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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.

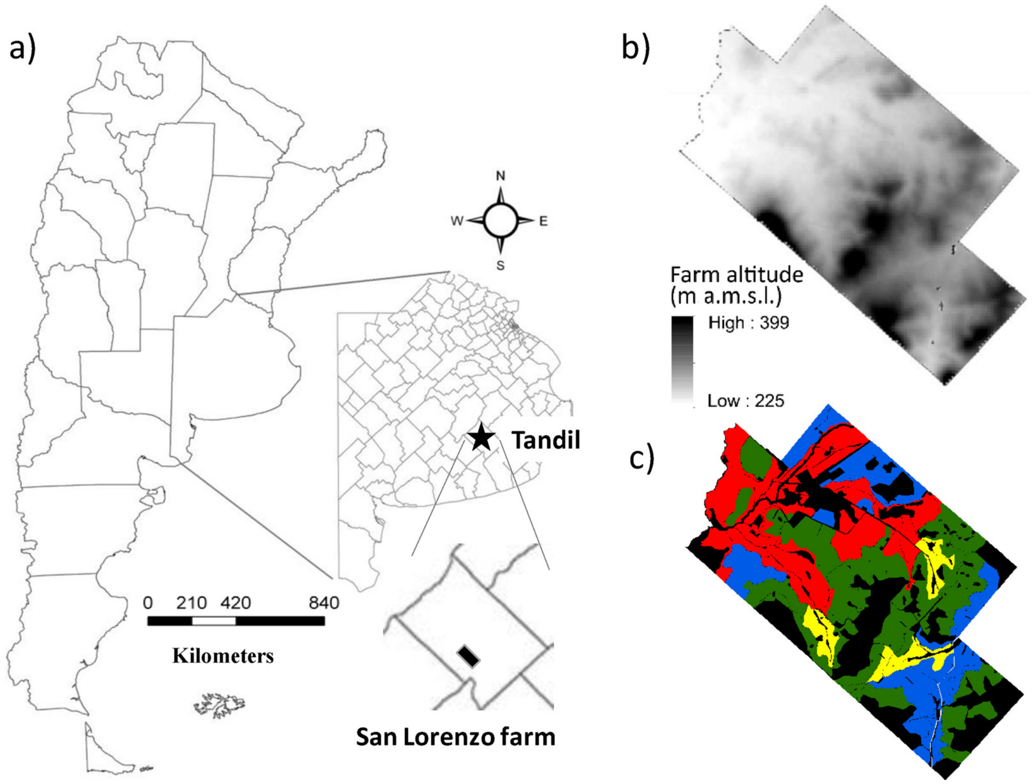

**Fig. 1.** a) Tandil department and San Lorenzo farm in the Pampas of Argentina, the scale is for the country map. b) San Lorenzo farm altitude map. c) San Lorenzo management zones, green = Zone 1, blue = Zone 2, yellow = Zone 3, red = Zone 4, and black = not for agricultural use. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

### *2.3.1. Soil depth*

During 1998–2000 soil depth and its effects on grain yield of soybean, wheat, sunflower and maize were measured (Sadras and Calviño, 2001). Soil depth effects are explained by soil water holding capacity. There was a marked difference in grain yield response to soil depth among crop species. The yield-based ranking of tolerance to shallow soil, wheat ≥ soybean > sunflower > maize, was mostly accounted for by: i) cropping season (autumn to late spring for wheat vs. spring to autumn for summer crops), ii) timing of the most critical period for yield determination (later in soybean than in sunflower and maize, Calviño and Monzon, 2009), and iii) plant features related to vegetative and reproductive plasticity (Sadras and Calviño, 2001). Maize showed the least tolerance to shallow soils mainly because of its high susceptibility to stress during the critical period around flowering (Cerrudo et al., 2013) and the high probability of drought occurrence during this stage (Calviño et al., 2003c).

From the 1999/2000 cropping season onwards, maize was progressively excluded from Zone 1 and 2 based on productive and economic results, this process was completed by 2002/03. Following the exclusion of maize, barley was incorporated in the crop sequence. This crop is sown at the same time as wheat but is harvested 10 days earlier. This change allowed for higher yields of Soy2 due to earlier sowing (Calviño et al., 2003a). Currently, Zone 1 and 2 soils are under a three years crop sequence of barley/Soy2-wheat/Soy2-Soy1 or sunflower, whereas maize is kept in Zones 3 and 4 where the crop sequence is maize-maize-Soy1 (Table 1).

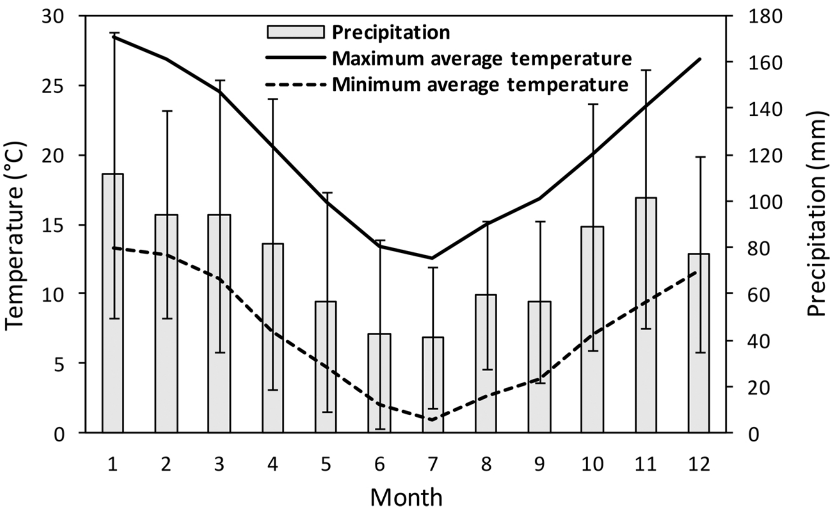

**Fig. 2.** Monthly average precipitation, maximum and minimum average temperatures for Tandil department, Argentina (from 1989 to 2015). Bars show standard deviation of precipitation.

