006; Kahlown et al., 2005). Understanding and quantifying the sign and intensity of groundwater influences on rainfed crops is critical in order to define management strategies designed to minimize risks and maximize benefits in shallow groundwater areas.

Groundwater influence on agro-ecosystems is manifested at different spatial and temporal scales. At a regional and farm scale, its negative influence is evident when shallow water-table levels generate the expansion of surface water bodies, reducing the area that can be farmed (Viglizzo and Frank, 2006). The retraction of these water bodies is often slow and sometimes, soils are affected by salinization afterwards, thereby the negative effect remains over time. At a plot scale, groundwater influence is strongly dependent on the water-table depth, among other factors. With a very shallow water-table (<1 m), the negative effects of waterlogging are dominant and the germination and establishment of crops can be compromised, or the performance of already established crops can be hampered as a result of anoxia or indirect effects on nutrient availability or root disease (McKevlin et al., 1998). Salinization of the root zone is another problem brought by shallow water-tables (Nosetto et al., 2013). Drops in water-table levels under these conditions generally result in an increase of crop yields. With intermediate water-table depths (~1.5 to 2.5 m in the case of maize), the greatest benefits from the groundwater are expected, since this appeared to be the optimum depth to provide water to the roots (Nosetto et al., 2009). Drops in water-table levels below these values translate into yield losses because of a decline of capillary upflow towards the root zone. With deeper water-tables (>4–5 m), the groundwater effects on shallow rooted crops tend to be negligible. In part of the Pampas, these contrasting influences may be simultaneously manifested into the same plot at distances of less than one kilometer as a result of local topographic variations controlling water-table level variation at that spatial scale (Nosetto et al., 2009).

With more than 3.5 million hectares planted every year, maize is widely distributed in the Pampas. This crop is mostly grown under rainfed conditions (Cárcova et al., 1998), and therefore it is very dependent on the water conditions occurred during the crop cycle and particular during flowering (Calviño et al., 2003; Hall et al., 1982). This high susceptibility of maize to water deficits is what largely explains the strong yield response of this crop to the presence of shallow water-tables, allowing to triple yields compared to areas with no groundwater access during years of poor rainfall inputs (Nosetto et al., 2009).

The sowing date of maize is a key management tool in the Pampas, especially in the center and north where a wide time-frame can be explored in order to modify the environmental conditions of the growing season and, particularly, those of the critical period of flowering. Early maize, sown during early spring (early September–early October), has a long growing season as the crop develops more slowly during its vegetative stage and has high radiation interception and biomass conversion rates, leading to maximum productivity under non-limiting conditions (Otegui et al., 1995). However, there is also an increased risk of water stress during flowering for early sown maize in the western Pampas, when the yield sensitivity of this crop to water supply is maximum (Hall et al., 1992) and the evaporative demand frequently exceeds the supply. On the other hand, late maize, sown during late spring (mid November–late December) grows faster until flowering, explores lower levels of radiation and finds lower temperatures during reproductive stages and therefore it has lower yield potential (Otegui et al., 1995). However, late maizes are exposed to lower water deficits during flowering and grain filling than early maizes so the expected variability of yields is reduced. The convenience of each sowing date depends on how it balances the higher yield potential of early sowing versus the lower risk of failure or poor crop performance offered by late sowing (Madonni, 2012). The presence of a shallow water-table should be an important determinant of this decision inclining it towards early sowing, considering that the positive effects of groundwater would be maximized given the higher potential and higher water demand of early maize. In addition, during very rainy springs, shallow water-tables could be more deleterious to late maize as they would reach higher levels under a longer fallow and increase the negative effects of waterlogging on flowering and on the incidence of diseases as the later stages of the crop occur closer to the fall. Besides these hypothetical connections, the effects of groundwater interacting with different sowing dates of maize are still unexplored.

In this paper we explored the influence of water-table depth on the performance of maize in different scenarios of water availability (dry and wet seasons) and sowing dates (early and late sowings). Two hypotheses guided the study. We propose that (a) the effect of water-table on maize yield and intercepted radiation, is stronger under early sowing, especially during dry years. Given the occurrence of higher water deficit in such situations, groundwater may mitigate more markedly such deficits. We also hypothesize that (b) maize yields are more stable through time and across variable water-table depths when sowing is delayed. Delaying sowing date defines the occurrence of the critical period in conditions of lower probabilities of water stress, which allows late maize to be less conditioned by the rainfall occurring during the growing season and the groundwater supply than early maize.

To address these hypotheses we worked in the central temperate region of Argentina particularly, in the west central region called Inland Pampa (Córdoba province). We characterized the water-table depth effect on the performance of maize by analyzing its influence on the yields of maize plots sown in early and late dates along eight growing seasons that we rated as dry or wet. In addition, we characterized the dynamics of the intercepted radiation along the whole crop growing season with the remote sensing NDVI product from MODIS in areas with contrasting access to groundwater. We also estimated the Crop Water Stress Index (CWSI) (Idso et al., 1981; Jackson et al., 1981), derived from the surface temperature provided by the Landsat 7 satellite, across a water-table depth gradient in order to explore the influence of groundwater on crop water status and its relation to maize productivity responses.

2. Materials and methods

2.1. Site description

The study was performed in “El Consuelo” farm (lat −34°12′, long −64°18′), located south of the town of Vicuña Mackenna in Córdoba (Argentina). The region was originally covered by grasslands (Soriano et al., 1991), however annual crops of soybean, maize and wheat are the dominant land cover today. In the study area, the average maize yield (2002–2012) is 5.8 Mg ha^{-1} (MAGyP, http://old.siia.gov.ar/index.php/series-por-tema/agricultura) and it tend to be more stable in regions with access to groundwater compared to others where its levels are deeper and its access limited (Nosetto et al., 2009).

Mean annual temperature is 16.5 °C and average wind speed is 15 km h^{-1} (Hall et al., 1992). Mean annual rainfall for the last hundred years was 720 mm yr^{-1}, but during the last 15 years (1992–2007) this value amounted to 920 mm yr^{-1}. Potential evapotranspiration is 1240 mm yr^{-1} (1991–2011). Rainfalls are mainly concentrated (~67%) in the austral spring and summer (September to March) and have high interannual coefficients of variation, often exceeding 70% for monthly totals, creating significant risks for rainfed agricultural production.

Soils are predominantly Entic Haplustolls, sandy, well drained and deep (>2 m), and they do not present any significant restrictions to crop growth (INTA-SAGyP, 1990). At regional scale, the landscape is extremely flat (slope <0.2%), which combined with a poor runoff network and a humid climate determine the existence of shallow water-tables (Degioanni et al., 2002). At local scale, topographic variations associated to the dune landscape determine water-table depth gradients that range on their extremes from ~ 7 m at the highest dune-crest topographic positions to superficial groundwater in the deepest inter-dune positions. However, typical ranges from deepest to shallowest depths in production plots span a level difference of ~5 m (Nosetto et al., 2009). Usually, water-tables become shallower during autumn and winter, when rainfall exceeds evapotranspiration, reaching their maximum depths during the summer (Degioanni et al., 2002; INTA-SAGyRR, 1987).

