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# Using site-specific nitrogen management in rainfed corn to reduce the risk of nitrate leaching

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ABSTRACT

Managing nitrogen (N) to achieve yield potential and limit losses to the environment is challenging due to the temporal and spatial variability in crop N uptake which affects the distribution of soil-N. Nitrogen fertilization using site-specific management (SSM) is one of a number of strategies that can improve the efficiency of N use and reduce the losses of N to the environment from cropping systems. The aim was to assess: (i) corn (*Zea mays* L.) grain yield and N uptake; and (ii) soil residual- and potentially leachable-N, and its relationship with N and water use efficiency using SSM vs. uniform management (UM) strategies in high-(HP) and low-(LP) productivity zones on soils of the Inland Pampas of Argentina. Differences in soil residual- and potentially leachable-N, corn grain yield, N uptake, water and N use efficiency were compared between treatments. In HP-zones, corn grain yield and total biomass were 2.7 and 4.2 Mg ha$^{-1}$ higher with SSM than UM, and corn grain N uptake and total N uptake increased by 21% and 18% with SSM when compared to UM. Soil residual-N at field-scale was reduced by 18% with SSM. Marginal differences in potentially leachable-N among treatments were observed throughout the soil profile; the highest nitrate concentration was 6.6 mg kg$^{-1}$ in LP-zones with UM within the 210–240 cm soil layer. Overall corn water use efficiency in total biomass was 16% higher with SSM than with UM in both LP- and HP-zones. Using SSM in the LP-zones increased corn N use efficiency in grain and total biomass by 50% and 43% respectively. In this context, SSM can be considered as a conservation practice that optimizes N and water use efficiency by corn under dry conditions.

## 1. Introduction

Globally, application of nitrogen (N) fertilizer has increased dramatically in recent decades and is projected to exceed 186 million Mg N yr$^{-1}$ by 2050. An average 10–30% of total N inputs in cropping systems are typically lost due to nitrate leaching (Schepers and Raun, 2008) which has led to environmental contamination and concerns regarding use of N fertilizers (Hatfield and Prueger, 2004; Li et al., 2007; Rimski-Korsakov et al., 2004). Therefore, development of alternative N management strategies is vital for sustainable cereal-based cropping systems. Managing N to achieve yield potential and limit losses to the environment is challenging due to the temporal and spatial variability in crop N uptake which affects soil residual- and potentially leachable-N (Delgado et al., 2005). Nitrogen leaching losses have been found to be larger for corn (*Zea Mays* L.) than for other cereals (St. Luce et al., 2011). It is assumed that nitrate content in the top 150 cm of the soil profile is available to corn roots. Below the rooting depth there is no active N uptake by roots and there is the potential for N to leach downwards to the aquifer (Follet et al., 1994; Delgado et al., 2005). The amount of nitrate accumulated in the lower layers of the unsaturated zone in the soil profile is useful for predicting potential N leaching losses (Costa et al., 2002; Rimski-Korsakov et al., 2004). In long-term experiments with corn crop on soils of the Pampas Region, the mean leaching losses of nitrate-N at 150 cm soil depth from eight consecutive seasons increased as the N fertilizer rate increased, and were 20, 38 and 56 kg ha$^{-1}$ for the three N rates of 0, 100 and 200 kg N ha$^{-1}$ respectively. This indicates that in order

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*Abbreviations:* HP, high productivity; LP, low productivity; SSM, site specific management; UM, uniform management.

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to minimize N losses to the environment, it is vital to adequately adjust the N fertilizer rates (Aparicio et al., 2008).

Nitrogen fertilization using site-specific management (SSM) is one of a number of strategies to reduce the risk of N leaching in cropping systems (Khosla et al., 2002; Delgado et al., 2005). The benefit of implementing SSM is in the ability to adjust N fertilizer application to match crop requirements by identifying and managing homogeneous areas within a field. These areas are commonly termed as management zones and are defined as sub-regions having similar limiting factors for crop grain quality and yield (Moral et al., 2011; Peralta et al., 2015a,b). Site-specific fertilization rates can be determined upon zone-based yield potential from analysis of multi-year yield maps (Khosla et al., 2002). The general principles of the SSM technology are transferable but the specific fertilization strategy for a given field requires development using locally-based climate, soil and production variability information (Bramley, 2009).

The Pampas Region is considered one of the most suitable areas for grain crop production in the world (Hall et al., 1992) and is divided into four sub-regions (León, 1992; Fig. 1) mainly due to their contrasting soil attributes, relief and climatic conditions. The dominant soil type in the Pampas are temperate Mollisols (Soil Survey Staff, 2014), representing 35% of Argentinean area. These soils have an aeolian origin, and are comparable to other loess-derived soils of the main cropping regions of the world (e.g. United States, China, Ukraine). The Inland sandy Pampas sub-region is characterized by contrasting landscape systems with coarse texture soils that vary considerably in crop yield potential within relatively small distances. In cropping soils of the Inland Pampas with significant topographic gradients, grain yields of the major cereals (corn, wheat, soybean) in the lowland positions can be 2–3 times the yields in the upland positions (Niborski et al., 2004; Urricariet et al., 2011). Consequently, water and N availability for crop production in the Inland sandy Pampas is affected by highly variable soils that can be found at the field-scale. Increasing corn water use efficiency can improve N use efficiency, being the latter dependent on crop response to both N and water availability during the crop growing season (Hatfield and Prueger, 2004).

The major soil types of the Inland sandy Pampas are Typic Hapludolls in the uplands and Entic Hapludolls in the lowland landscape positions (Niborski et al., 2004). Since the in-field soil heterogeneity in the Inland Pampas can lead to great variability in corn yields (Nosetto et al., 2009), corn N uptake can be spatially variable within fields (Urricariet et al., 2011). In this context, an N fertilization strategy accounting for in-field variability such as SSM, is needed. However, most of the agricultural production is still conducted in regular fields under the assumption that the optimal practice is to use a single UM strategy (Bramley, 2009). In highly variable soils, N applications based on UM strategy can result in under- and/or over-fertilized areas within a field. In the latter case, there is a greater risk of nitrate leaching losses (Delgado et al., 2005). Nitrogen fertilization technologies using SSM have been shown to be more efficient than UM by increasing corn N use efficiency (Khosla et al., 2002) while sustaining maximum crop grain yield (Delgado et al., 2005).

In Argentina, 35% of the cultivated area has adopted Precision Agriculture tools, with SSM one of the main and most explored areas. However, there is still a need for the development of understanding of the factors affecting crop yield variability and N uptake to efficiently adopt SSM technology (INTA, 2013). Despite the increasing interest in Argentina, to date there are no studies that have reported the use of SSM to reduce the risk of nitrate leaching losses to the environment. This study aims to assess: (i) corn grain yield and N uptake; and (ii) soil residual- and potentially leachable-N, and its relationship with corn N and water use efficiency using SSM vs. UM strategies in high and low productivity zones.