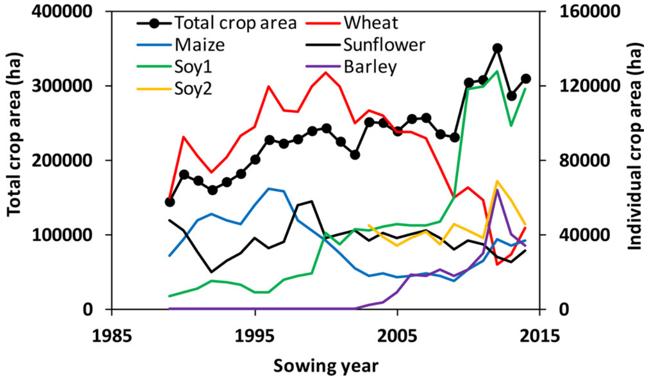

**Fig. 3.** Evolution of total crop area (left axis) and individual crop area (right axis) for Tandil department as function of sowing year (1989 to 2014); data from Ministry of Agroindustry (https://datos.agroindustria.gob.ar/). Soybean includes: i) soybean sown as a single crop per year (Soy1), and ii) double-cropped soybean following a winter cereal (Soy2). Total crop area does not include Soy2.

**Table 1**
a) San Lorenzo management zones based on three topographic criteria: soil depth, frost risk (minimum temperature < 0 °C) and water table influence. A threshold of 3.0 m below soil surface was used to discriminate water table influence (Nosetto et al., 2009). Values between brackets indicate percentage of cropping area. b) Four simulated scenarios including zone-specific crop sequences and sowing dates. Soy 1 is soybean sown as a single crop per year and Soy 2 is double-cropped soybean following a winter cereal.

**a) Management zones**

| **Criteria** | **Definition** | | | |
|---|---|---|---|---|
| | **Zone 1 (42)** | **Zone 2 (25)** | **Zone 3 (6)** | **Zone 4 (27)** |
| Soil depth | < 0.8 m | 0.8 to 1.8 m | > 1.8 m | |
| Frost risk | Low | Low | Low | High |
| Water table | No | No | No | Yes |

**b) Simulated scenarios**

| **Scenario**[a] | **Crop sequence and sowing date** | | |
|---|---|---|---|
| BASE | Wheat/Soy 2 - Maize - *Soy 1*[b]<br>20 Jul/7 Jan – 25 Oct – *20 Nov* | | |
| SOIL DEPTH | Wheat/Soy 2 - Barley/Soy 2 - *Soy 1*<br>20 Jul/7 Jan – 20 Jul/26 Dec – *20 Nov* | Maize – Maize - *Soy 1*<br>25 Oct – 25 Oct – *10 Nov* | |
| FROST | Wheat/Soy 2 - Barley/Soy 2 - *Soy 1* | Maize – Maize - Soy 1 | Maize – Maize - *Soy 1*<br>10 Nov – 10 Nov – *10 Nov* |
| WATER TABLE | 1 Jun/1 Jan – 1 Jun/21 Dec – *20 Nov* | 5 Oct – 5 Oct – 10 Nov | Plus adjustments in maize density |

[a] Scenarios are BASE, encompassing a typical crop sequence and management irrespective of zone; DEPTH where crop sequence is tailored to soil-depth based zones, FROST: similar to DEPTH, plus adjustments accounting for frost risk; WATER TABLE, similar to FROST, plus adjustments to take advantage of high water supply from water table.

[b] Wheat/Soy 2 in year 1, Maize in year 2 and Soy 1 in year 3.

### *2.3.2. Frost risk*

Slopes in San Lorenzo range from 0.5 to 7.5%, with most of the acreage between 2.5 to 6.0%. For several years the farmer observed that frost damage was more severe in the lowland than in the upland zones. These differences were quantified using temperature sensors in 2006. Minimum temperature in the lowland was around 2 °C lower than in the upland zones with no differences in maximum temperatures. Assuming a 20% frost risk (we considered frost when temperature < 0 °C), the first frost occurred 21 days earlier and the last frost 33 days later in the lowland in comparison to the upland zones, yielding frost free periods of 203 and 149 days for the upland and lowland zones, respectively.

The lower frost risk associated with upland zones allows sowing of wheat and barley 40 days earlier than in the lowland zones, with a similar frost risk. Early sowing increased modeled wheat grain yield by 3.7% (250 kg $ha^{-1}$) in deep soils (1.40 m depth, Zone 2) and by 6.6% (370 kg $ha^{-1}$) in shallow soils (0.80 m depth, Zone 1). The early sowing to anticipate wheat flowering in the uplands increased Yw because of lower vapor pressure deficit that leads to higher water use efficiency during reproductive growth (Abbate et al., 2004) and, to a lesser extent, higher photothermal quotient (Fischer, 1985). For a 1st of June sowing, simulations showed that anthesis occurred 11 days earlier and harvest 7 days earlier than in a 10 July sowing. This allowed advancing Soy2 sowing which has a strong effect in yield in this cool-temperate region (Calviño et al., 2003b; Monzon et al., 2007). The actual increase in Soy2 yields associated with this sowing anticipation was of 250 kg $ha^{-1}$ in both shallow and deep soils (Zone 1 and 2, Calviño et al., 2003a; Monzon et al., 2007). The winter crop/Soy2 was excluded from Zones 3 and 4. In Zone 3, winter crop/Soy2 was less profitable that maize-maize-Soy1 crop sequence. In Zone 4, winter crop/Soy2 was excluded because the short frost-free period does not allow completing Soy2 grain filling, the most critical stage in this crop (Andrade, 1995). Short cycle soybeans for Soy1 were selected to suit the short frost-free period in Zone 4. These cultivars show high yield potential because they compensate a short duration of the critical stages with high crop growth rates (Calviño et al., 2003b). Finally, maize sowing was delayed to early November in Zone 4 (Table 1) because of the high late frost risk.