2.2. Crop management conditions

We evaluated the yield response to water-table depth at 44 maize plots sown between 2004 and 2012. These plots were sown between September 8 and October 14, corresponding to early sowing dates, and between November 16 and December 19, corresponding to late sowing. Growing seasons were categorized as wet when accumulated rainfall during the critical period, defined as 30 days before and 20 days after the flowering day (Calviño et al., 2003), exceeded the average rainfall of the past 50 years and as dry when they were below that value. As a result of the combination of sowing dates and growing seasons water attributes, four conditions were defined: early-wet (EW, $n = 9$), early-dry (ED, $n = 16$), late-wet (LW, $n = 11$) and late-dry (LD, $n = 8$). While there were differences of up to 60 days between sowing dates (1st October vs. 1st December on average), time difference between average flowering dates was reduced to 30 days (December 15 vs. January 15) due to the response of maize development to a warmer environment. Flowering dates were defined according to field measurements and by checking with NDVI curves. Mean cumulative rainfall values at critical periods were 194 and 204 mm for early and late maize, respectively. The corresponding mean PET values for the last 20 years were 270 and 264 mm, in each case. The ratio Pp/PET during the critical period for the four situations was EW: 1.52, ED: 0.32, LW: 1.32 and LD: 0.26.

All plots were subject to no tillage system and they were maintained free of weeds throughout the whole cycle with herbicides, particularly glyphosate. Hybrids used were DK747MGRR and AW190 for early and late maize equally. The seeding density was 6 seeds m^{-2} and urea was applied at sowing at a dose of 115 kg N ha^{-1} on average.

2.3. Groundwater depth mapping

We developed water-table depth maps according to the methodology applied by Nosetto et al. (2009), which is based on a ground elevation map and water-table depth data from a network of 18 observation wells located in three plots of the farm. Briefly, we generated a fine resolution ground elevation map (FR E-map) with a spatial resolution of 20 m from differential GPS measurements (Trimble 4600 LS, horizontal kinematic accuracy = 1 cm vertically kinematic accuracy = 2 cm) mounted on a vehicle. In order to highlight the regional topographic gradient and remove local topographical variation, a smoothed topographic map with a coarse resolution (CR E-map) was generated using a moving mean filter of 1km-1km on FR E-map. To identify local topographic variations associated to the wind-shaped landscape, we generated a map of elevation residues (ER-map) computing the difference between FR E-map and CR E-map. The elevation residue data around each observation well was used to correct the measured water-table depth and thus calculate the average water-table depth (AWTD = measured WT depth–elevation residue). Later, the AWTD was extrapolated to the rest of the farm (AWTD-map) from a linear regression model between AWTD of each one of the 18 observation wells and geographic latitude (mean $r^2 = 0.74$). Finally, the water-table depth map (WTD-map) was calculated for each plot using the average water-table depth maps and elevation residues (WTD-map = AWTD-map + ER-map). Based on this methodology, it was possible to generate water-table depth maps for each plot with a spatial resolution of 20 m and an error lower than 20 cm. Water-table depth measurements in observations wells were performed with a frequency of 30–45 days and those dates around flowering were used to generate the water-table depth maps.

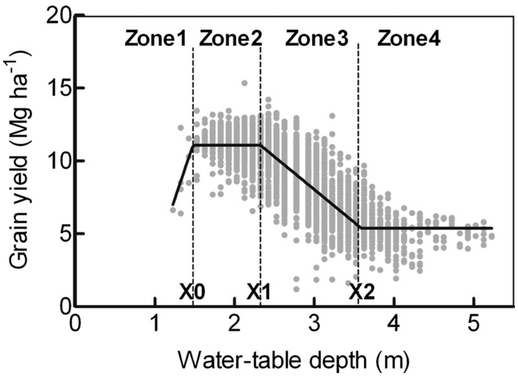

Fig. 1. Relationship between water-table depth (m) and maize grain yield (Mg ha^{-1}) for one plot analyzed. Points represent yield measurements and water-table depth estimates for each sampling unit. The water-table depth points X_0, X_1 and X_2 define the four zones of groundwater influence. The segmented line was derived through adjusting a segmented regression model (Eq. (1)).

2.4. Crop yield mapping

Yield maps for each plot were obtained from the information generated by yield monitors (TM Greenstar, John Deere Inc., Moline, Illinois) and GPS (Trimble 4600 LS) mounted on harvesters. Yield and location data were recorded at 2 s intervals, allowing to obtain a yield data every 34 m^2 (harvester head width = 8.5 m, average velocity = 7 km h^{-1}). Yield monitors were calibrated according to the manufacturer's recommendations. The maps were processed in order to filter out the erroneous (values lower than zero) or doubtful (data points on plot edges or patterns clearly associated with harvester problems) data.

2.5. Data analysis

The relationship between maize yield and water-table depth was characterized by a segmented regression model with two or three breakpoints in the explanatory variable (Piegorsch and Bailer, 2005). The model sought to represent the four groundwater depth ranges (Nosetto et al., 2009) identified as: Zone 1, water-table depth range where waterlogging effects predominate and yield increases with increasing water-table depth; Zone 2, optimal depth range in which yields are high and show little response to water-table depth, Zone 3, depth range where yields decrease as water-table deepens due to lower capillary upflow fluxes, and Zone 4, depth range where yields are low and no longer responsive to water-table depth (Fig. 1).

The adjusted model relating yield and water-table depth for each plot was defined as follows:

$$\begin{aligned}
&Y = \mathrm{IF}\quad (X < X_0, Y_1, \mathrm{IF}\quad (X < X_1, Y_2, \mathrm{IF}\quad (X < X_2, Y_3, Y_4)))\\
&Y_1 = \mathrm{intercept1} + \mathrm{slope1} \times X\\
&Y\quad \mathrm{at}\quad X_0 = \mathrm{intercept1} + \mathrm{slope1} \times X_0\\
&Y_2 = Y\quad \mathrm{at}\quad X_0\\
&Y\quad \mathrm{at}\quad X_1 = Y\quad \mathrm{at}\quad X_0\\
&Y_3 = Y_2 + \mathrm{slope2} \times (X - X_1)\\
&Y\quad \mathrm{at}\quad X_2 = Y_2 + \mathrm{slope2} \times (X_2 - X_1)\\
&Y_4 = \mathrm{Y}\quad \mathrm{at}\quad X_2
\end{aligned} \tag{1}$$

where Y and X represent yield (Mg ha^{-1}) and water-table depth (m) variables, respectively (Fig. 1). Intercept1 is the intercept value, slope1 is the rate of yield increase between intercept1 and X_0, and slope2 is the rate of yield decline between X_1 and X_2. X_0, X_1 and X_2 corresponds to water-table depth breakpoints that separate zone 1 and zone 2, zone 2 and zone 3, and zone 3 and zone 4, respectively (Fig. 1). Yield variables Y_1, Y_2, Y_3 and Y_4 correspond to yields registered in zones1, 2, 3 and 4.

