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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 timeframe 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