### *2.3.3. Water table*

A comparison between maize yield data from yield map monitors and water table depth at San Lorenzo showed a positive influence of water table on crop yields in several areas of the farm. Water quality from this source was adequate for crops (ECw < 0.5 dS $m^{-1}$, SAR < 0.3). Since 2008 the zones with presence of water table were identified and the water table dynamic was measured and related to crop water consumption and precipitation at different positions of the farm and through the cropping season.

From sowing to commercial maize maturity, the water table depression averaged 1.0 m and varied from 1.5 m in a dry season (2008/09), to 0 m in seasons with positive water balances (2009/10, 2014/15). From May to October the water table stayed at a similar depth. Thus, the acreage with water table influence can be estimated before maize sowing and crop management can be adjusted accordingly. Around 27% of San Lorenzo farm is influenced by a water table, strongly associated with low topographic positions and high frost risk (Fig. 1c, Zone 4).

In Zone 4, maize yields are high and stable, and the most profitable crop sequence is two consecutive maize crops, followed by one year of Soy1 to reduce the amount of straw (Table 1). Crop management was adjusted according to water availability and expected Yw (Andrade et al., 2005; Aramburu Merlos et al., 2015). When water table is deeper than 2.4 m from the surface, maize density is set between 6.0 and 6.5 pl $m^{-2}$ and N fertilization is adjusted to a target Yw of 9000 kg $ha^{-1}$.When water table is 1.5 to 2.4 m depth (Nosetto et al., 2009), maize density is set to 7.5-8.0 pl $m^{-2}$ and N fertilization is adjusted to a target Yw of 11,000 kg $ha^{-1}$.

## 2.4. *Quantification of zone management impact*

We combined several measures to assess the impact of zone management, including farm output, crop yield and yield gaps, economic performance and simulation scenarios.

### *2.4.1. Farm output, crop yield and yield gaps*

The amount of grains that can be produced in a hectare (farm output) was estimated as the total amount of grains produced in the farm divided by the total crop area of the farm (total crop area does not include Soy2). Farm output and individual yield gain rates were estimated for the whole time series (1989/90 to 2014/15) using actual grain yields (Ya) for barley, wheat, maize, sunflower, Soy1 and Soy2 from San Lorenzo records and for Tandil using data from Ministry of Agroindustry (https://datos.agroindustria.gob.ar/). Grain yield was expressed at commercial moisture: 14.0% for wheat, 14.5% for maize, 12.5% for barley, 11.0% for sunflower and 13.5% for soybean. Yield grain rates were expressed in kg $ha^{-1}$ $y^{-1}$, or % $y^{-1}$ (relative to 2010 yield) as proposed by Fischer et al. (2014).

Yield gaps were estimated for both Tandil and San Lorenzo as $Yg = Yw – Ya$, and expressed as percentage of Yw, where Y means yield, and subscripts indicate gap (g), actual (a) and water-limited (w) (van Ittersum et al., 2013). Attainable yield was estimated to be 80% of Yw since economic drivers lead to an irreducible yield gap of about 20% in rainfed cropping (i.e. $Ya/Yw = 0.8$) (van Ittersum et al., 2013; Sadras et al., 2015; van Dijk et al., 2017). To estimate Ya we used a time series long enough to capture seasonal variation, and short enough to avoid large technological trends (Calviño and Sadras, 2002; van Ittersum et al., 2013; Sadras et al., 2015). Following this principle, the last seven seasons of our data base were used to calculate average Ya (Aramburu Merlos et al., 2015). Yw was derived from Aramburu Merlos et al. (2015).

### 2.4.2. Economic analysis

The economic performance of San Lorenzo and Tandil was compared using Ya and the corresponding crop sequences for the 2008–2014 period, and historical on-farm costs and commodity prices (Table 2). Total crop costs (including harvest) and net farm prices (market price minus transport and trade costs) were obtained from the Research and Development unit of CREA (Regional Agricultural Experimentation Consortia, www.crea.org.ar) and San Lorenzo farm data base. Net farm prices (US\$ $ton^{-1}$) were 175, 159, 115, 263, 276, 257 for wheat, barley, maize, Soy1, sunflower and Soy2, respectively. Gross margins were calculated as net income (net farm price by quantity) minus total costs (crops costs + farm expenses), expressed in current US \$ $ha^{-1}$.

**Table 2**

Actual grain yield (Ya, 2008–2014 average), Ya percentiles (20 and 80%, between brackets), grain yield ratio, and yield gain rates from 1989 to 2014, expressed in kg $ha^{-1}$ $year^{-1}$ (standard error between brackets), and in % $y^{-1}$ (italics) in relative terms to 2010 yields (Fischer et al., 2014) for San Lorenzo farm and Tandil department. Soy 1 is soybean sown as a single crop per year and Soy 2 is double-cropped soybean following a winter cereal. Data sources: farm records for San Lorenzo, and Ministry of Agroindustry for Tandil (https://datos.agroindustria.gob.ar/).

| | Ya (kg $ha^{-1}$) | | Grain yield ratio [a] | Yield gain rate (kg $ha^{-1}$ $year^{-1}$, % $y^{-1}$) | |
|---|---|---|---|---|---|
| Crop | Tandil | San Lorenzo | | Tandil | San Lorenzo |
| Barley | 4757<br>(4380-5320) | 5877<br>(5307-6396) | 1.24 | 140 (26)<br>*3.0* | [b] |
| Wheat | 4678<br>(3950-5254) | 5724<br>(4723-6418) | 1.22 | 101 (16)<br>*2.3* | 107 (22)<br>*1.9* |
| Maize | 6380<br>(4800-7647 | 9651<br>(8770-10801) | 1.51 | 116 (30)<br>*1.9* | 183 (36)<br>*2.0* |
| Soy1 | 2369<br>(2160-2580) | 2845<br>(2514-3233) | 1.20 | 28 (10)<br>*1.1* | 43 (11)<br>*1.5* |
| Soy2 | 1371<br>(1160-1500) | 1147<br>(885-1447) | 0.84 | [b] | [b] |
| Sunflower | 2300<br>(2140-2580) | 3052<br>(2742-3321) | 1.33 | 33 (8)<br>*1.5* | 52 (9)<br>*1.8* |

[a] San Lorenzo / Tandil.