In some of the plots analyzed, water-table was not shallow enough to generate the negative waterlogging effects expected for zone 1. In these cases, the adjusted model had only three segments (zones 2–4) (Fig. 1). Analysis of variance (ANOVA) and Tukey test were performed to evaluate the effects of the four conditions on different parameters of the adjusted segmented regression models. This analysis allowed us to characterize how sowing date and water availability determine water-table depth influence on maize yields.

In addition, we characterized the interannual variability of maize yields in early and late sowing for the four zones of groundwater influence. After the results obtained in the previous analysis, the water-table depth ranges of the four zones were defined as follow: Zone 1 = <1.5 m, Zone 2 = 1.5–2.5 m; Zone 3 = 2.5–3.8 m, and Zone 4 = >3.8 m. These zones were characterized in terms of their average yield and interannual standard deviation. According to the water-table depth ranges defined, we calculated the proportional areas of the farm that corresponded to each water-table zone for each year.

We also examined the relationship between precipitation during the critical period and yield in areas with optimal water-table depth (Zone 2) and deep groundwater (Zone 4) and compared the relationships found with those presented by Calviño et al. (2003) for situations without groundwater in other areas of the Pampas. For this purpose, accumulated rainfall was computed for the period −30/+20 days of flowering using field rainfall measurements. Average yields for each growing season obtained at both water-table depth zones were associated with accumulated rainfall for both early and late maize. In order to standardize this comparison, the relative yield used by Calviño et al. (2003) was taken into account and it was equaled to the average yield of zone 2 for all analyzed growing seasons between 2004 and 2012 for early maize.

2.6. *Satellite analysis*

2.6.1. *Intercepted radiation dynamic in areas with contrasting groundwater access*

The NDVI product (Normalized Difference Vegetation Index) from MODIS images was used to characterize the evolution of the fraction of photosynthetically active radiation intercepted (fIPAR) by crop canopies in areas with different water-table depths in dry and wet seasons. This index has shown to be directly related to the radiation intercepted by vegetation and the vegetation productivity (Houborg et al., 2007; Paruelo, 2008). NDVI was transformed to fIPAR according to the relationship described by Ruimy et al. (1994) (Eq. (2)). Later, the intercepted radiation (IR, MJ m^{-2}) was calculated considering that the photosynthetically active radiation (PAR) is equivalent to 0.45 of the incident solar radiation (Otegui et al., 1996) (Eq. (3)).(2)$\mathrm{fIPAR} = 0.025 + 1.25 \times \mathrm{NDVI}$

(3)$\mathrm{IR} = \mathrm{fIPAR} \times \mathrm{PAR}$

In order to obtain NDVI values for the study areas, we used the MOD13Q1 product derived from MODIS sensor aboard the Terra satellite. This product uses information from red and near-infrared bands of the electromagnetic spectrum derived from daily surface reflectance product (MOD09), which incorporates corrections for atmospheric aerosols, ozone absorption and molecular scattering. The product used has a temporal resolution of 16 days and a spatial resolution of 250 m. In order to develop the temporal composite, a filter based on the data quality, cloud cover and geometry of the observation is applied and only those pixels with high quality are used in the composition. Images were downloaded from Oak Ridge National Laboratory Distributed Active Archive Center (http://daac.ornl.gov/MODIS/).

We characterized the dynamic of radiation interception in areas with optimal water-table depth (1.5 to 2.5 m) and in areas with limited groundwater access (>3.4 m). Given the size of the MODIS pixel (250 m), it was not possible to select homogeneous areas with deeper water-table depths. A total of 61 pixel were selected from all growing seasons, with 33 pixel corresponding to early maize (20 and 13 pixel for optimal and deep water-table depth, respectively) and 28 pixel corresponding to late maize (15 and 13 pixel for optimal and deep water-table depth, respectively). The period considered for the analysis extended from October to April for early maize and November to May for late maize. Different parameters that defined intercepted radiation curves, such as accumulated intercepted radiation in the cycle, average and maximum value, were compared by analysis of variance (ANOVA) and Tukey tests.

2.6.2. *CWSI patterns across groundwater depth gradients*

It has been shown that the canopy temperature, which can be easily derived from satellite images, can be used to characterize the water status of vegetation (Cárcova et al., 2000). The Crop Water Stress Index (CWSI) specifically used canopy temperature to quantify the water stress suffered by vegetation. This characterization is of particular interest when it is performed during the critical period, given the strong impact of water deficits on final yields. On the other hand, satellite images allow a spatial characterization of such index and in turn allow analyzing the influence of water-table depth on it.

The CWSI was estimated from the equation used by Zia et al. (2011):

$$\mathrm{CWSI} = \frac{(T_\mathrm{c} - T_\mathrm{wet})}{\left(T_\mathrm{dry} - T_\mathrm{wet}\right)} \tag{4}$$

where T_c is the canopy temperature estimated from the surface temperature derived from the Landsat 7 satellite, T_dry is the maximum surface temperature estimated empirically in this case from the surface temperature of the crop in areas with water-table depth >3.8 m and T_wet is wet bulb temperature. We used two Landsat 7 images obtained on dates close to the critical period. The image used for the dry season was taken on 01/14/2008 and for the wet season on 01/23/2009, for both early and late maize. In order to characterize the response of CWSI to water-table depth, we selected one plot for each condition (late-dry, late-wet, early-dry, early-wet). The surface temperature was calculated from band 62 using the algorithm proposed by Qin et al. (2001). Additionally, the NDVI from the same Landsat 7 images was calculated from the reflectance of bands 3 and 4 and this information was used to discard those plots with low vegetation cover, which may have some soil influence on the signal recorded by the satellite sensor. Landsat images were geometrically corrected using ground control points (Eastman, 1999). To minimize atmospheric effects, bands 3 and 4 were corrected using the dark object subtraction methodology described by Chavez (1989).

3. Results

The water-table depth exerted a strong and variable influence on maize yields according to the sowing date and rainfall amount occurring during the growing season (Fig. 2). The four conditions (early-dry, early-wet, late-dry, late-wet) showed a similar yield response curve to water-table depth, being the main differences observed for water-table depths >2.5 m (zones 3 and 4). A similar optimum depth range was observed for the four conditions (depth = 1.5–2.5 m, $p > 0.1$ for the parameters X_0 and X_1) where yields were highest and stable (~11.6 Mg ha^{-1} on average). With water-table above this range, yields declined in all conditions at similar rates ($p > 0.1$), evidencing the negative effects of waterlogging. As the water-table deepened below the optimal zone (>2.5 m), there was also a noticeable drop in yields that was significantly higher in early maize during dry seasons than in other cases, reaching the lowest observed yield ($p < 0.01$). Despite these contrasts, there were no differences among the four conditions for the water-table depth breakpoint below which there is no water-table influence ($X_2 = \sim 4.2$ m, $p > 0.1$, Fig. 2).

