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Precision agriculture based on crop physiological principles improves whole-farm yield and profit: A case study

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ABSTRACT

Precision agriculture has under delivered partially because it has been based on technologies focused on increasing the resolution of spatial variation in soil and yield and more recently automation, with less effort in incorporating the physiological principles of crop responses to environmental variation. Here we show how a whole-farm precision agriculture approach accounting for the physiological processes underlying the relationship between environment and crop development, growth and yield ("zone management"), bridge yield gaps, increased farmer profit and reduced risk, on San Lorenzo, a 5000 ha dryland farm in the southern Pampas. The farm grows wheat and barley in winter, and soybean, maize, and sunflower in summer; winter grain cereal/double-cropped soybean is a main activity. Four management zones were defined: i) Zone 1, shallow soils (< 0.8 m) with low frost risk and deep water table (> 3 m below surface); ii) Zone 2, intermediate soil depth (0.8 to 1.8 m) with low frost risk and deep water table; iii) Zone 3, deep soils (> 1.8 m) with low frost risk and deep water table; and iv) Zone 4, deep soils (> 1.8 m) with high frost risk and water table < 3 m from surface. Crop choice and practices were tailored to each zone based on ecophysiological principles including the relative sensitivity of crop growth and yield to soil depth, frost and water supply during the species-specific critical window for yield determination; for example, maize is the most sensitive crop to stress during its critical window, therefore it was excluded from Zone 1 and 2, with a substantial reduction of risk and improvement of farm output (amount of grains that can be produced in a hectare) and profit. In comparison with neighboring farms, San Lorenzo had a 54% higher farm output, and 46% higher gross margin (or 112 US\$ ha^{-1} year^{-1}); this was driven by a higher net income (244 US\$ ha^{-1}) despite increased total costs (132 US\$ ha^{-1}).

> *"We're in a maze, not a highway; there is nowhere that speed alone can take us".*
> *Julie Dehghani*

1. Introduction

Global agricultural production must significantly increase to meet the greater food demand in the coming decades (Bruinsma, 2009; Tilman et al., 2011; van Ittersum et al., 2013). The strategies to increase grain production while maintaining the current cropping area (Bruinsma, 2009) can focus on i) intensification of individual crops including increase in potential yield and yield gap closure (www.yieldgap.org, Fischer et al., 2014; Sadras et al., 2015), ii) increasing cropping intensity (Evans, 1993; Pires et al., 2015; Sandler et al., 2015) or a combination thereof.

Technological breakthroughs are needed to sustainably elevate crop yields, while increasing resource and input productivity with no further environmental impact (van Rees et al., 2014; Andrade, 2016). Precision agriculture (PA) could contribute to these goals (Cassman, 1999, 2017; Robert, 2002; Gebbers and Adamchuk, 2010). Several definitions have been proposed for PA, but they all summarize the concept of "use every acre within its capability and treat it according to its needs" (USDA, 2007). The most significant achievements in this technology relate to the amount of precise data that farmers now have about their fields and the use of this information to customize crop inputs "to each square foot" (Lowenberg-DeBoer, 2015). But up to date, PA has had limited

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results; the U.S. Department of Agriculture in a recent review indicated that in spite of years of subsidies and educational efforts, less than 20 percent of maize acreage is managed using the technology, and, when applied, the net impact on farm profit was below 2% (Lowenberg-DeBoer, 2015; Schimmelpfennig, 2016).

Precision agriculture has under delivered partially because it has been based on technology focused on increasing the resolution of spatial variation in soil and yield and more recently automation, with less effort in incorporating the physiological principles of crop responses to environmental variation. We considered that a successful implementation of PA at farm level requires a detailed characterization of the yield limiting factors such as soil water holding capacity and extreme temperatures, the identification of agronomically meaningful, homogeneous management macro zones, and the selection of the most appropriate crops and their management for each zone. We will refer to this type of PA as “zone management”. Crop physiological principles are critical to develop and implement effective zone management at farm level (Cassman, 1999; Andrade et al., 2005, 2010). These principles include the processes governing the relationship between environment and crop development, growth and yield.

The objective of this paper is to illustrate the development and adoption of zone management based on crop physiological principles. This approach has supported two decades of steady improvement in yield and profit in a 5000 ha farm in Argentina. The variables and principles used to define and manage the zones are described, and the impact of zone-based practices on yield, yield gaps, profit and risk are quantified using farm data, crop modeling and comparisons with neighboring farms.