[b] not significant ($P > 0.05$).

### 2.4.3. Simulation scenarios

The process of dividing San Lorenzo in management zones included three overlapping steps (section 2.3.). The contribution of every step to the farm output and it variability is not easy to determine because of the overlapping among these steps. Thus, we used crop models to separate and quantify the contribution of the different steps of the zone management process to farm output. The simulated scenarios were crop sequences and crop management as indicated: i) BASE, typical for Tandil department, ii) DEPTH, adjustments based on soil depth, iii) FROST, adjustments based on frost risk as associated with topography, and iv) WATER TABLE, similar to iii) in Zones 1, 2 and 3 and adjusted for influence of water table in Zone 4 (Table 1).

Data on crop management practices not included in Table 1 were retrieved from San Lorenzo data base. Dominant soil series were based on the National Research Institute of Agricultural Research (http://geointa.inta.gov.ar/), and corroborated with on farm measurements. Functional soil properties required to run models (e.g., lower and upper limits of soil moisture) were derived from soil series descriptions following Ritchie and Crum (1988), as revised by Gijsman et al. (2003). Maximum rooting depth for wheat, maize and soybean was set at 1.8 m except where a caliche layer restricts root growth (Dardanelli et al., 1997). In order to account for the previous crop effect on soil water, the entire crop sequence was simulated (Sequence module), assuming 50% of plant available soil water in the first year of the time series. No nutrient limitations to crop growth were assumed. Water table effects were simulated as an increase in water holding capacity (soil depth was set to 3.0 m), corroborated with on farm yield data. Soy2 was sown as early as possible based on estimated winter crop harvest date (Monzon et al., 2007).

Simulations were performed using CERES-Barley, CERES-Maize, CERES-Wheat, and CROPGRO-Soybean models embedded in DSSAT v 4.5 (Jones et al., 2003; Hoogenboom et al., 2010). Genetic coefficients were derived from Mercau et al. (2007, 2014), Monzon et al. (2007, 2012), and Aramburu Merlos et al., (2015). Daily maximum and minimum temperature and precipitation were derived from Tandil weather station (-37° 14´, -58° 14´, http://siga2.inta.gov.ar, 45 km N from San Lorenzo). NASA-POWER (http://power.larc.nasa.gov/) was used as source of daily solar radiation. The models were evaluated by comparison of simulated and measured yields from well-managed rainfed and irrigated field experiments that explored a wide range of sowing dates, sites, years, and water availability (see in Fig. 1 Aramburu Merlos et al., 2015). The sunflower crop was excluded from this analysis because the model has not been calibrated for our conditions.

## 3. Results

### 3.1. Farm output evolution

On a grain yield basis, the farm output increased at 102.6 and 43.6 kg $ha^{-1}$ $year^{-1}$, or 1.9 and 1.2% $year^{-1}$ (in relative terms to 2010 yields, Fischer et al., 2014), for San Lorenzo and Tandil, respectively (Fig. 4). Farm output was 54% higher in San Lorenzo than in Tandil (5571 vs 3621 kg $ha^{-1}$, $year^{-1}$, 2008–2014 average, Fig. 4). On a glucose equivalent basis, the farm output for San Lorenzo was 45% higher than in Tandil (7755 vs 5343 kg $ha^{-1}$ $year^{-1}$ Fig. 4), as a consequence of the higher proportion of soybean for Tandil in comparison with San Lorenzo.

There was a strong positive correlation between San Lorenzo and Tandil detrended grain yields ($0.57 < R < 0.85$ for all crops, $P < 0.01$), highlighting the dominant seasonal effect as a source of variation in yield and the agronomic relevance of the comparison

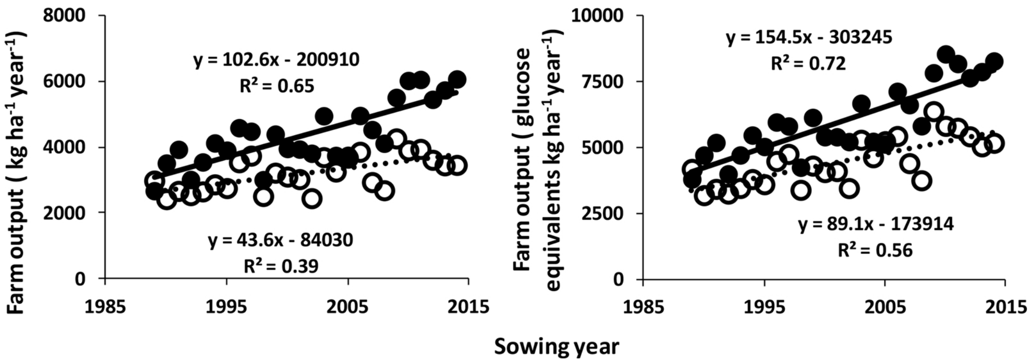

**Fig. 4.** Farm output expressed as grain (left) or glucose equivalent (right) as a function of the sowing year (1989–2014) for San Lorenzo (full circles) and Tandil department (empty circles). See Andrade et al, (1995) to convert grain values to glucose equivalents. Farm output was estimated as the total amount of grains produced in the farm divided by the total crop area of the farm (total crop area does not include Soy2). Data sources: farm records for San Lorenzo, and Ministry of Agroindustry for Tandil (https://datos.agroindustria.gob.ar/).