## 2. Materials and methods

### 2.1. The study site

The study was conducted in Vedia, Province of Buenos Aires (34° 23′ S, 61° 35′ W) located in the Inland sandy Pampas sub-region (Fig. 1) on corn producing fields under no-tillage system. The crop

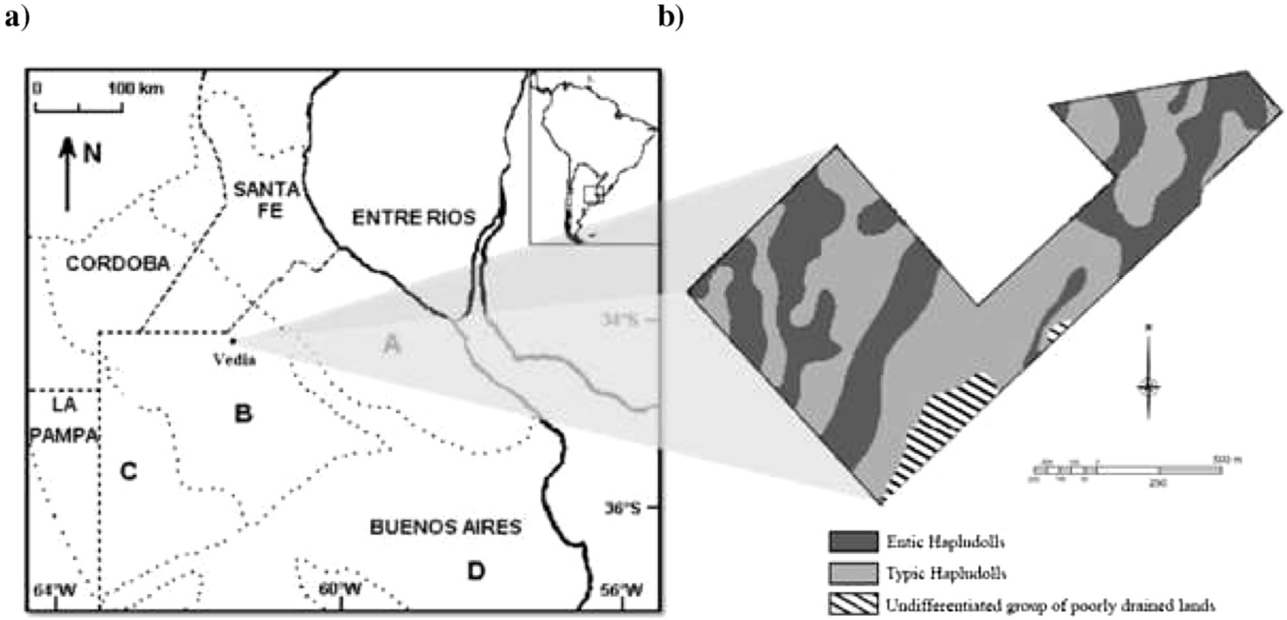

**Fig. 1.** Location of the study site in Argentina within South America and sub-regions of the Pampas (a). Dotted lines (• • •) indicate the boundaries of the sub-regions of the Pampas (León, 1992). A: Rolling Pampas, B: Inland sandy Pampas; C: Western Inland Pampas, D: Flooding Pampas. Dashed lines (–) indicate provincial boundaries. The right panel (b) shows the map soil at 1:20,000 scale of one the fields (area = 295 ha) representing the soil types (Soil Survey Staff, 2014) identified at field-scale. This map was generated by conventional methods from photo-interpretation of panchromatic photograms (1:20,000 scale). A preliminary map was developed using geomorphologic and physiographic integrated criteria. The final soil map was developed after checking for soil limits in the field. Soils were characterised by open-pits in which samples were collected and analysed in the laboratory. The approximate density of field observations was one pit every 35 has.

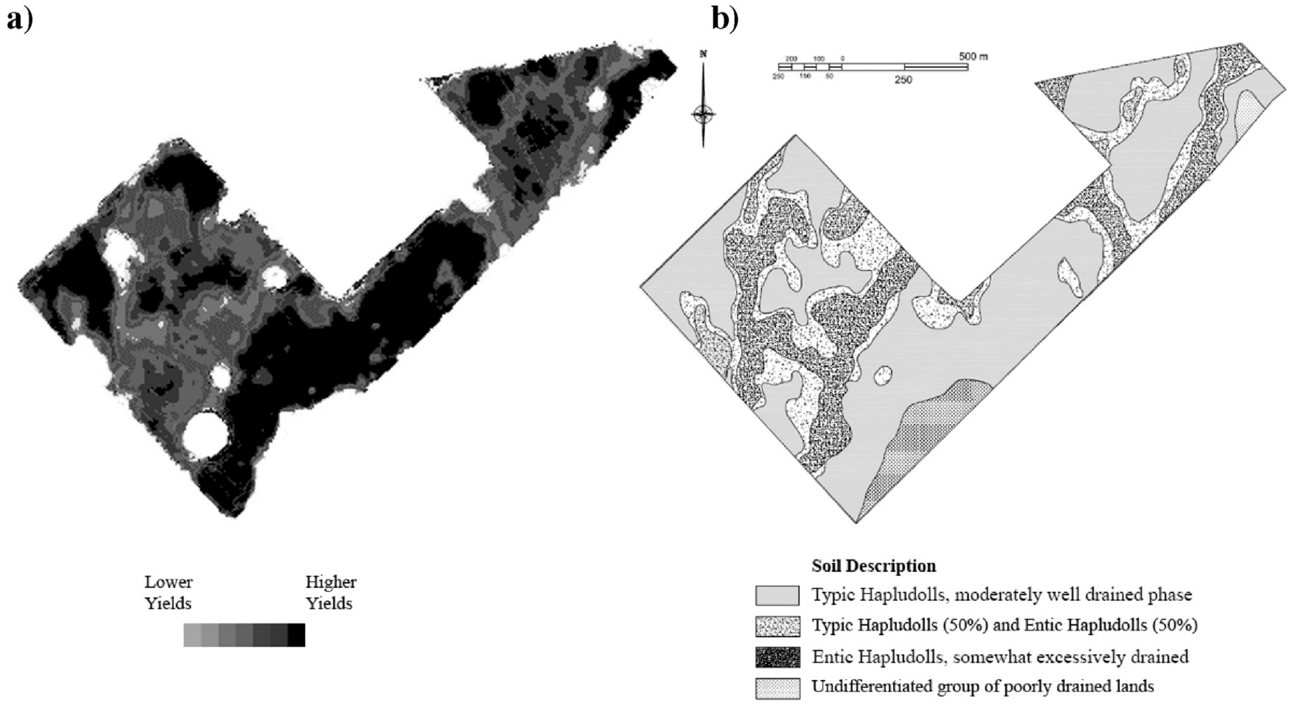

**Fig. 2.** An example of a multi-year (2000–2006) yield map (a) showing the relative crop yields in one field (area = 295 ha). White areas within the yield map indicate no recorded yield data; and an example of the re-definition of the soil map of the same field (b) obtained using the original soil map at 1:20,000 scale as illustrated in Fig. 1b, and the multi-year yield map that is shown in Fig. 2a.

rotation sequence was corn – wheat (*Triticum aestivum* L.)/late soybean (*Glycine max.* L., in the same season) – early soybean. Eight corn fields were selected over two corn growing seasons and soybean was the crop predecessor in each corn growing season (total analyzed area = 2000 ha).

