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Balancing agricultural and hydrologic risk in farming systems of the Chaco plains

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ABSTRACT

Like in other semiarid areas of the world, farming systems in semiarid Chaco tend to use water-conservative crop systems to minimize production risks associated to water stress. While this strategy aims to stabilize crop yields and farmers income, the underutilization of water resources in wet years may result in heavy deep drainage water losses which could potentially lead to the development of dryland salinity. Conversely, more intensive crop systems that consume water exhaustively present lower drainage rates but are more prone to crop failure. We employed a monthly soil water balance approach to analyze the productive and ecohydrologic effects of five different farming systems across the region (winter, spring, summer, late-summer and a winter–summer double crop system) and to assess the possibility of minimizing emerging trade-offs between them through flexible water-informed cropping sequences. Our results indicate that water stress diminishes as crop systems are delayed towards the rainy season (winter > spring > summer > late-summer), but the productively safer late-summer strategy is the one with highest drainage rates. In most of the region, the relatively high production risk and insignificant drainage probability generally determine the convenience of conservative late-summer systems. However, in areas (or years) with higher amount and/or seasonality of rainfall, more intensive double-crop systems are necessary to minimize the likely high drainage fluxes. As rainfall is highly variable from one year to the other, the knowledge of soil water content at the onset of the season is useful to predict part of the available water offer and to asses expected production and ecohydrologic risks. In the most drainage-prone areas the implementation of flexible sequences that alternate conservative and intensive crop systems depending on soil water status, significantly reduced mean annual drainage with an acceptable increase in mean water stress index.

1. Introduction

Farming systems have to yield food, feed, fiber and/or fuel products while protecting the environment and ensuring their long term sustainability (Connor et al., 2011). Water is the major driver of plant productivity in dryland agricultural systems of arid and semi-arid regions but it also represents a potential threat to their sustainability when it is misused (Asbjornsen et al., 2008). In those regions, where water availability is both limited and highly variable, farmers typically apply water-conservative farming systems and low-cost management practices to minimize the productive and financial risk of crop loss in dry years (Sadras et al., 2003; Connor et al., 2011). This type of strategies intends to stabilize crop yields and ensure a minimum and safe profit to the farmer at the cost of increasing unproductive water losses in wet years (Sadras and Roget, 2004). Besides the losing opportunity of high productive output in wet years, the "excess water" generated when available water resources are underutilized may cause detrimental environmental outcomes such as erosion, flooding or dryland salinization (Sadras et al., 2003; Sadras and Roget, 2004; Asbjornsen et al., 2008). These outcomes could be partially prevented by applying more intensive (and profitable) cropping systems, which use exhaustively water resources when availability is high (Keating et al., 2002; Díaz-Ambrona et al., 2005; Salado-Navarro and Sinclair, 2009). So, in this sense, the implementation of flexible systems that alternate conservative and intensive cropping schemes, depending on expected water availability, could contribute to both productive and environmental objectives (Tanaka et al., 2002; Hanson et al., 2007).

So far, increasing world population demand for agricultural products has been supplied by both extensification (*i.e.* the addition of new cropped areas on arable lands generally replacing natural

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ecosystems) and intensification (*i.e.* more production per unit area of land already used for agriculture) of farming systems (Gregory et al., 2002). In South-American semiarid-Chaco, which presents one of the highest deforestation rates of the world, the former process accounts for most of the growth in agricultural production of the last decades (Grau et al., 2005; Boletta et al., 2006; Volante et al., 2012). Nearly 13 M hectares of dry forest have been cleared for agricultural and grazing purposes, mainly dryland soybean production, and there still remain 38 M hectares potentially suitable for agriculture in the region (Houspanossian et al., submitted for publication). These broad-scale land cover changes may affect the provision of essential ecosystem services such as erosion control or water regulation (Volante et al., 2012). Although there is crescent concern about the sustainability of current farming systems in the region (Boletta et al., 2006; Recatalá Boix and Zinck, 2008a; Caviglia and Andrade, 2010; Volante et al., 2012; Caviglia et al., 2013), agricultural expansion is likely to continue in areas which are often environmentally more fragile and less productive than typical agricultural land (Recatalá Boix and Zinck, 2008a; Calviño and Monzon, 2009).