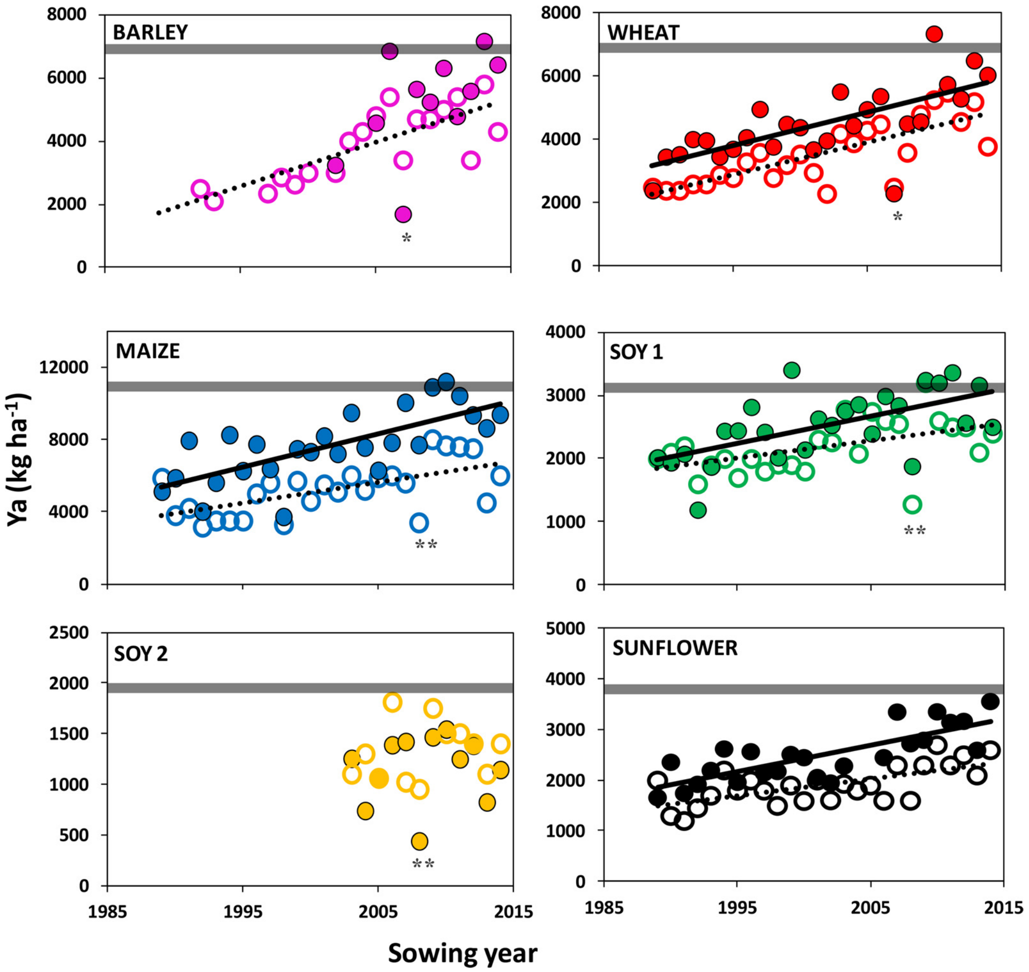

**Fig. 5.** Actual grain yield (Ya) for different crops as a function of sowing year (1989–2014) in San Lorenzo farm (full symbols) and Tandil department (empty symbols). Horizontal grey lines indicate water-limited yield potential (see Table 3 for more details). The regression lines are shown when statistically significant (full line for San Lorenzo and dashed line for Tandil). Table 2 shows regression slopes. Asterisks indicate low yields related to anomalous events: * strong late frost event (14 Nov 2007), and ** low precipitation in 2008/09 (46% below the annual mean). Soy 1 is soybean sown as a single crop per year and Soy 2 is double-cropped soybean following a winter cereal. All yields expressed at their corresponding commercial moisture. Data sources: farm records for San Lorenzo, and Ministry of Agroindustry for Tandil (https://datos.agroindustria.gob.ar/).

between these two data sources. Grain yields were higher in San Lorenzo than in Tandil except for Soy2 (Fig. 5, Table 2), despite the lower soil productivity index of San Lorenzo. Yield gain rates in San Lorenzo were higher or similar to those in Tandil (Table 2). Grain yield ratio indicated that San Lorenzo out-yielded Tandil by 38–48% for sunflower and maize and by 15–20% for Soy1, wheat and barley (Table 2).

Yg were lower for San Lorenzo than for Tandil with the only exception of Soy 2, and varied from 9 to 41% for San Lorenzo and from 24 to 43% for Tandil (Table 3). Extrapolating from yield gain rates (Table 2), Tandil would reach 80% of Yw by 2013 to 2036 depending on crop, while San Lorenzo already reached this benchmark between 2001 to 2012 (Table 3). San Lorenzo grain yields are on average 15 years ahead of Tandil department, with a minimum of 6 years for wheat and a maximum of 24 years difference for sunflower (Table 3).

Ya data from Tandil and San Lorenzo were detrended to 2014 to estimate Yg for every crop season (from 1989 to 2014) and related to Yw values. In San Lorenzo and Tandil, Yg had a positive relationship with Yw (Fig. 6), probably reflecting that crop management is better adjusted to low Yw years. Yield gaps in San Lorenzo were lower than those for Tandil at all levels of Yw provided Yg are > 0. In general, the difference in Yg between both locations tended to increase with Yw with the exception of soybean at Yw > 4500 kg ha$^{-1}$.

The amount of crops per hectare per year, or crop intensity, varied between San Lorenzo and Tandil (2008–2014 average, $P < 0.01$), and was related to the percentage of winter crop/Soy2. In San Lorenzo, crop intensity was 1.32 (from 1.21 to 1.40) i.e. 32% of San Lorenzo has Soy2, whereas in Tandil, crop intensity was 1.16 (from 1.12 to 1.21).