### 2.2. Spatial variability of crop grain yield

The spatial dependence of crop grain yield was quantified using semivariograms to characterize and determine distribution patterns such as randomness, uniformity and spatial trend (Peralta et al., 2015a,b, 2016). The semivariogram shows the spatial correlation between two points in space as separation (lag) changes and it was estimated according to Isaaks and Srivastava (1989). The semivariograms for each field were used to interpolate the grain yield by means of ordinary kriging method, after checking for common geo-statistical assumptions. Geostatistical analysis was performed using the ArcGIS Geospatial Analyst (ArcGIS v9.3.1, Environmental System Research Institute Inc. (ESRI), Redlands, CA, USA). Crop yield data from the 6-year yield maps of previous crops (wheat, soybean and corn) of each field was interpolated (by ordinary krigging method) by direct average yields points within a radius of 15 m, resulting in a grid of 5 × 5 m (pixel), following the methodology proposed by Kitchen et al. (2005) and Peralta et al. (2016).

### 2.3. Management zone delineation

Management zone delineation in each field was performed according to zone-based grain yield using a multi-year yield map from 2000 to 2006 (e.g. Fig. 2a). The relative yields to average field yields for each map were calculated per pixel (yield per pixel/field average yield in each year x 100). Subsequently, the average yield from all yield maps was calculated and these data were averaged to obtain a map of historical yields in each field (Kitchen et al., 2005) as shown in Fig. 2a. Using the pre-existing soil map at 1:20,000 scale (Fig. 1b) and the multi-year yield map (Fig. 2a) the limits of the cartographic units were adjusted (Fig. 2b). The use of multi-year yield maps allowed a mapping segregation of the topographical sites and the location of the limits with a greater accuracy than the one obtained with the pre-existing soil map illustrated in Fig. 1b (Niborski et al., 2004; Urricariet et al., 2011). The segregation of the management zones was performed using the multi-year yield map, and the multi-year yield values and amplitude were classified by equal quantile areas (Peralta et al., 2013) using the Geostatistical Analyst in ArcGIS 9.3.1 (Environmental System Research Institute, Redlands, CA). As a result, two contrasting management zones in all fields were identified: high-productivity (HP) and low-productivity (LP) zones (e.g. Fig. 3). The HP-zones showed an average crop grain yield of 20% above field average, whereas LP-zones showed an average yield of 30% below the field average.

An elevation survey was performed in all fields using a total station (Kolida R455). The study sites have a maximum gradient of 0.006–0.019 m $m^{-1}$; HP-zones have an average relative elevation of 0.75 m below the field average, whereas LP-zones have an average relative elevation of 0.83 m above the field average. From the interpretation of the soil maps and multi-year maps (8 fields), the proportion of each management zone was estimated; LP-zones of the study sites represent an average 35% of the total weighed productive area of the field, with HP-zones accounting for the remaining 65%.

### 2.4. Experimental design and nitrogen fertilizer rates

The experiment followed a split-plot design with 4 treatments and 8 replicates. The whole-plot effect was the “management zone” with two levels (LP- and HP-zones) and the sub-plot effect was the “N fertilization strategy” with two levels (site-specific management –SSM- and uniform management –UM-); both single effects and their interaction were treated as fixed effects. The experiment has eight blocks that resulted from the combination of four different “fields” in two “seasons”, being that both corn growing seasons were very similar (i.e. 2007–2008 and 2008–2009). Block effect was treated as a random effect in the model.

The N fertilization rate was estimated based on the economic optimal rate according to corn yield potential, with locally adjusted fertilization recommendation models (Salvagiotti et al., 2011) as defined in Eq. (1). Corn yield potential was estimated from the attainable yield in each management zone. Attainable yield was defined from the historical average corn yield records (2000–2007) in each management zone and was on average 6.3 and 11.1 Mg ha$^{-1}$ in LP- and HP- zones. Assuming that the attainable yield is 75% of the corn yield potential (Sadras et al., 2015), corn yield potential was on average 8.4 and 14.8 Mg ha$^{-1}$ in LP- and HP- zones.

$$\begin{aligned}
&\text{N fertilizer rate}\,(\text{kg ha}^{-1}) = [\text{corn N requirement} \\
&\quad (\text{kg N Mg yield}^{-1})\,\text{x yield potential}\,(\text{Mg ha}^{-1})] \\
&\quad -[\text{soil initial-N}-\text{soil mineralized-N}\,(\text{kg ha}^{-1})] \qquad (1)
\end{aligned}$$

For the UM strategy, the same N fertilizer rate was applied in HP- and LP-zones based on the average yield potential, soil initial-N and mineralized-N for the whole field. For the SSM strategy, different N fertilizer rates were applied in HP- and LP-zones based on the corn yield potential for each management zone. The corn N requirement was 22 kg N per Mg of grain yield on a dry matter basis (Ciampitti and García, 2011). Mean soil initial-N was the sum of nitrate-N to 60 cm depth prior to sowing and was 43 and 90 kg ha$^{-1}$ in the LP- and HP-zones, the estimated soil mineralized-N during the corn growing season was 78 and 108 kg ha$^{-1}$ in the LP- and HP-zones, based on measures of the N mineralization rates from previous studies on the site (Zubillaga et al., 2009).

Therefore, N fertilization technology based on management zones resulted in four treatments with eight replicates; LP-SSM: low-productivity zones with site-specific management, LP-UM: low-productivity zones with uniform management, HP-SSM: high-productivity zones with site-specific management, and HP-UM: high-productivity zones with uniform management. The fertilizer N rates in kg N ha$^{-1}$ of each replicate per treatment are listed in order as replicate 1–8 respectively; for LP-SSM: 69, 69, 64, 64, 74, 64, 51, 51; for HP-SSM: 138, 138, 129, 124, 115, 129, 133, 120; for both LP-UM and HP-UM: 120, 129, 110, 110, 92, 115, 106, 83. As an example, the mean effective N rates (eight replicates) for each treatment were shown in Fig. 3.