In zone 1 of groundwater influence, yields increased at an average rate of 5.87 Mg ha^{-1} per meter of water-table depth increase, with no significant differences between conditions ($p > 0.1$) (Fig. 2). Even though in zone 2, where maximum yields were observed, no statistical differences among the four conditions were found, we observed higher yields for late sowings in dry years compared to wet years (12.2 vs. 10.8 Mg ha^{-1}, $p = 0.1$). In zone 3, the yield decline rate, as water-table deepens, was significantly higher for early maize in dry years (−5.1 Mg ha^{-1} m^{-1}) than for the other conditions (−2.9 Mg ha^{-1} m^{-1}, on average), evidencing a greater reliance on groundwater supply. In zone 4, where the influence of groundwater would be minimal, we found that during wet years both early and late maize reached similar minimum yields (6.5 and 6.7 Mg ha^{-1}, respectively), which approaches 55% and 62% of yields observed in the optimum zone, respectively. On the other hand during dry years, late maize had a similar performance than during wet years (6.9 Mg ha^{-1}), while early maize showed significant lower yields (2.7 Mg ha^{-1}, $p < 0.01$), reaching only 23% of the observed yield in the optimal depth (Fig. 2).

Precipitation occurring during the critical period around flowering had different effects on yields in areas with optimal and restricted groundwater access (Fig. 3). For early maize, increases in rainfall during this critical period resulted in increased yields in areas without groundwater access (Fig. 3a). This response was similar to that found by Calviño et al. (2003) for early maize sown in areas without access to groundwater when the same range of precipitation (50–300 mm) is considered. However, in areas where water-table was at the optimum depth, yields remained stable, suggesting some independence of precipitation occurred during this period (Fig. 3A). On the other hand, the yield of late maize did not show a clear response to precipitation occurred around flowering in both areas with and without access to groundwater (Fig. 3B), suggesting low influence of rainfall when the sowing was late. From this analysis also emerged that the separation of water conditions between wet and dry years that we made (vertical lines in Fig. 3) matched the value of precipitation in which the Calviño et al.'s model (2003) reached the plateau yield.

Areas with optimum water-table depth showed lower yield interannual variability than areas with shallower or deeper water-table (Fig. 4A and B). The interannual standard deviation (SD) of yields in areas with optimal water-table depth (1.5 to 2.5 m) was the lowest one compared to other positions, approaching 0.41 Mg ha^{-1} for early sowings and 1.28 Mg ha^{-1} for late sowings. In areas with shallower water-tables (<1.5 m), yields showed high variability among years, mainly in early sowings (SD = 3.88 Mg ha^{-1}), showing similar yields to the optimal zone in some years (e.g. 2007–2008, 2009–2010 seasons) and minimum yields in others (e.g. 2005–2006 and 2011–2012 seasons). These contrasts could results from differences in the time span the crop suffered waterlogging conditions during the growing season and the depth of the water-table within the waterlogging zone. While during 2005–06 and 2011–12 growing seasons the crop was exposed to waterlogging conditions (water-table depth <1.5) during most of the growing cycle, during the 2009–2010 growing season the crop suffered waterlogging only around flowering. In addition, during 2007–2008, 2008–2009, 2009–2010 and 2010–2011 growing seasons, when maize of zone 1 showed a good performance (Fig. 4A), we noticed that water-table was located just below the 1.5 m threshold, likely not exposing the crop to very strong waterlogging conditions. In areas with negligible groundwater influence (depth > 3.8 m), yields also showed large interannual variability for both early (SD = 1.78 Mg ha^{-1}) and late sowings (SD = 1.72 Mg ha^{-1}). Finally, areas with moderate water-table depths (zone 3), showed intermediate interannual yield variability between those observed in areas with optimal water-table depth and those with negligible groundwater access, being 1.24 Mg ha^{-1} and 1.52 Mg ha^{-1} for early and late sowing, respectively.

Considering the groundwater influence zones altogether, we found that the yield interannual coefficient of variation for early and late maize was 35% and 21%, respectively. The average CV for areas with groundwater influence (zones 1, 2 and 3) and areas with water-table at >3.8 m depth was 20% and 33%, respectively, for early maize, and 14% and 24%, respectively, for late maize. The impact of this yield variation on the total farm production depended on the proportion of the landscape under each range of groundwater influence.

The proportions of the farm that corresponded to the different groundwater influence zones also showed large interannual variability (Fig. 4C and D), largely associated to rainfall occurred during each season and to the specific altimetry of plots that were sown during early or late dates each year. For example, the proportion of the farm with waterlogging effects (zone 1) varied between a minimum of 0.59% (2004–2005) and a maximum of 26.4% (2010–2011) for early maize, and between 0.18% (2011–2012) and 17.5% (2007–2008) for late maize. On the other hand, the proportion of the farm with optimal water-table depth (zone 2) ranged from 17% and 52% for early maize, and between 16% and 36% for late maize. Taking into account the proportions of the farm that corresponded to each groundwater influence zone and considering the yield observed in zone 4 as control with no groundwater influence, we estimated that the contribution of water-table to maize production for the whole farm averaged 47% for early maize and 27% for late one. These percentages increased to 70% and 44% for early and late maize during 2010–2011 and 2009–2010 seasons, respectively.

Water-table depth and rainfall affected the dynamic of the intercepted radiation along the crop cycle in early and late maize (Fig. 5). The evolution of intercepted radiation differed between dry and wet seasons especially in early maize with deep water-table (depth > 3.4 m), but no significant differences were found when the water-table was at optimal depths. In areas with deep water-table, the intercepted radiation by the early maize throughout the growing season was 5% higher in wet than in dry years