**Table 3**
Water-limited yield potential (Yw) and yield gap (Yg, 2008–2014 average) for both San Lorenzo farm and Tandil department. Yield gap is the difference between Yw and actual yields (Ya), expressed as percentage of Yw. Year to reach 80% Yw was based on linear extrapolation of yield gain rates in Table 2; Soy2 was not calculated because the rate of yield change was not significant (Fig. 5). Soy 1 is soybean sown as a single crop per year and Soy 2 is double-cropped soybean following a winter cereal. Data sources: farm records for San Lorenzo, and Ministry of Agroindustry for Tandil (https://datos.agroindustria.gob.ar/) for Ya.

| Crop | Yw (kg $ha^{-1}$) | Yg (%) | | Year to 80% Yw | |
|---|---|---|---|---|---|
| | | Tandil | San Lorenzo | Tandil | San Lorenzo |
| Barley | 6909 [a] | 31 | 15 | 2016 | 2010 |
| Wheat | 6909 [a] | 42 | 17 | 2021 | 2011 |
| Maize | 10944 [a] | 43 | 12 | 2032 | 2007 |
| Soy1 | 3124 [a] | 24 | 9 | 2013 | 2001 |
| Soy2 | 1954 [a] | 30 | 41 | | |
| Sunflower | 3800 [b] | 39 | 20 | 2036 | 2012 |

[a] from Aramburu Merlos et al., 2015.
[b] from Hall et al., 2013.

### 3.2. Economic analysis

The gross margin of San Lorenzo was 112 US\$ $ha^{-1}$ $year^{-1}$ higher than that for Tandil (Fig. 7). This difference was related to a 244 US\$ $ha^{-1}$ $year^{-1}$ higher net income in San Lorenzo despite 132 US\$ $ha^{-1}$ $year^{-1}$ higher total cost. This difference in total cost relates to a higher cropping intensity in San Lorenzo (1.32 vs 1.16 crops per year), a lower frequency of Soy1 (a less expensive crop to grow), and a greater frequency of the more expensive maize and winter crop/Soy2 compared to Tandil.

### 3.3. Modeled impacts of zone management

Simulated crop yields (Yw) increased 48% and 12% for maize and Soy2, respectively, from the BASE to the WATER TABLE scenario, with no significant changes for wheat, barley and Soy1 (Fig. 8a). For the BASE scenario, simulated farm output for San Lorenzo was 6292 kg $ha^{-1}$ $year^{-1}$, with a maize:soybean:wheat ratio of 48:31:21 (BASE, Fig. 8b). This benchmark was used to evaluate the single effects of the different steps of the zone management process, with the associated crop sequence and management (section 2.3.). When crops were managed according to soil depth (DEPTH, Fig. 8b), farm output increased 15% compared to the BASE scenario. An additional 5% was added when sowing dates were adjusted as a function of frost risk (FROST, Fig. 8b). The crop models used did not take into account the effect of frost, so yield increases were exclusively associated with changes in sowing dates (Table 1). Finally, consideration of the effect of the water table on maize and soybean added 3% to farm output and returned a total of 7768 kg grain $ha^{-1}$ $year^{-1}$ (WATER TABLE, Fig. 8b). From the BASE to the highest yielding scenario, farm output increased 23%. On the other hand, farm risk as reflected in the farm output CV (coefficient of variation) was reduced from 31% in the BASE scenario to 25% in the WATER TABLE scenario (Fig. 8b).

Increases across scenarios reflected changes in both simulated yields and proportions of individual crops (Table 1). Farm output (sunflower excluded) based on Ya was 78% of the simulated farm output for the WATER TABLE scenario for San Lorenzo (6067 vs. 7768 kg grain $ha^{-1}$ $year^{-1}$, Fig. 8b), in line with the suggested 80% of Yw for the attainable yield (Cassman et al., 2010; van Ittersum et al., 2013; Sadras et al., 2015), whereas for Tandil Ya was 49% of the simulated values (3797 vs. 7768 kg grain $ha^{-1}$ $year^{-1}$, Fig. 8b),.

The impact of zone management on farm output and farm output CV varied across zones (Table 4). Three main pattern were identified: i) increase in farm output and decrease in farm output CV (Zone 1), ii)

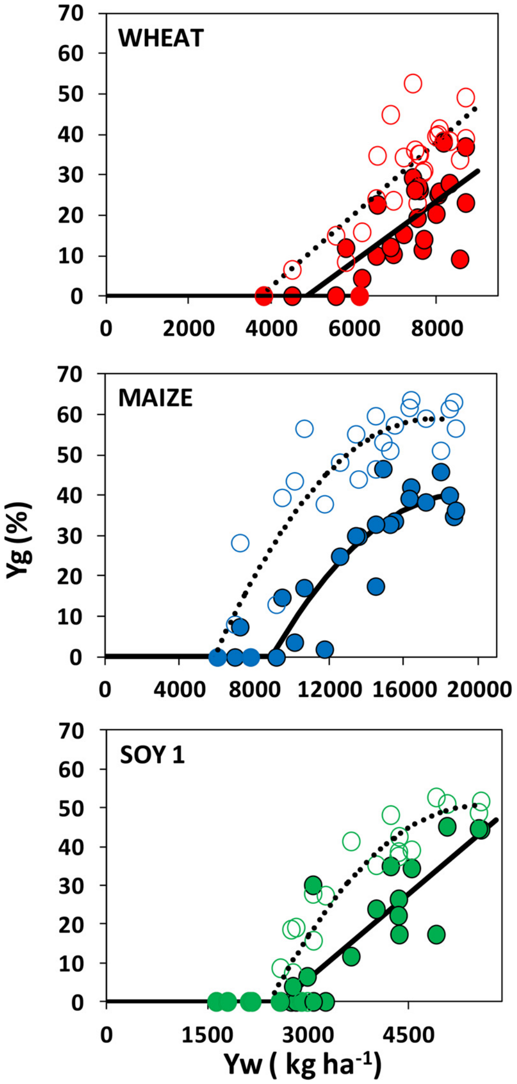

**Fig. 6.** Yield gap (Yg, 2008–2014 average) as a function of water-limited yield potential (Yw) in San Lorenzo farm (full symbols, regression in black lines) and Tandil department (empty symbols, regression in dashed lines). Yield gap is the difference between Yw and actual yields (Ya), expressed as percentage of Yw. When Ya > Yw we assumed that Yg = 0. Data sources: farm records for San Lorenzo, and Ministry of Agroindustry for Tandil (https://datos.agroindustria.gob.ar/) for Ya and simulated values for Yw.