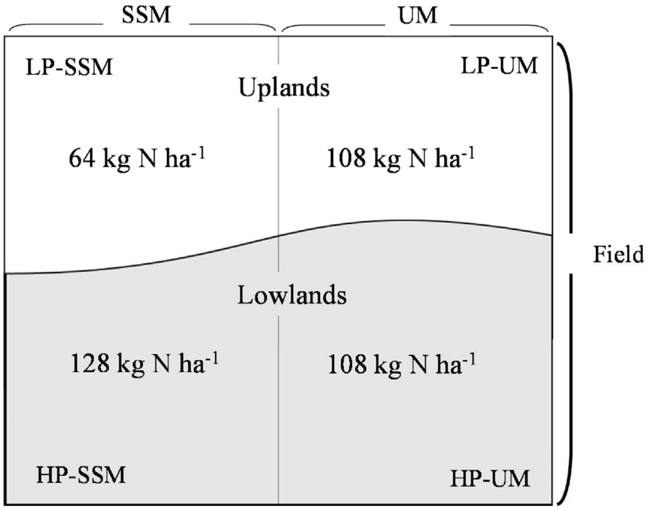

**Fig. 3.** This scheme represents the experimental design per field (square) showing the effective N fertiliser rates in all treatments (LP-SSM, LP-UM, HP-SSM, HP-UM). Landscape position of each management zone within the field is indicated as uplands (white area), and lowlands (grey area). LP- SSM = low-productivity zones with site-specific management, LP-UM: low-productivity zones with uniform management, HP-SSM: high-productivity zones with site-specific management, and HP-UM: high-productivity zones with uniform management.

### 2.5. *Agronomic management of the site*

Corn crop (cv. DK747MG) was planted at a row spacing of 52.5 cm in all fields. Crop density was 69,000 plants ha$^{-1}$ on average in all fields. The agronomic management of the experimental site included weeds, pests and diseases control, and nutrient sufficiency to ensure the crop was grown under optimum conditions. Nitrogen fertilizer was applied with surface broadcast urea (46-0-0) prior to sowing the corn crop with a variable rate fertilizer controller in all fields. Phosphorus (P) fertilizer was broadcast applied prior to sowing the corn crop with triple superphosphate (0–46-0) based on a P replenishment approach, ensuring that corn was grown with no P nutrition limitation at an effective rate of 45 kg P ha$^{-1}$. Potassium sulphate ($K_2SO_4$) was spread prior to sowing to supply effective rates of 17 kg S ha$^{-1}$ and 20 kg K ha$^{-1}$. In all fields the weed control was performed with atrazine as a selective herbicide prior to sowing the corn crop, with S-Metholachlor as a pre-emergent herbicide to control narrow leaf weeds, and in-crop glyphosate as a broad-spectrum systemic herbicide.

### 2.6. *Soil characterization by management zones*

Soils were characterized by management zones in each field by excavating a pit to 150 cm depth per management zone on sites that were different to those used for the plant and soil sampling (as described below). Four soil samples were collected in each horizon throughout the soil profile to determine: soil organic carbon (Walkey and Black, 1934), extractable P (Bray and Kurtz, 1945), particle size composition (Gee and Or, 2002), pH (Page et al., 1982), bulk density, and water holding capacity (Klute, 1986).

Soils in the HP-zones were identified as coarse-loamy, mixed, thermic Typic Hapludolls (Soil Survey Staff, 2014) with a mean water holding capacity to 100 cm depth of 120 mm m$^{-1}$ (Table 1). Soils in the LP-zones were identified as coarse-loamy, mixed, thermic Entic Hapludolls with a higher bulk density, lower organic carbon and extractable P in the A horizon, a lower water holding capacity (70 mm m$^{-1}$), and a coarser texture than in the HP-zones (Table 1). The water table depth varied between 150 and 170 cm in the HP-zones, whilst the water table was below 200 cm depth in the LP-zones.

### 2.7. *Plant and soil measurements*

In each treatment, three deep soil cores to 300 cm depth in 10 increments at 30 cm depth were collected 5 days before corn N fertilization and 10 days after corn harvest using a machine-corer (i.d. 4.6 cm, Eijkelkamp, Netherlands), segmented and combined in each layer, totalling 1920 soil samples (3 samples x 4 treatments x 10 soil layers x 2 sampling times x 8 replicates). All soil samples were immediately stored at −5 °C until their analysis in the laboratory. Samples were homogenised, mixed, subsampled, weighed and analyzed for soil water and nitrate-N content. Soil gravimetric water content was calculated on oven-dried samples at 105 °C to constant weight and was converted to volumetric water by using the measured bulk density for each soil layer. Soil nitrate-N to 150 cm depth prior to N fertilization was considered as soil initial-N, soil nitrate-N content to 150 cm depth at corn post-harvest was considered soil residual-N, and below 150 cm depth was considered potentially leachable-N as previously defined (Follet et al., 1994; Rimski-Korsakov et al., 2004). Nitrate concentration (mg kg$^{-1}$) was determined in each soil sample by the colorimetric method (Page et al., 1982). Nitrate-N content (kg ha$^{-1}$) was calculated as the prod-

**Table 1**
Mean values for main soil properties in each management zone.

| Soil horizons | Layers (cm) | Sand (%) | Clay (%) | Silt (%) | Bulk density ($g\ cm^3$) | WHC (mm) | pH (1:2.5) | Organic C ($g\ kg^{-1}$) | Extractable P ($g\ kg^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|
| Low productivity zones – Entic Hapludolls (exposed phase) | | | | | | | | | |
| A | 0–29 | 66.5 (0.2) a | 10.8 (0.3) b | 21.5 (0.2) b | 1.46 (0.0) a | 23.5 (2.2) b | 5.5 (0.0) a | 12.0 (0.4) b | 21.4 (0.2) a |
| $AC_1$ | 29–56 | 72.1 (1.5) a | 10.2 (1.1) b | 19.1 (0.3) b | 1.41 (0.2) a | 21.0 (2.1) a | 6.0 (0.1) a | | |
| $AC_2$ | 56–80 | 73.0 (0.4) a | 9.2 (0.2) b | 16.2 (0.1) b | 1.41 (0.1) a | 15.3 (1.8) b | 6.5 (0.1) b | | |
| C | 80–118+ | 77.9 (1.1) a | 7.3 (0.4) b | 15.5 (0.0) b | 1.41 (0.1) a | 13.2 (3.2) b | 6.4 (0.2) b | | |
| High productivity zones – Typic Hapludolls | | | | | | | | | |
| A | 0–31 | 46.6 (0.3) b | 18.1 (1.1) a | 30.4 (1.1) a | 1.36 (0.2) b | 36.1 (1.8) a | 5.9 (0.0) a | 19.1 (0.7) a | 16.5 (0.1) b |
| $B_w$ | 31–54 | 54.0 (1.1) b | 17.6 (1.0) a | 28.4 (1.2) a | 1.40 (0.3) a | 24.1 (0.8) a | 6.2 (0.1) a | | |
| BC | 54–77 | 54.4 (0.8) b | 19.4 (0.8) a | 28.5 (0.5) a | 1.41 (0.2) a | 27.8 (0.8) a | 7.4 (0.2) a | | |
| C | 77–106+ | 59.2 (0.6) b | 15.1 (0.6) a | 25.7 (0.3) a | 1.41 (0.2) a | 32.6 (0.6) a | 7.6 (0.4) a | | |

Different letters indicate significant differences (paired *t*-test, bilateral, $p < 0.05$) between management zones within the same soil layer. Data is presented as means with standard errors in parentheses (8 replicates). C = carbon; WHC = water holding capacity.

uct of nitrate concentration ($mg\ kg^{-1}$) by bulk density ($g\ cm^{-3}$) by soil thickness (cm), summed over the soil profile.