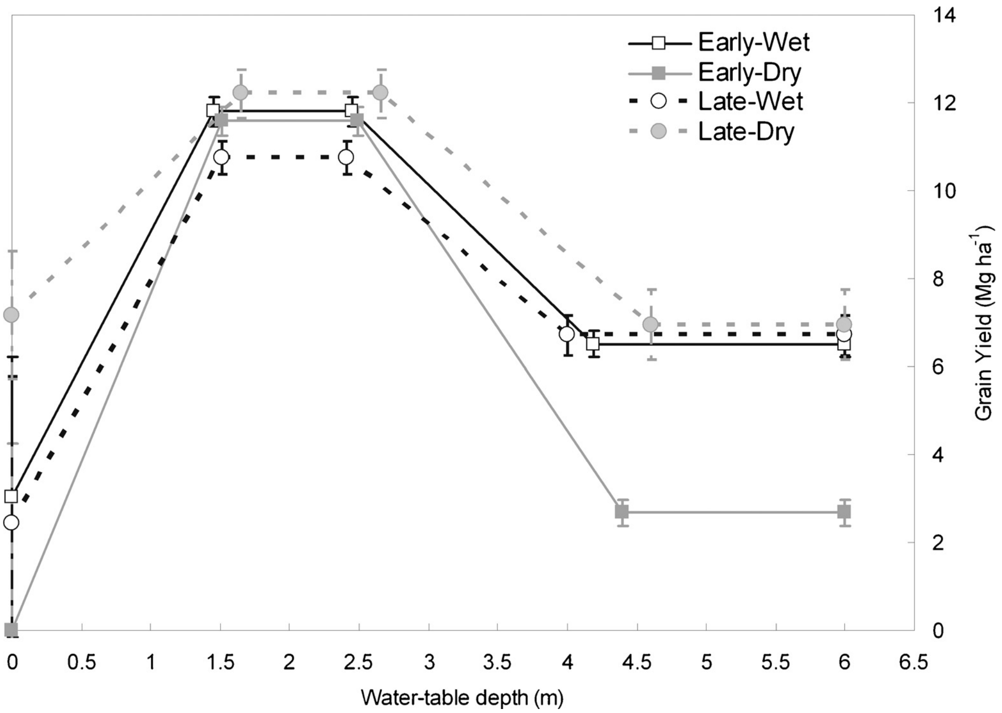

Fig. 2. Relationship of water-table depth (m) and maize grain yield (Mg ha^{-1}) for the four different conditions. Water-table depth corresponds to the flowering period. The curves were derived by averaging the curve parameters adjusted for the different analyzed plots corresponding to the different conditions (early-wet $n = 9$, early-dry $n = 16$, late-wet $n = 11$, late-dry $n = 8$). The vertical lines on symbols show the standard error of grain yield.

(1523 vs. 1446 MJ m^{-2}, $p < 0.01$), whereas no significant differences were found between both rainfall conditions in areas with optimal water-table depth. The maximum values of intercepted radiation of early maize were also significantly higher in wet seasons than in dry ones when water-table was deep (13.6 MJ m^{-2} d^{-1} and 12.8 MJ m^{-2} d^{-1} for wet and dry seasons, respectively, $p < 0.01$), but no differences were observed for early maize with optimal water-table depth (13.7 MJ m^{-2} d^{-1} and 13.1 MJ m^{-2} d^{-1} for wet and dry seasons, respectively, $p > 0.1$).

In late maize, significant differences in intercepted radiation were observed between areas with optimum and deep water-table depth, but not between dry and wet growing seasons (Fig. 5B). Averaging dry and wet seasons, the cumulative radiation of late maize was 4% higher in areas with optimum groundwater access than in areas with negligible groundwater influence (1406 MJ m^{-2} and 1349 MJ m^{-2} for optimal and deep water-table, respectively, p: 0.02). Similarly, the maximum intercepted radiation was 5% higher in areas with optimal water-table depth ($p < 0.01$, Fig. 5B).

Crop water stress, quantified through the Crop Water Stress Index (CWSI) derived from satellite imagery, showed a strong influence of water-table depth (Fig. 6). Minimum CWSI values were observed in areas with water-table depth of ~1.3–1.7 m for both early and late maize, matching the response of yield to water-table depth. The CWSI increased when the water-table was deeper than this range and also when it was shallower, likely evidencing the waterlogging stress. This pattern suggests that during flooding conditions the crop water consumption is reduced, which would generate a positive feedback on water-table levels increasing the waterlogging stress. In the wet season, the CWSI showed a similar response to the water-table depth in late and early maize (Fig. 6A), which is consistent with yield responses showing no differences between sowing dates when the year was wet (Fig. 2). By contrast

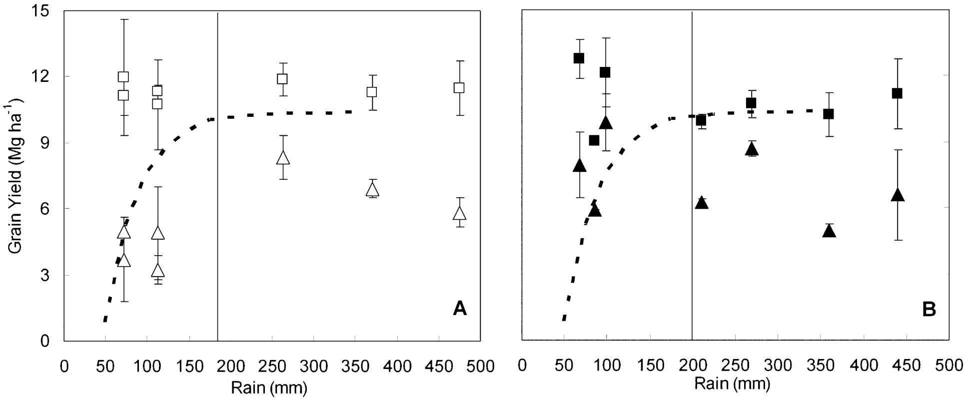

Fig. 3. Relationship between cumulative rain (mm) and maize grain yield (Mg ha^{-1}) for early (A) and late maize (B). Cumulative rain corresponds to the period −30/+20 days around flowering. Square symbols correspond to areas with optimum water-table depth (1.5–2.5 m) and triangle symbols correspond to areas with water-table deeper than 3.8 m. (A). Points were derived by averaging the yield observed at the different plots analyzed. The dash curve shows the model adjusted by Calviño et al. (2003). The vertical line represents the rainfall amount that separates dry and wet growing seasons. Vertical lines on symbols show the standard error.