One of the expected environmental consequences of massive replacement of native vegetation with annual crops is a disruption in the hydrological cycle and water balance (Hatton and Nulsen, 1999; Jobbágy et al., 2008; Santoni et al., 2010; Nosetto et al., 2012). Native dry forest make an exhaustive evapotranspirative use of rainfall generating little runoff and null deep drainage flux as evidenced by relatively dry soil profiles with high chloride accumulation underneath the vegetation (Jobbágy et al., 2008; Santoni et al., 2010; Amdan et al., 2013). They are composed by a diversity of species with deep root systems and perennial life cycle which sustain water consumption for long periods. On the contrary, agricultural crops generally present shorter (annual) lifecycles, shallower root systems and often relies on soil water storing during fallow periods to supply crop water demands (Jobbágy et al., 2008). As a consequence, water use in cropping systems is less than that of the original natural vegetation, and the excess water can be lost in the form of deep drainage below the root zone (Pannell, 2001; Keating et al., 2002). In the semiarid plains of W and SE Australia, the replacement of native vegetation by European settlers with water-conservative farming systems based on low-input cereal crops and long fallow periods (*i.e.* up to 18 months), has lead to a gradual but steady rise in regional water table levels and to the mobilization of high amounts of salt accumulated and stored in the soil profile for millennia towards the soil surface (George et al., 1997). This process resulted in large-scale secondary salinisation of land and water resources affecting 5.7 M ha many decades later (National Land and Water Resources Audit, 2001). Nowadays dryland salinity is recognized as one of the most serious environmental and resource management problems in the country (Pannell, 2001).

Although the ecohydrologic consequences of current farming systems in the Chaco plains had not been thoroughly assessed yet, recent evidences indicate that at least some areas in the region are potentially prone to dryland salinity (Nitsch, 1995; Santoni et al., 2010; Jayawickreme et al., 2011; Amdan et al., 2013). In order to preserve the potential and sustainability of agricultural production in the region, more intensive farming systems aimed to reduce drainage rates need to be employed in those areas with higher risk (Díaz-Ambrona et al., 2005). Although a great deal of variability in rainfall, evapotranspiration, crop yields and deep drainage is expected for the semi-arid Chaco in both the spatial and temporal dimensions (Kropff et al., 2001; Calviño and Monzon, 2009; Houspanossian et al., submitted for publication), little work has been done to explore which are the most suitable and productive farming practices for the region not to mention which could be their potential ecohydrologic outcomes. In this sense, science-based mathematical models and computer simulation provide useful and objective tools to analyze both, the performance of different farming systems and the potential biophysical consequences of resource management options at regional scale (Kropff et al., 2001; Bah et al., 2009). So, the aims of this work are to simulate and analyze the productive and hydrological effects of different farming strategies in semi-arid Chaco, and to assess the possibility of minimizing emerging trade-offs between productive and environmental objectives through the implementation of flexible and "water stock-informed" cropping sequences.

Firstly, a monthly-step soil—water balance model is used in the whole region to address the effect of different farming systems on productive and ecohydrologic risks in the spatial dimension (30′ x 30′ spatial resolution). Then, the analysis focuses on 4 or 5 contrasting locations and the most important crop systems to address the temporal dimension in drainage variability, and to relate production and drainage risks to the initial soil water condition. Finally, the possibility of reducing both production and hydrological risks across the region, through flexible cropping sequences that alternate conservative and intensive cropping systems based on initial soil water content is discussed.

2. Materials and methods

2.1. Description of the study region

The semi-arid Chaco region is a vast sedimentary plain of over 65 M hectares in the north-central part of Argentina, east of Bolivia and the western part of Paraguay (Olson et al., 2001; Fig. 1). The ecoregion presents a monsoonal climate with strong seasonality (dry winters, rainy summers) that increases from east to west (Riveros, 2003). Annual rainfall is highly variable in the region, from 500 mm year^{-1} in the center to 1000 mm year^{-1} in the eastern and western extremes. Mean annual temperature increases from south to north, varying from 18 °C to 21 °C (Minetti, 1999). The months with highest temperature, January and February, coincide with

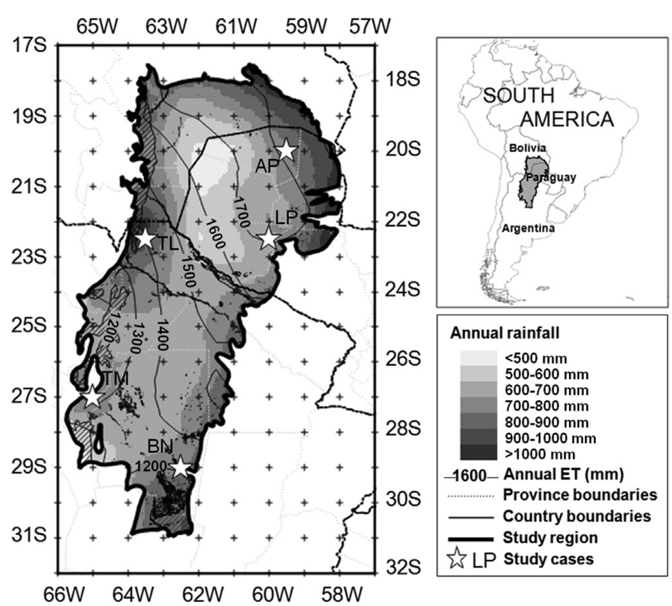

Fig. 1. Map of the study region (Olson et al., 2001) and location of the five study cases analyzed in this work: Alto Paraguay (AP), Loma Plata (LP), Tartagal (TL), Tucumán (TM) and Bandera (BN). Striped areas are floodplains, water bodies or mountainous soils (leptosols) not considered in the analysis.