Four replicates of corn plant samples were collected in two rows (equivalent to 3 $m^2$ crop area) in each treatment (total of 128 plant samples) for determining grain yield, total above-ground biomass, and N uptake (stubble and grain) at physiological maturity ($R_6$ growth stage) (Ritchie et al., 1997). Corn above-ground biomass and grain yield were expressed on a dry matter basis. Corn plants were oven-dried to a constant weight, ground, sieved (1 mm mesh) and were analyzed for total N by Kjeldahl method (Page et al., 1982). Nitrogen uptake (stubble and grain) was determined by the percentage of total N in each fraction multiplied by the biomass weight, and converted to kg N $ha^{-1}$.

Total N supply for the corn growing season was calculated as the sum of N inputs: N fertilizer rate, sum of soil initial-N to 150 cm depth, and mineralized-N. Soil mineralized-N at each management zone (LP-zone, HP-zone) during the growing season was estimated on a control plot (with no N fertilizer application) within a corn productive field, according to Eq. (2) (Schepers and Raun, 2008).

$$\begin{aligned}\text{Soil mineralized-N} &= \text{sum of soil residual-N to 150 cm depth} \\ &\quad + \text{corn N uptake (stubble} + \text{grain) at harvest} - \text{sum of} \\ &\quad \text{soil initial-N to 150 cm depth} \end{aligned} \tag{2}$$

### 2.8. Climate, water balance, and water and nitrogen use efficiency of corn

Daily rainfall and air temperature were monitored by a weather station located near the experimental site over two consecutive growing seasons (2007–2008, 2008–2009). Maximum air temperatures were above historical average in both seasons. Mean air temperature during the first growing season (2007–2008) was similar to historical records (last 3 decades), whereas in the second growing season (2008–2009) it surpassed the historical average by 18 and 14% during November and March. Total cumulative rainfall during 2007–2008 was 454 mm, 47% below the historical average. Total cumulative rainfall during 2008–2009 was 419 mm, 52% below the historical average. In order to assess the water conditions during corn crop stages, a soil water balance for all fields was calculated as the difference between the potential crop evapotranspiration and rainfall during each corn growing season. The potential crop evapotranspiration was estimated by Penman-Monteith FAO (Allen et al., 1998) for daily data, and then converted to a monthly basis.

Water use efficiency in corn grain and total biomass were calculated as the ratio of corn grain yield and total biomass (kg dry matter $ha^{-1}$) to total water depth (mm) respectively. Total water depth was calculated as the difference between the soil initial water to 150 cm depth (prior to sowing corn) and the soil residual water to 150 depth (at corn post-harvest), plus the total cumulative rainfall during the growing season. The water depth (mm) was calculated as the product of soil gravimetric water, bulk density ($g\ cm^{-3}$) and soil thickness (mm).

Nitrogen use efficiency in corn grain was calculated as the product of the N uptake efficiency and N utilization efficiency. Nitrogen utilization efficiency was calculated as the ratio of corn grain yield to N uptake (stubble + grain) at harvest, and the N uptake efficiency was determined as the ratio of N uptake (stubble + grain) at harvest to N supply. Nitrogen use efficiency in total biomass was calculated as the ratio of total biomass (stubble + grain) at harvest to N supply (Moll et al., 1982).

### 2.9. Corn grain yield evaluation

Corn grain yield was measured on one second intervals and recorded using calibrated commercial yield monitors mounted on combines equipped with DGPS. The width of the combine was 10.6 m. Grain yield data were corrected to 15% grain moisture, spatially located and analyzed with ArcGis. The data points located approximately 20 m from the borders of the sites were deleted before the analysis because the combine was unlikely to be full (Blackmore and Moore, 1999). The yield monitor data were filtered using the software *yield editor* (Sudduth and Drummond, 2007).

### 2.10. Statistical analysis

Results were analyzed using a split-plot analysis of variance (ANOVA). A Tukey HSD test was used to detect differences between treatment means ($p < 0.05$). Soil residual-N was weighted by the proportion of HP- and LP-zones in each field to compare the effect of N management strategy at field-scale. These results were analyzed using a Student *t*-test for paired samples ($p < 0.05$). Nitrate concentration throughout the soil profile was analyzed using an ANOVA for a general linear model with repeated measures where each replicate was nested within the soil depth. Then, a Tukey HSD test was performed to detect significant differences between treatments means ($p < 0.05$). In addition, analysis of correlation were performed on the measured variables. Statistical analysis were performed with InfoStat (2017).

## 3. Results

### 3.1. Water and nitrogen supply to corn crop by management zone

Contrasting measures for soil initial-N and water to 150 cm depth and for the estimated soil mineralized-N were observed between management zones. Soil initial-N and water to 150 cm depth were 2 and 1.7 fold higher in HP-zones when compared to

**Table 2**
Mean values of soil initial-N and water to 150 depth prior to sowing corn, and the estimated soil mineralized-N during the corn growing season at each management zone.

| Management zone | Soil initial-N (kg nitrate-N ha$^{-1}$) | Soil initial water (mm) | Soil mineralized-N (kg nitrate-N ha$^{-1}$) |
|---|---|---|---|
| LP-zones | 57.5 (13.8) b | 251.3 (15.4) b | 34.6 (12.9) b |
| HP-zones | 114.2 (19.3) a | 422.3 (38.5) a | 103.0 (14.3) a |

Different letters indicate significant differences ($p < 0.05$) between management zones within the same column. Data is presented as means with standard errors in parentheses (16 replicates).

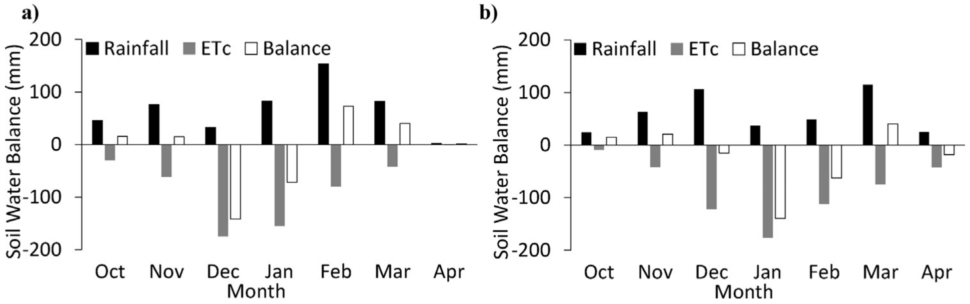

**Fig. 4.** Soil water balance calculated as the difference between potential corn crop evapotranspiration (ETc) and rainfall during the 2007–2008 (a) and the 2008–2009 (b) corn growing seasons.