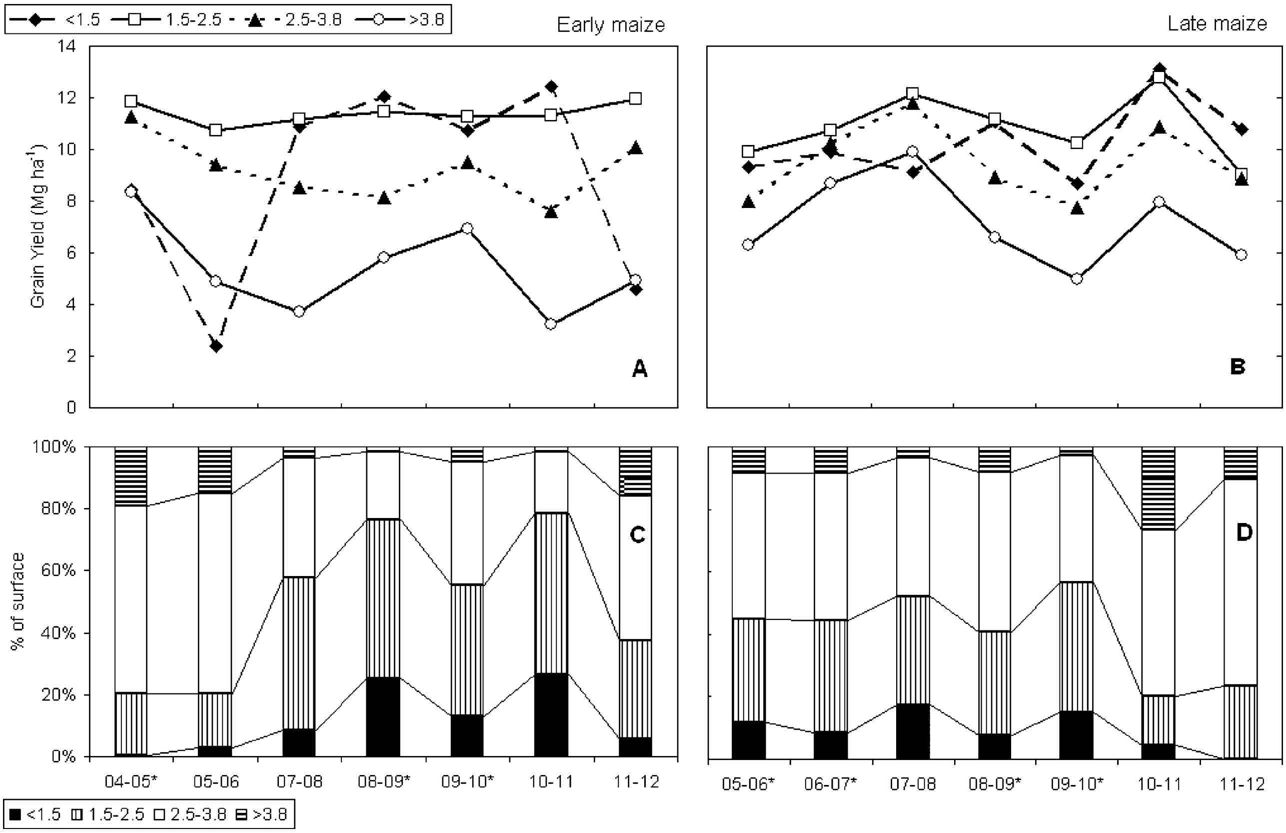

Fig. 4. Temporal variability of maize grain yield (Mg ha^{-1}) and percentage of the farm (%) corresponding to the different groundwater influence zones. The temporal variability of grain yield is shown for the four zone of groundwater influence (<1.5 m; 1.5–2.5 m; 2.5–3.8 m; >3.8 m) in early (A) and late maize (B). The percentages of the study farm that corresponds to the different groundwater influence zones for early and late maize are shown in panels (C) and (D), respectively. Growing seasons that were classified as wet are indicated with stars.

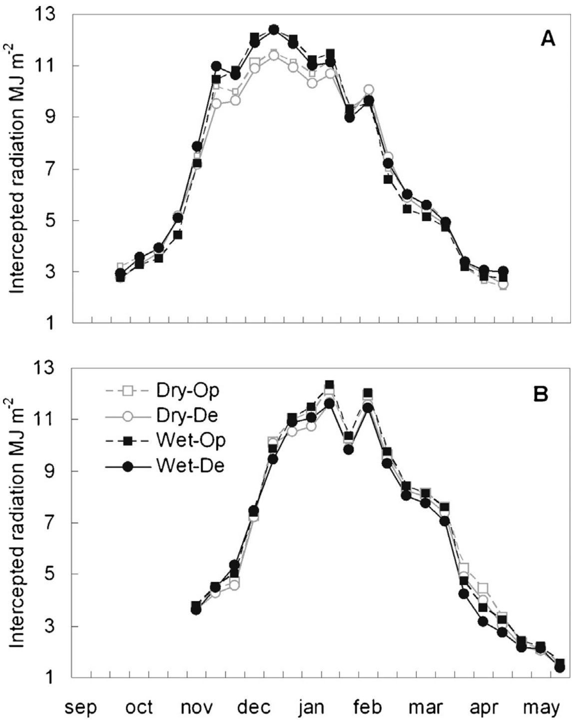

Fig. 5. Intercepted radiation (MJ m^{-2} d^{-1}) dynamic along the growing season of early (A) and late maize (B) in areas with optimum (1.5–2.5 m) and deep water-tables (>3.4 m). Intercepted radiation was derived from NDVI product from MODIS images and Eqs. (2) and (3). A total of 61 pixel were selected (early maize and optimum water-table = 20; early and deep = 13, late and optimum = 15, late and deep = 13).

in the dry season (Fig. 6B), it was observed that even though both sowing dates showed CWSI increases as the water-table deepens, the contrast between optimal and deep water-table was higher in early maize. Probably, the higher impact of groundwater observed in early maize was associated with the fact that it was in a more advanced growth stage than late maize, and soil moisture would have been depleted to a higher level, limiting transpiration more strongly.

4. Discussion

This study highlights the strong influence of groundwater on maize yield, providing new insights on its interaction with sowing date and rainfall conditions. Early and late maize, in both wet and dry years, showed similar yield response to water-table depth, with an optimum depth range (1.5 to 2.5 m) where yields were highest (Fig. 2). Possibly, the low salinity of groundwater (conductivity < 1500 μS cm^{-1}) and the high hydraulic conductivity of sandy sediments did not restrict groundwater consumption by the crop, which would have been lastly determined by crop water demand (Nosetto et al., 2009). With water-tables above this range, groundwater influence switches to negative, likely as a result of waterlogging (Reicosky et al., 1985), since anoxic conditions severely affect germination and seedling establishment during early stages (Lone and Warsi, 2009; McKevlin et al., 1998) and photosynthesis and senescence processes throughout the whole cycle (Grassini et al., 2007). Water-tables deeper than the optimum range also caused yield declines and reduced the interception of radiation, being remarkably higher for early maize during dry seasons. Despite these differences, thresholds depths defining the different

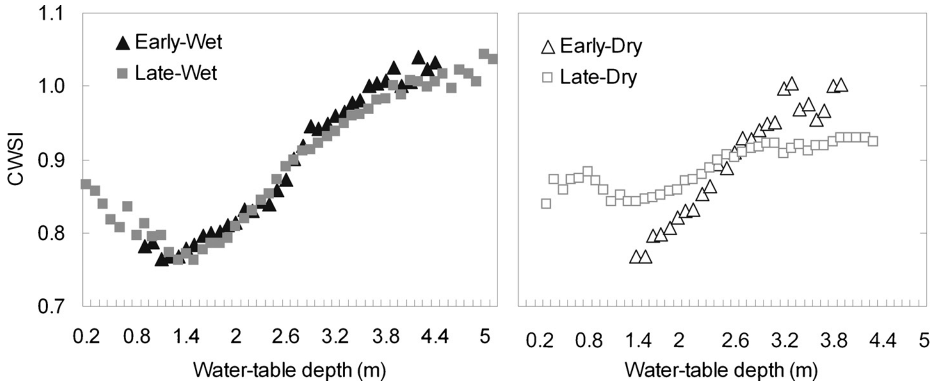

Fig. 6. Relationship between the Crop Water Stress Index (CWSI) and water-table depth (m) for a wet (A) and a dry growing season (B) in early and late maize. The CWSI was derived from band 62 of Landsat images and Eq. (4).

groundwater influence zones were similar for all the combinations of sowing dates and water regimes. Water-table depth effects were also clearly evidenced with satellite remote sensing, through the CWSI and the dynamic of intercepted radiation (IR).