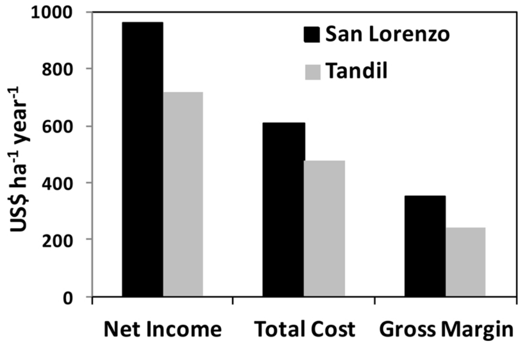

**Fig. 7.** Average annual net income, total cost and gross margin for San Lorenzo farm and Tandil department (2008–2014 average). Actual yield data from Table 2.

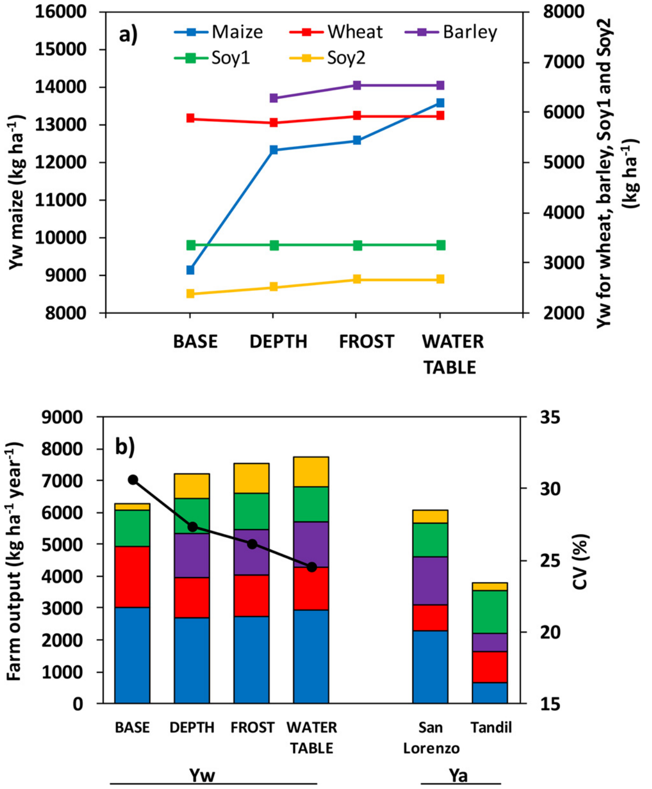

**Fig. 8.** a) Water-limited yield potential (Yw) for individual crops for the different scenarios. b) Farm output for San Lorenzo based on Yw and actual yields (Ya, 2008–2014 average) for San Lorenzo farm and Tandil department. Farm output was estimated as the total amount of grains produced in the farm divided by the total crop area of the farm (total crop area does not include Soy2). The coefficient of variation (CV) for the simulated farm output scenarios is included. Owing to the lack of calibrated model, sunflower was excluded from the analysis.

**Table 4**
Farm output and farm output coefficient of variation for the different zones of San Lorenzo based on Yw for the initial (BASE) and final scenarios (WATER TABLE). Farm output was estimated as the total amount of grains produced in the farm divided by the total crop area of the farm (total crop area does not include Soy2).

| | Farm output (kg $ha^{-1}$ $year^{-1)}$ | | Change | Farm output CV | | Change |
|---|---|---|---|---|---|---|
| | BASE | WATER TABLE | | BASE | WATER TABLE | |
| Zone 1 | 4849 | 6068 | 25% | 35% | 27% | −23% |
| Zone 2 | 6778 | 7295 | 8% | 33% | 24% | −28% |
| Zone 3 | 7819 | 9618 | 23% | 29% | 29% | 0% |
| Zone 4 | 7571 | 10510 | 39% | 30% | 29% | −2% |

minor changes in farm output and decrease in farm output CV (Zone 2) and iii) increase in farm output and no changes in farm output CV (Zone 3 and 4).

## 4. Discussion

Yield increments required to meet increasing demand for food and feed cannot rely mainly on the expansion of the cultivated land (Lobell et al., 2009; Andrade, 2016). Consequently, the greatest efforts to increase production should focus on the intensification of land use. There is however, an important trade-off whereby increasing inputs to close yield gaps leads to reduced input use efficiency, particularly important for nutrients (Sadras and Denison, 2016) and to environmental damage. Intensification should therefore focus on technologies based on processes and knowledge (Andrade, 2016; Cassman, 2017). These novel technologies can lead to i) input use reductions and preservation of resource base without yield penalties, ii) increases in production while maintaining the levels of input use and, when necessary, iii) increases in input application without reductions in input use efficiency (Byerlee, 1992). This paper presents a clear example of this type of technologies driving a substantial increase in production in a real farm.

It is important to make the distinction between the requirements to develop a “potential” technology in a research setting, and the requirements for technologies to become “actual” in farms. Development of potential zone-management technologies requires accurate data on the variability in soil properties and climatic variables, as well as relevant knowledge of crop response to this variability (Cassman, 1999, 2017). With the increasing capacity to characterize environments at the relevant spatial scales, we argue that knowledge of crop responses is the bottleneck for developing such technologies. The step from a “potential” to an “actual” technology implemented in real farms requires three conditions; the technology must increase profit by increasing yield, reducing cost or both; it must fit with the overall management of the farm; and it should be environmentally neutral or positive.