LP-zones. The estimated soil mineralized-N during the corn growing season was 3 fold higher in the HP-zones (Tables 2, A.1) as a result of the differences in the estimated N mineralization rates of 0.7% in the LP- and 1.6% in the HP-zones (Table 2).

Total soil water balance resulted in a deficit during both of the analyzed corn-growing seasons (Fig. 4). The potential corn crop evapotranspiration was higher than the water supply by rainfall, especially during the critical crop stage (flowering ±15 days). Mean rainfall was 68% below the historical average during the critical period for corn (December) in both growing seasons.

### 3.2. *Grain yield, total above-ground biomass and nitrogen uptake of corn*

Corn grain yield and total above-ground biomass (stubble + grain), and corn grain and total above-ground N uptake (stubble + grain) showed a significant interaction between N fertilizer strategies and management zones (Table A.2). In LP-zones a higher rate of N applied under UM did not increase corn yield, and both grain and total N uptake were similar between fertilization strategies (Table 3). In the HP-zones, mean grain N uptake was 21% higher with SSM, and mean total N uptake was 19% higher with SSM than with UM strategy (Table 3).

### 3.3. *Soil residual- and potentially leachable-nitrogen*

In the LP-zones, SSM was significant in lowering mean soil residual-N to 150 cm depth by 36% (Fig. 5a) and by 18% at the field-scale (Fig. 5b). Soil nitrate concentration tended to decrease in the profile with depth. However, differences in soil nitrate concentration were difficult to detect between treatments ($p < 0.05$) due to the large variability observed (coefficients of variation = 10-65%). Mean soil nitrate concentration below 150 cm depth was less than 7 mg kg$^{-1}$ in all treatments (Fig. 6). Although marginal differences in soil potentially leachable-N among treatments were observed throughout the profile, greater soil nitrate concentration in the lower layers indicate a higher potential risk for N leaching. Mean concentration of soil potentially leachable-N in the 180–210 cm soil layer was higher in the LP-UM and HP-SSM treatments. In the 210–240 cm soil layer the highest mean nitrate concentration was 6.6 mg kg$^{-1}$ in the LP-UM treatment (Fig. 6), increasing the risk of N losses to the environment using higher N rates with UM strategy.

### 3.4. *Water and nitrogen use efficiency of corn crop*

Water and N use efficiency in grain and total biomass of corn crop showed a significant interaction between management zones and fertilization strategies (Table A.3). Overall mean water use efficiency of corn was increased by 18% with SSM in both LP- and HP-zones when compared to UM (Table 4).

In LP-zones corn N use efficiency in grain yield was 50% higher with SSM strategy. Furthermore, N use efficiency in total biomass was increased 43% by adopting SSM in these environments (Table 4). A relationship between N use efficiency in grain and N fertilizer rate was established. Nitrogen use efficiency in corn grain yield decreased with increasing N fertilizer rates ($R^2 = 0.7$; $p = 0.02$) but only in LP-zones (Fig. 7a). Moreover, in LP-zones a negative linear relationship between water use efficiency in corn grain yield and N fertilizer rates was observed ($R^2 = 0.5$, $p = 0.02$) (Fig. 7b). This therefore resulted in a positive linear relationship between N and water use efficiency in corn grain yield in LP-zones ($R^2 = 0.3$; $p = 0.02$). Added to this, a quantitative relationship between soil residual-N and N use efficiency in total biomass was established (data not shown). Soil residual-N had a negative linear relationship with N use efficiency in total biomass for all treatments ($R^2 = 0.5$; $p = 0.001$) indicating that soil residual-N can be minimized by improving N use efficiency.

**Table 3**
Mean values of corn N grain and total N uptake (stubble and grain), corn grain yield and total above-ground biomass (stubble and grain) at harvest for all treatments.

| Treatments | Grain N uptake (kg N ha$^{-1}$) | Total N uptake (kg N ha$^{-1}$) | Grain yield (Mg dry matter ha$^{-1}$) | Total biomass (Mg dry matter ha$^{-1}$) |
|---|---|---|---|---|
| LP-SSM | 99.5 (13.8) c | 134.2 (11.9) c | 8.0 (0.2) c | 15.6 (0.3) c |
| LP-UM | 104.5 (8.1) c | 145.6 (22.4) c | 7.4 (0.1) c | 15.7 (0.8) c |
| HP-SSM | 178.0 (13.6) a | 250.4 (21.1) a | 13.9 (0.4) a | 24.7 (0.6) a |
| HP-UM | 140.8 (10.2) b | 211.0 (15.9) b | 11.2 (0.5) b | 20.5 (0.7) b |

Different letters indicate significant differences ($p < 0.05$) between treatments within the same column. Data is presented as means with standard errors in parentheses (8 replicates).

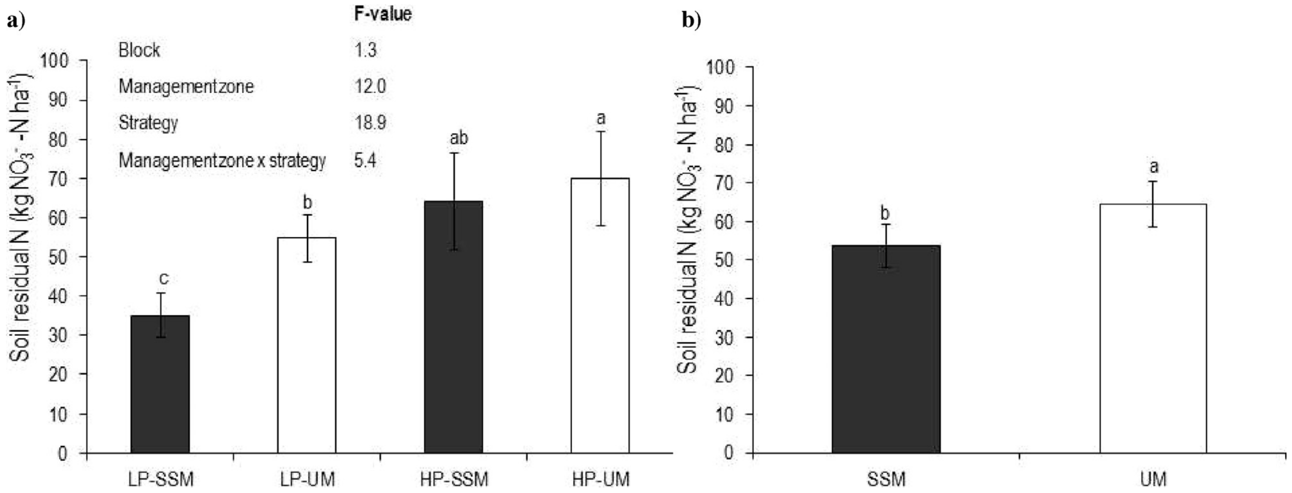

**Fig. 5.** Mean values of soil residual-N to 150 cm depth for all treatments (a); mean values for soil residual-N weighted by the proportion of each management zone at field-scale (b). Bars with different letters are significantly different ($p < 0.05$) between treatments. Vertical lines indicate standard error of the mean. Split-plot ANOVA table is shown for soil residual-N in Fig. 5a.