The highest positive impact of groundwater on yield was observed in early maize during dry seasons (Fig. 2), confirming our hypothesis that such situations experiencing higher water stress will evidence the positive impact of groundwater influence more strongly. In late maize, rain during the critical period was also much lower during dry than wet seasons (80 vs. 350 mm) and similar to early maize (90 mm vs. 330 mm), but the groundwater positive impact was lower (Fig. 2), suggesting that late maize experienced less water stress than early maize regardless of groundwater availability. This contrast may emerge from the fact that later maize began its cycle with a soil profile that has higher chances of being fully recharged with moisture down to the second meter of depth. From historical rainfall data (1910–2011), we estimated for the study area that the probability of starting the growing cycle with a soil profile full of water by the accumulation of >200 mm (water stored down to 2 m in a typical profile of the region) during the fallow period increases from 10% to 80% by delaying sowing from October 1st to December 1st. This analysis agrees with probabilistic models suggesting that water content in soil at sowing is a major climatic constrain for early maize in the study area (Madonni, 2012). Especially in rainfed systems, starting the growing cycle with a soil profile full of water will reduce the risk of water stress, representing for late maize a potential advantage over early maize. In order to deepen this analysis, we estimated, from a daily water balance that took into account the rainfall occurred during the growing cycle and fallow period and the evolution of K_c according to sowing dates, that early maize during dry years had higher water deficits throughout its cycle than late maize (127 vs. 53 mm). These contrasts would explain the different yield responses to rainfall occurred during the critical period between early and late maize in areas with no groundwater access (Fig. 3).

While previous studies suggest that the productivity of maize for late sowing dates tend to be lower than for early sowing (Madonni, 2012), we found no significant yield differences between sowing dates with optimal water-table depth and with deep water-table during wet years (Fig. 2). According to an empirical model that takes into account incident radiation, accumulated temperature and a constant radiation use efficiency (RUE = 3.39 g MJ^{-1}) (Otegui et al., 1996), early maize has ~10% higher yield potential than late maize. By delaying the sowing date, vegetative growth occurs at higher temperatures with a consequent shortening of the cycle and therefore lower total intercepted radiation (Otegui et al., 1995). We estimated a shortening in the cycle of late maize of only six days and that the intercepted radiation was slightly lower in late maize than in early maize (900 vs. 993 MJ m^{-2} respectively), considering that plant emergence occurs at 116 °C d^{-1} and physiological maturity at 1800 °C d^{-1}. In this case, the shorter cycle of late maize would not been compensated by higher radiation interception, as observed in some situations by other authors (Otegui et al., 1995). Nevertheless, differences in radiation interception between sowing dates did not translate to yields in those areas with optimal water-table depth (11.7 and 11.5 Mg ha^{-1} for early and late maize, respectively), and maximum observed yields were only slightly lower than potential yields suggested by the empirical model. Probably, maize yields with optimal water-table depth have not been limited during any sowing date by the intercepted radiation and the constant provision of water by the shallow groundwater would have allowed maize crop to achieve yields that were very close to potential yields estimated with Otegui et al' s model (1996) under no water and nutrient limitations.

Water-table depth had a clear effect on crop water status evidenced through the CWSI (Fig. 6), which was minimum in areas with optimum water-table depth. With deeper water-table, the rate of capillary upflow from the saturated zone to the root zone decreases, which would generate suboptimal water status that would cause a partial stomatal closure manifesting as canopy temperature increment (Cárcova et al., 1998). It is worth noting that even during wet seasons with no significant water deficits, there was a decline of the crop water status with water-table deeper than 2 m (Fig. 6A). Perhaps, just a slight decrease in soil water content is enough to generate a partial closure of stomata, mainly taking into account the high stomata sensitivity of maize to water deficits (Tardieu and Davis, 1993). The daily water balance suggested that prior to the Landsat image acquisition date, several days with soil moisture below 70% of available water occurred in areas without groundwater access in both early and late maize plots. Furthermore, it is interesting to note that not only deep water-table conditions caused a decline in the crop water status, but very shallow water-table conditions (~1 m) did it too. In this case, waterlogging would have lead to a partial stomata closure, which resulted in lower photosynthesis rates and yields (Fig. 2), as it has been documented in controlled greenhouse experiments (Ashraf and Habib-ur-Rehman, 1999).

The contrasting influence of groundwater according to its depth and the large temporal variation of the area that is under each water-table influence zone (Fig. 4) require a dynamic and site-specific agronomic management to minimize risks and maximize the benefits associated to groundwater. Overall, as hypothesized in this study, late maize was a more stable production alternative between years and across groundwater influence zones. However, the inclusion of both late and early maize on the farm management portfolio would be required not only to diversify risks, but to optimize times by synchronizing operational tasks and the use of their associated machinery, which in the Pampas is often limiting. By knowing the proportion of the farm under each groundwater zone of influence and the risks and potential offered by each one of them (Fig. 4), it would be possible to make decisions with a lower level of uncertainty. In areas with flooding risk (WT depth < 1.5 m), a feasible strategy would be to establish a winter crop such as wheat before maize, which performs better under shallow water-tables (Nosetto et al., 2009). This strategy would promote groundwater consumption and water-table level declines before maize sowing. If at maize sowing date the waterlogging risk remains, it would be a good strategy to reduce and split the nitrogen fertilizer dose because high nitrate levels may have detrimental effects on maize under waterlogging (Ashraf and Habib-ur-Rehman, 1999). Alternatively, a crop with lower planting cost (e.g. soybean) could be preferred because if it fails the economic loss would be lower.

Given that in areas with optimum water-table depth (1.5 to 2.5 m) there would not be any water limitation for maize crop, it would be convenient trying to achieve potential yield, independently of climate forecast, through the use of hybrids with high yield potential, high densities and high fertilizer dose. Furthermore, since there are no differences in yield between early and late sowings with optimal water-table depth, the plots of the farm can be distributed conveniently between early and late sowings. Based on the estimation of the area of the farm within the optimal water-table range and its yield stability, it would be possible to estimate a minimum production achievable which would help to make decisions. Finally, with conditions of deep water-tables and dry fallow period that prevents filling the soil profile, choosing late sowing would be a more safe option because if a dry season progresses, higher yields would be expected with this alternative than with early sowing, while no differences would arise if the season results wet. The strategy of including late maize, besides its productive advantages during dry seasons, could entail environmental benefits facilitating the possibility of including winter crops or cover crops which by consuming groundwater would reduce waterlogging risks and also protect soils from wind erosion during winter. It should be considered however, that during dry years, the water consumption of winter/cover crops could limit water recharge of soil profiles and compromise the performance of late maize, particularly in areas with no groundwater access.

Shallow water-tables pose important management challenges for farmers, particularly in regions with high temporal rainfall variability. A better understanding of their influence on crop performance and their interaction with sowing date and rainfall will help farmers to take better decisions oriented to minimize hydrological risks and maximize the benefits of shallow water-tables.

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References

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

Ashraf, M., Habib-ur-Rehman, 1999. Interactive effects of nitrate and long-term waterlogging on growth, water relations, and gaseous exchange properties of maize (*Zea mays* L.). Plant Sci. 144, 35–43.