2. Material and methods

2.1. Some features of the cropping systems of the region

Argentina is an important food producing country that exports 65 to 95% of the grain production depending on the crop (http://faostat3.fao.org/). Crops are grown over more than 33 million hectares, where soybean, wheat and maize collectively account for 84% of the cropped area. Argentina has a favorable temperate climate for rainfed crop production, with total annual precipitation that ranges, across cropping regions, from 600 (south-west) to 1400 mm (north-east) (Hall et al., 1992). Most soils belong to the Mollisol group with minimum constrains for crop growth (Hall et al., 1992; Calviño and Monzon, 2009). Between 1991 and 2012, crop yields have increased at rates of 28, 40 and 128 kg ha^{-1} y^{-1} for soybean, wheat and maize, respectively (https://datos.agroindustria.gob.ar/; Aramburu Merlos et al., 2015). This has been driven by a wide adoption of no-till, increasing usage of fertilizers, and improved crop varieties with high yield potential, herbicide- and insect-resistant traits (Satorre, 2011). Even though rates of yield increase are relatively high, Aramburu Merlos et al, (2015) determined that yield gaps, expressed as percentage of water-limited yield potential (Yw), are 41% for both wheat and maize and 32% for soybean. Besides increases in Yw, closing the yield gap may further increase crop production, provided that narrower gaps are economically justifiable (Lobell et al., 2009; van Dijk et al., 2017).

San Lorenzo (-37° 37´, -59° 04´) is a leading farm located at Tandil department (-37° 19´, -59° 09´) in the temperate-cool region of the southern Pampas of Argentina (Fig. 1a). Annual precipitation for Tandil varies from 524 to 1393 mm, averages 905 mm (Fig. 2), and 61% falls between October and March. Mean annual reference evapotranspiration is 950 mm. Monthly maximum average temperature varies from 12.5 to 28.4 °C, and minimum average temperature from 0.9 to 13.3 °C (Fig. 2). Climatic data for San Lorenzo is similar to those presented for Tandil.

Topography and its related aspects (soil depth, frost risk and influence of water table) were similar between Tandil and San Lorenzo (Fig. 1a). Dominant soils in San Lorenzo and in Tandil are Petrocalcil Paleudoll, with an average depth to the petrocalcic horizon of 0.80 m, Typic Argiudoll and Aquic Argiudoll (Pazos and Mestelan, 2002). Plant available water varies from 0.14 to 0.16 m^3 m^{-3} of soil. The mean soil productivity index (scale from 0 to 100, Riquier et al., 1970) for agricultural soils in San Lorenzo is 53, whereas that for Tandil department is 59. So, agricultural soils of San Lorenzo have around 90% of the soil productivity of the surrounding region.

The main crops for Tandil are soybean, wheat, sunflower and maize, and more recently barley (Fig. 3). Currently, around 60% percent of acreage is produced in rented land, 90% of the agricultural land is under no-till, and soybean is the main crop accounting for more than half of the total cropped area (Fig. 3). All soybean cultivars used are transgenic glyphosate resistant and 90% of the maize crops are transgenic glyphosate and/or Bt resistant. During the time series analyzed here, two periods were clearly distinguishable for Tandil: i) the first decade, where a two year crop sequence of wheat – summer crops (maize, sunflower or soybean as a sole crop) was dominant, and ii) the last decade, with an increase in barley and soybean area (soybean includes: soybean sown as a single crop per year, Soy1, and double-cropped soybean following a winter cereal, Soy2, Fig. 3). This shift was related to a combination of technological and policy drivers that discouraged wheat and other summer crops in favor of soybean.

2.2. San Lorenzo zone management

San Lorenzo farm comprises 5000 ha, of which 87% are used for rainfed grain production. Zone management identification and crop management adjustment accordingly was primarily motivated by the improvement of profit and reduction of risk at the farm level, and are partially documented in the scientific literature (Calviño and Sadras, 1999, 2002; Sadras and Calviño, 2001; Calviño et al., 2003a, b,c; Monzon et al., 2007; Calviño and Monzon, 2009). This section thus combines some documented principles and practices and unpublished on-farm determinations. The approach developed has two components: definitions of management zones based on topography and development of management practices tailored for each zone on the bases of crop physiological principles.

The farm was divided to capture spatial variation in: i) soil depth; ii), frost risk, and iii) influence of water table (Fig. 1c, Table 1). All three aspects of zone management are related to topography (Fig. 1b), and are not independent. Four management zones were defined that account for tradeoffs and synergies: i) Zone 1, shallow soils ($<$ 0.8 m) with low frost risk and no influence of water table, ii) Zone 2, intermediate soil depth (0.8–1.8 m) with low frost risk and no influence of water table, iii) Zone 3, deep soils ($>$ 1.8 m) with low frost risk and no influence of water table and iv) Zone 4, deep soils with high frost risk and with influence of water table (Table 1). These management zones occupy 42, 25, 6 and 27% of the agricultural area of the farm (Fig. 1c). Appropriate crop sequence and technology were indentified for each management zone (Table 1).

2.3. Tailoring crop management to zones

Crop management was adjusted to zones based on crop physiological principles, including: i) the elimination of the maize crop from Zone 1 and 2, ii) the restriction of the winter crop/Soy2 to Zone 1 and 2, iii) the early sowing of wheat and barley to anticipate flowering in Zone 1 and 2, iv) the use of short cycle soybeans in Zone 3 and 4, v) the adjustment of sowing date in maize according to frost risk in Zone 4 and vi) the input adjustment to the higher Yw of maize in Zone 4.

The zone management process in San Lorenzo started by 1999, and it was completed around 2012. This process included three sequential and overlapping steps that involved the measurement of soil depth, frost risk and, the presence of water table and the corresponding adjustment of crop management.