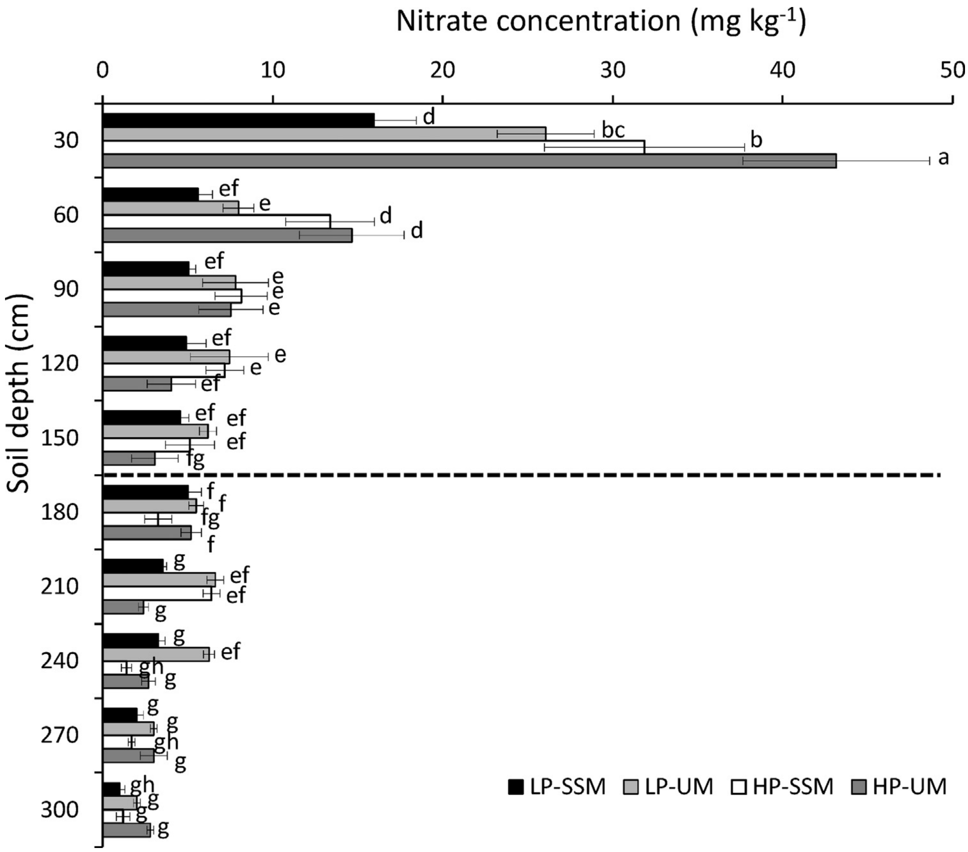

**Fig. 6.** Soil nitrate concentration in the profile to 300 cm depth for all treatments. Horizontal lines indicate mean standard error for each treatment (8 replicates). Horizontal broken line indicates the limit for nitrate leaching. Bars with different letters indicate significant differences for the 3rd order interaction between "management zones", "N fertiliser strategy" and "soil depth" ($p < 0.05$).

## 4. Discussion

### 4.1. *Differential water and nitrogen supply to corn crop by management zone*

In our study, soils in the HP-zones provided with a higher water and N supply to corn crop prior to sowing and during the growing season as a result of a greater water holding capacity and mineralization rates than those in the LP-zones. These findings were in agreement with previous studies conducted in soils of the Inland Pampas of Argentina (Gregoret et al., 2011; Zubillaga et al., 2009). Drought for crop production is described as a prolonged dry period which can be caused by a lack of water availability for crops due to rainfall scarcity, shallow soils with low water-retention, impaired root penetration, or high evaporative demand due to high temperatures and radiation, low relative humidity and strong winds (Andrade and Sadras, 2002). According to the climatic conditions prevailing over the analyzed period and the resulting soil water bal-

**Table 4**
Mean values of water use efficiency in grain and in total above-ground biomass, nitrogen use efficiency in grain and in total above-ground biomass of corn crop for all treatments.

| Treatments | Water use efficiency in grain (kg grain ha$^{-1}$ mm$^{-1}$) | Water use efficiency in total biomass (kg dry matter ha$^{-1}$ mm$^{-1}$) | Nitrogen use efficiency in grain (kg grain kg N$^{-1}$) | Nitrogen use efficiency in total biomass (kg dry matter kg N$^{-1}$) |
|---|---|---|---|---|
| LP-SSM | 15.3 (1.9) c | 33.4 (2.4) c | 53.1 (2.2) a | 104.2 (2.6) a |
| LP-UM | 13.9 (0.9) c | 28.2 (1.1) d | 35.4 (1.6) b | 72.8 (3.0) b |
| HP-SSM | 24.9 (1.4) a | 46.1 (2.3) a | 34.2 (2.6) bc | 60.2 (3.5) c |
| HP-UM | 19.8 (1.1) b | 39.2 (2.0) b | 28.5 (2.9) c | 52.0 (3.8) c |

Different letters indicate significant differences ($p < 0.05$) between treatments within the same column. Data is presented as means with standard errors in parentheses (8 replicates).