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

Calviño, P.A., Andrade, F.H., Sadras, V.O., 2003. Maize yield as affected by water availability, soil depth, and crop management. Agron. J. 95 (2), 275–281.

Cárcova, J., Maddonni, G.A., Ghersa, C.M., 1998. Crop water stress index of three maize hybrids grown in soils with different quality. Field Crops Res. 55 (1–2), 165–174.

Cárcova, J., Maddonni, G.A., Ghersa, C.M., 2000. Long-term cropping effects on maize: crop evapotranspiration and grain yield. Agron. J. 92 (6), 1256–1265.

Chavez Jr., P.S., 1989. Radiometric calibration of landsat thematic mapper multispectral images. Photogramm. Eng. Remote Sens. 55 (9), 1285–1294.

Degioanni, A., Cisneros, J., Cantero, A., Camarasa, A., 2002. Las inundaciones en la Provincia de Córdoba (Argentina) y las tecnologías de información geográfica: ejemplos de aplicación. Serie Geográfica 10, 143–163.

Eastman, R.J., 1999. IDRISI 32 Guide to GIS and Image Processing, 1. Clark Labs, Worcester, pp. 193.

Grassini, P., Indaco, G.V., Pereira, M.L., Hall, A.J., Trápani, N., 2007. Responses to short-term waterlogging during grain filling in sunflower. Field Crops Res. 101 (3), 352–363.

Hall, A.J., Rebella, C.M., Ghersa, C., Culot, J., 1992. Field crop systems of the Pampas. In: Pearson, C.J. (Ed.), Ecosystems of the World, Field Crop Ecosystems. Elsevier, Amsterdam, pp. 413–450.

Hall, A.J., Vilella, F., Trapani, N., Chimenti, C.A., 1982. The effects of water stress and genotype on the dynamics of pollen-shedding and silking in maize. Field Crop Res. 5, 349–363.

Houborg, R., Soegaard, H., Boegh, E., 2007. Combining vegetation index and model inversion methods for the extraction of key vegetation biophysical parameters using Terra and Aqua MODIS reflectance data. Remote Sens. Environ. 106 (1), 39–58.

Idso, S.B., Jackson, R.D., Pinter Jr., P.J., Reginato, R.J., Hatfield, J.L., 1981. Normalizing the stress-degree-day parameter for environmental variability. Agric. Meteorol. 24 (C), 45–55.

INTA-SAGyP, 1990. Atlas de suelos de la República Argentina. Instituto Nacional de Tecnología Agropecuaria—Secretaría de Agricultura, Ganadería y Pesca, Buenos Aires.

SAGyRR, I.N.T.A., 1987. Carta de Suelos de la República Argentina. In: Hoja Laboulaye. Instituto Nacional de Tecnología Agropecuaria—Secretaría de Agricultura Ganadería y Recursos Renovables, Córdoba, pp. 71.

Jackson, R.D., Idso, S.B., Reginato, R.J., Pinter Jr., P.J., 1981. Canopy temperature as a crop water stress indicator. Water Resour. Res. 17 (4), 1133–1138.

Jobbágy, E.G., Nosetto, M.D., 2008. Como hacer de las napas un aliado Pautas y criterios para el monitoreo de niveles freáticos en sistemas de producción agrícola en la región pampeana. Revista CREA 328, 32–38.

Kahlown, M.A., Ashraf, M., Zia-ul-Haq, 2005. Effect of shallow groundwater table on crop water requirements and crop yields. Agric. Water Manage. 76, 24–35.

Lone, A.A., Warsi, M., 2009. Response of maize (*Zea mays* L.) to excess soil moisture (ESM) tolerance at different stages of life cycle. Bot. Res. Int. 2, 211–217.

Madonni, G.A., 2012. Analysis of the climatic constraints to maize production in the current agricultural region of Argentina—a probabilistic approach. Theor. Appl. Climatol. 107, 325–345.

McKevlin, M.R., Hook, D.D., Rozelle, A.A., 1998. Adaptations of plants to flooding and soil waterlogging. In: Messina, M.G., Conner, W.H. (Eds.), Southern Forested Wetlands. Ecology and Management. CRC-Press, Boca Raton, FL, pp. 173–204.

Nosetto, M.D., et al., 2013. Land-use and topography shape soil and groundwater salinity in central Argentina. Agric. Water Manage. 129, 120–129.

Nosetto, M.D., Jobbágy, E.G., Jackson, R.B., Sznaider, G., 2009. Reciprocal influence between crops and shallow ground water in sandy landscapes of the Inland Pampas. Field Crops Res. 113, 138–148.

Otegui, M.E., Nicolini, M.G., Ruiz, R.A., Dodds, P.A., 1995. Sowing date effects on grain yield components for different maize genotypes. Agron. J. 87, 29–33.

Otegui, M.E., Ruiz, R.A., Petruzzi, D., 1996. Modeling hybrid and sowing date effects on potential grain yield of maize in a humid temperate region. Field Crop Res. 47, 167–174.

Paruelo, J., 2008. La caracterización funcional de ecosistemas mediante sensores remotos. Ecosistemas 17 (3), 4–22.

Piegorsch, W., Bailer, J., 2005. Analyzing Environmental Data. John Wiley & Sons, Ltd., Hoboken, NJ, pp. 512.

Qin, Z.-h., Karnieli, A., Berliner, P., 2001. A mono-window algorithm for retrieving land surface temperature from Landsat TM data and its application to the Israel–Egypt border region. Int. J. Remote Sens. 22 (18), 3719–3746.

Reicosky, D.C., Smith, R.C.G., Meyer, W.S., 1985. Foliage temperature as a means of detecting stress of cotton subjected to a short-term water-table gradient. Agric. For. Meteorol. 35, 193–203.

Ruimy, A., Saugier, B., Dedieu, G., 1994. Methodology for the estimation of terrestrial net primary production from remotely sensed data. J. Geophys. Res. 99, 5263–5283.

Soriano, A., et al., 1991. Río de la Plata Grasslands. In: Coupland, R.T. (Ed.), Natural Grasslands: Introduction and Western Hemisphere. Ecosystems of the World 8A. Elsevier, Amsterdam, pp. 367–407.

Tardieu, F., Davis, W.J., 1993. Integration of hydraulic and chemical signalling in the control of stomatal conductance and water status of droughted plants. Plant, Cell Environ. 16, 341–349.

Viglizzo, E.F., Frank, F.C., 2006. Ecological interactions, feedbacks, thresholds and collapses in the Argentine Pampas in response to climate and farming during the last century. Quat. Int. 158, 122–126.

Yang, J., Wan, W., Deng, W., Zhang, G., 2007. Water fluxes at a fluctuating water table and groundwater contributions to wheat water use in the lower Yellow River flood plain, China. Hydrol. Processes 21, 717–724.

Zia, S., et al., 2011. Monitoring physiological responses to water stress in two maize varieties by infrared thermography. Int. J. Agric. Biol. Eng. 4 (3), 7–15.