The long-term engagement between farmers and scientists was critical to both the development and implementation of these technologies in San Lorenzo (Calviño and Sadras, 1999, 2002; Sadras and Calviño, 2001; Calviño et al., 2003a, b,c; Monzon et al., 2007; Calviño and Monzon, 2009). As a result, the performance of this farm in terms of farm output, farm risk, crop yields and economic performance is superior to its surrounding farming environment. The farm output is a simple measure that allowed us to compare the impact of zone management at a farm level, taking into account differences in crop yields and crop sequences between farms. Assuming a required annual intake of 500 kg $ha^{-1}$ per head (Connor et al., 2011), San Lorenzo farm output could feed 11.0 persons per ha per year, compared with 7.2 persons per ha per year for Tandil. Taking the output of Tandil department (300.000 ha) to the level of San Lorenzo’s would feed an additional 1,000,000 people. Moreover, yield gain rates in San Lorenzo, 1.9% $y^{-1}$ for farm output and from 1.5 to 2.0% $y^{-1}$ for individual crop yields (in relative terms to 2010 yields) are above those required to meet projected demand for cereals in 2050, i.e. 1.1 to 1.3% $y^{-1}$(Hall and Richards, 2013; Fischer et al., 2014). The division of San Lorenzo farm into four management zones combined with adequate management practices were the main reasons that explain the higher productivity and lower risk of this farm in comparison to Tandil.

In a global context, Yg for Tandil are moderate (24–43%, Table 2), and yield gaps for San Lorenzo, except for Soy2, are even lower (9–20%). San Lorenzo takes more advantage of high yielding years as reflected by a lower Yg at the same level of Yw in comparison with Tandil. Moreover, Yg and farm output at San Lorenzo are close to those of low-risk cropping systems, e.g., maize in Nebraska, USA, where gaps are ~20% (Grassini et al., 2011). Double-cropped soybean yield was higher in Tandil, probably because cropping intensity (percentage of wheat + barley acreage sown with double-cropped soybean) was higher in San Lorenzo than in Tandil which implies a wider range of sowing dates, including late sowings which are associated with lower yields (Calviño et al., 2003a,b,c). Consistent with this finding, Egli (2008) reported a negative correlation between the rate of improvement in soybean yield and the frequency of double-crops in some counties of Kentucky, USA. Yield gap for Soy1 was only 9% for San Lorenzo and 24% for Tandil. Accordingly, Aramburu Merlos et al, (2015) found lower gaps for soybean in comparison with maize and wheat in Argentina.

Grain yield ratio between San Lorenzo and Tandil was higher for sunflower and maize (1.33 to 1.51) than for Soy1, wheat and barley (1.20 to 1.24). Our simulations showed that crop management as a function of soil depth was the practice that contributed most to yield increases in San Lorenzo. The exclusion of maize from shallow soils was crucial to increase the farm-level yield of this crop; recently, other practices have emerged to manage maize in environments prone to water deficits, including reduction in plant density (Andrade et al., 2005; Grassini et al., 2014), and delayed sowing to reduce the water deficit around the critical period (Maddonni, 2012; Caviglia et al., 2014). All these practices are being tested for the southern Pampas, and maize could become a profitable alternative for shallow soils with low frost risk (Cerrudo, A.A., personal communication).

Winter crops in San Lorenzo were excluded from the most productive soils (Zone 4), because of the better performance of summer crops in these environments. Winter crops yields remained unchanged, however, because of improved yields in Zone 1 and 2, associated with early sowing, that results in a more favorable water balance during grain filling (Abbate et al., 2004), that allowed to use higher yielding varieties and increasing doses of fertilizers with adequate practices. Advancing Soy2 sowing from 10 January to 20 December at Tandil increased both the average temperature during the R1–R7 stage (by 1.5 °C) and the crop season length (by 20 days) (Calviño et al., 2003b). The resulting higher temperatures increase radiation-use efficiency, pod set and grain filling rate in late-sown soybean (Calviño et al., 2003b). The increase in winter crop and Soy2 yield in Zone 1 and 2 and the restriction of the maize crop to Zone 3 and 4 had a dramatic impact on farm profit and risk. In San Lorenzo, the depth of the water table is measured 4 to 5 months before sowing to fine-tune cropping decisions. A water table between 1.5 and 2.4 m from surface favors yield (Nosetto et al., 2009; Mercau et al., 2016), and when this condition is met, sowing density and fertilizer rates are increased to capture additional yield. Otherwise a more conservative package is implemented.

As a result of the zone management process the farm output increased for all the zones of San Lorenzo (from 8 to 39%). Moreover the areas of the farm that were previously regarded has the most risky (Zone 1 and 2) now have lower farm output variability than the most productive areas (Zone 3 and 4).

Crop costs were higher (28%) in San Lorenzo than in Tandil, even though farm profit was enhanced by 46% (112 US$ ha$^{-1}$), driven by the sharp increase in net income (34%). Higher costs in San Lorenzo were mostly related to increased inputs, particularly fertilizer and seed; the cost of professional advice to implement management practices was less than 1 US$ ha$^{-1}$ highlighting the large return on investment of knowledge based technology.

During the last two years, the farm has focused on further opportunities for enhanced production, social and environmental outcomes. The following practices are being tested: a) nitrogen management for barley and wheat as a function of soil water content and climate forecasts at the beginning of the critical period for grain set (van Rees et al., 2014; Rodriguez et al., 2018), b) disease management for Soy1 as a function of precipitation during the critical period (Carmona et al., 2015), and c) soil water measurement to decide Soy2 sowing (Monzon et al., 2007).

Moreover, San Lorenzo has certified its crop production according to the protocol of the Argentinean Association of No-till Farm (http://www.aapresid.org.ar/ac). This implies ongoing training for employees, a careful control of soil nutrient and carbon balance, and a reduction in the toxicity of the agrochemicals used and how they are managed in the farm. Riparian areas of 30 m wide have been implemented along the stream that crosses the farm (even though they are not legally required), which have resulted in reduction of the level of pesticides measured at the exit of a stream at the farm.

## 5. Conclusions

In the terms of Julie Dehghani, “We’re in a maze, not a highway; there is nowhere that speed alone can take us”. The question must thus be asked – to what extent is agricultural production limited by information? and to what extent our conceptual tools, theories and their application are lagging behind, effectively constraining the potential of technologies focusing on data density?. This paper presents a clear example of a substantial increase in production and profit, and a reduction in risk based on zone management that links major aspects of environmental variation associated with soil and climate with crop physiological principles. This low cost technology is in contrast to the mainstream emphasis on big-data.

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