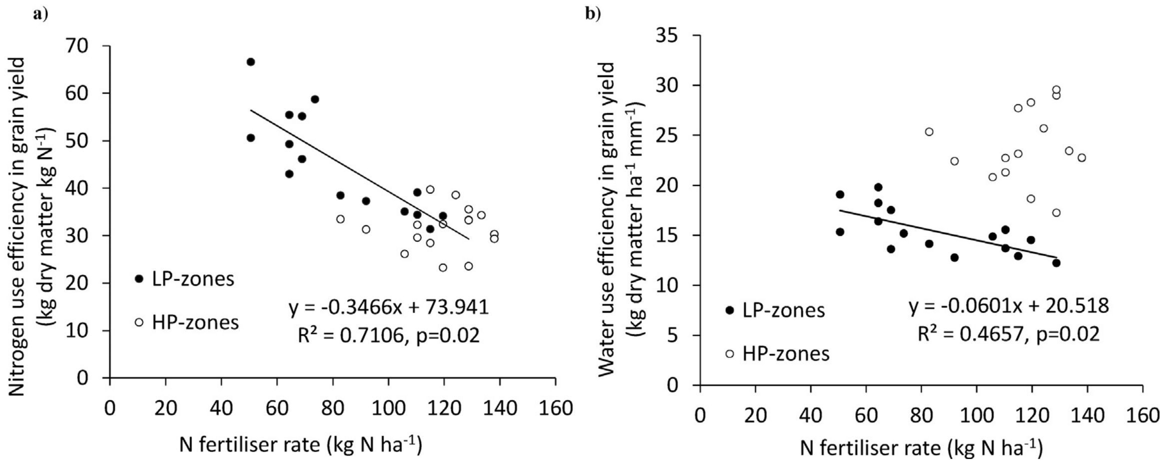

**Fig. 7.** Nitrogen use efficiency (a) and water use efficiency in grain yield (b) of corn as a function of nitrogen fertiliser rate in low productivity (LP) and high productivity (HP) zones. Regression line is shown for low productivity zones in both graphs.

ance this experiment was performed under dry conditions (Fig. 4) and corn was probably subjected to water stress (Sadras, 2005).

### 4.2. *The effect of the nitrogen fertilizer strategy on soil residual-nitrogen, grain yield, total above-ground biomass and nitrogen uptake of corn relative to the management zones*

The extra soil residual-N accumulated with UM strategy during dry years could be leached over wet periods, increasing the risk for N losses to the environment (Delgado et al., 2005; Rimski-Korsakov et al., 2004). In our study site the probability of having wet growing seasons (>870 mm) is ~30%. In this context, SSM strategies based on management zones in these environments can help to identify the areas of the field that are more vulnerable to N leaching losses as it was previously stated in similar studies (Delgado et al., 2005; Li et al., 2007). However, a study conducted in irrigated corn in Nebraska (USA) concluded that using SSM did not reduce soil residual-N to 90 cm depth and no grain yield differences were observed between SSM and UM strategies at field-scale (Ferguson et al., 2002).

Our results on corn response to N fertilization were consistent with those observed by Delgado et al. (2005) in LP-areas, where a lack of water storage limited corn response to N fertilizer addition. Crops grown in low-water holding capacity soils (Hatfield and Prueger, 2004) or under water stress conditions (Benett et al., 1989) may have no response to N fertilizer application (Sadras, 2005). Previous studies conducted in soils of the Inland sandy Pampas demonstrated that about 65–70% of corn yield variability was explained by soil water holding capacity (Niborski et al., 2004). In HP-zones a higher rate of N fertilizer applied under SSM resulted in greater corn grain yield and total above-ground biomass compared with UM. In these sites, water stored in the high-water holding capacity soils was able to supply water for corn productivity during dry periods, as indicated by Nosetto et al. (2009). Corn growing in soils with sufficient water requires more N to achieve maximum grain yield than those subjected to water stress conditions (Moser et al., 2006).

### 4.3. *Drivers of higher water and nitrogen use efficiency of corn crop under site-specific nitrogen management*

In soils of the Rolling Pampas Pedrol et al. (2008) found similar mean values of water use efficiency in corn grain yield (15.5 kg dry matter ha$^{-1}$ mm$^{-1}$) to those observed in our study in the LP-zones (Table 4). Also, mean water use efficiency in grain yield in HP-zones coincided with the value reported by Andrade and Sadras (2002) of 20 kg dry matter ha$^{-1}$ mm$^{-1}$ in similar environments. It is important to note that the environmental factors such as weather, water holding capacity and texture may have modulated crop response regarding water use efficiency, depending on the water supply (Katerji et al., 2010) and the N management strategy (Kim et al., 2008). Our results were in line with the findings addressed by Katerji et al. (2010) being that under water stress conditions a lower water use efficiency was found in low water holding capacity soils (e.g. LP-zones) compared with high water holding capacity soils (e.g. HP-zones).

It is generally assumed that N use efficiency decreases with increasing N fertilizer rates (Ciampitti and Vyn, 2012). It is expected a progressively decrease in corn response to higher N fertilizer rates, and thus, a decrease in corn N use efficiency, because this nutrient ceases to be the limiting factor for crop production (Salvagiotti et al., 2011). Additionally, Benett et al. (1989) found that applying high N fertilizer rates, a water stress can reduce the ability of corn to use the extra N fertilizer added.

This finding was in line with recent studies that found a positive relationship between N and water use efficiency (Quemada, 2016). Although several experiments mostly found a positive effect of N supply on water use efficiency, differences in response to

N supply indicate that effects are not straightforward, and plants interactively control water use efficiency by physiological and morphological processes in a very complex manner (Brueck, 2008). In previous studies, Badr et al. (2012) found that under water deficit conditions, N fertilizer application would not be the limiting factor for improving yields as N fertilizer efficiency is reduced, likely due to the inhibition of the crop growth rate as well as to impaired N transport to plant roots. Such results may explain our findings in LP-zones, being soils with a lower water holding capacity and coarser texture than in HP-zones.

The differences detected in corn response between N fertilization strategies could be partially explained by the dry conditions during the analyzed seasons. In long-term studies the greatest differences in corn yield and water use efficiency were found under water deficit scenarios (Katerji et al., 2010). Although N use efficiency from the fertilizer was not quantified in our study, the magnitude of the differences in corn grain yield detected among N fertilization strategies could be explained by a possible synergistic relationship between water and N under severe dry conditions (Kim et al., 2008). This relationship could have influenced crop ability to use N (either from soil and/or fertilizer) to improve crop N uptake (especially in grain), and hence, for a greater yield potential in HP-zones. However, these assumptions need to be interpreted with caution due to the experimental limitations of our study.

## 5. Conclusions

In high-productivity zones, corn grain yield and total biomass were 2.7 and 4.2 Mg ha$^{-1}$ higher with site-specific than with uniform N management. Both N in grain and total N uptake by corn increased by 21% and 18% with site-specific N management. Also, soil residual-N at field-scale was reduced by 18% with site-specific N management. Under water deficit conditions as it was found in the low-productivity zones, corn had no response to N supply, a fact reflected in a lower N and water use efficiency with higher N rates under the uniform management strategy. On the other hand, under conditions of increased water supply (through the crop being able to access stored water as in the high-productivity zones), corn response showed enhanced water and N use efficiency with site-specific Nmanagement strategy. This relationship may have influenced the ability of corn to use N (either from the soil or the fertilizer) improving its accumulation in the crop (particularly grain) with site-specific management. In this context, site-specific N management can be considered as a conservation practice that optimizes N and water use efficiency of corn crop in order to reduce N leaching losses to the environment.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.agwat.2017.12.002.

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