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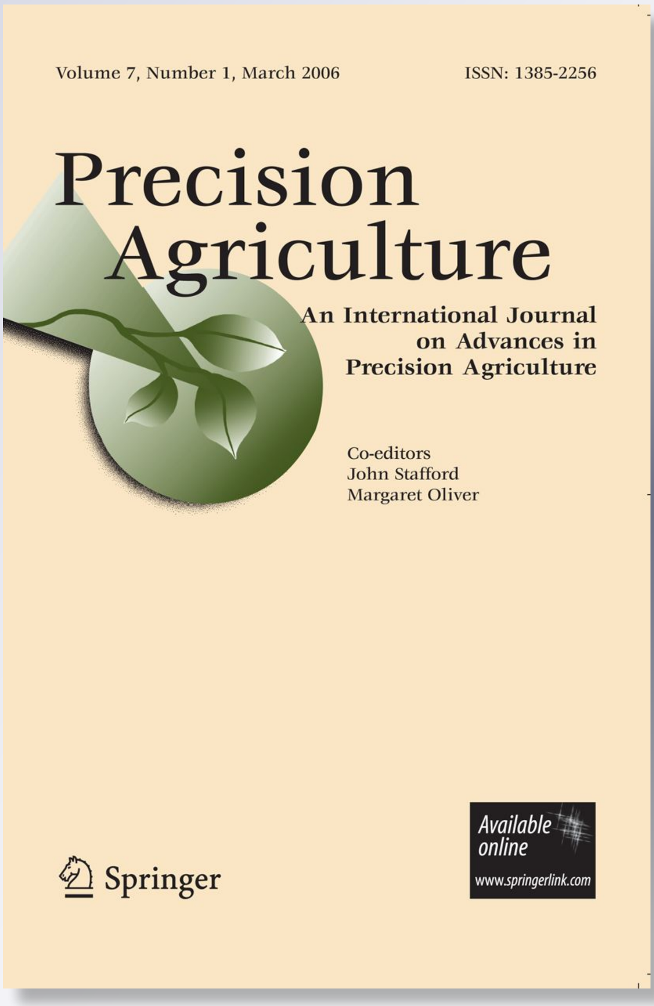
**Precision Agriculture**
An International Journal on Advances in Precision Agriculture

ISSN 1385-2256
Volume 12
Number 6

Precision Agric (2011) 12:831-849
DOI 10.1007/s11119-011-9224-7



Springer

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# Regional model for nitrogen fertilization of site-specific rainfed corn in haplustolls of the central Pampas, Argentina

**M. C. Gregoret · M. Díaz Zorita · J. Dardanelli · R. G. Bongiovanni**

**Abstract** In semi-arid regions, soil water and nitrogen (N) are generally limiting factors for corn (*Zea mays* L.) production; hence, implementation of appropriate N fertilization strategies is needed. The use of precision agriculture practices based on specific site and crop properties may contribute to a better allocation of fertilizer among management zones (MZ). The aim of this study was to develop a model for diagnosis of N availability and recommendation of N fertilizer rates adjusted to MZ for dryland corn crops growing in Haplustolls. The model considered variability between MZ by including site-specific variables [soil available water content at sowing (SAW) and Available Nitrogen (soil available N-$NO_3$ at planting + applied N, Nd)] using spatial statistical analysis. The study was conducted in Córdoba, Argentina in Haplustolls and consisted in four field trials of N fertilizer (range 0–161 kg N ha$^{-1}$) in each MZ. The MZ were selected based on elevation maps analysis. Grain yields varied between MZ and increased with larger SAW and Nd at sowing. Grain responses to Nd and SAW in any MZ were not different between sites, allowing to fit a regional model whose parameters (Nd, Nd$^2$, SAW, SAW$^2$) contributed significantly ($p < 0.001$) to yield prediction. Agronomical and economically optimum N rates varied among MZs. However, the spatial variability of optimum N rates among MZs within sites was not enough to recommend variable N fertilizer rates instead of a uniform rate. Variable N fertilizer rates should be recommended only if variability in SAW and soil N among MZ is greater than that found in this work.

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**Keywords** Variable fertilizer rates · Nitrogen · Spatial statistics · Semi-arid regions

**Abbreviations**

| | |
|---|---|
| AON | Agronomically-optimum N rate |
| BD | Soil bulk density |
| EC | Soil electrical conductivity |
| EON | Economically-optimum N rate |
| HP | High productivity |
| LP | Low productivity |
| MP | Medium productivity |
| MZ | Management zone |
| Nd | Available Nitrogen (soil available N-$NO_3$ at planting + applied N) |
| NUEf | Agronomic Fertilizer N use efficiency |
| P | Soil extractable phosphorus |
| PA | Precision agriculture |
| SAW | Soil available water content at sowing |
| SOM | Soil organic matter |
| TN | Total soil nitrogen |
| VRF | Variable rates of fertilizer |

## Introduction

Corn grain yield varies within a field. Hatfield (2000) defined three types of variability based on the causal factors: (i) natural (soil and topography); (ii) random (precipitation, temperature and radiation); and (iii) management (fertilization, plant population, etc.). The interaction of these types of variability generates effects that may not match the physical limits of the fields, justifying the use of precision agriculture (PA) technology which involves site-specific or localized management practices. Site-specific management may be used to improve production and profitability of agricultural systems by adjusting fertilizer rates to the characteristics of different management zones (MZ), i.e., zones that may differ in factors such as the type of soil, topography, water and nutrient availability. The analysis of spatial and temporal variability between MZ within a field reveals the dynamic nature of soil properties (Cox et al. 2003). In the Pampas region, the difference between high nitrogen (N) crop demand and the usually limited soil N supply makes N the most limiting nutrient for corn (*Zea mays* L.) growth and yield (Andrade et al. 1996). N-fertilizer application adjusted to MZ requires knowing each MZ's history of N demand, N-use efficiency and soil capability to supply a fraction of crop N during the growing season (Hatfield 2000). Haplustoll soils are representative of the semi-arid Pampas regions, where water and nutrient availability are usually limiting factors in the production of different crops (Jarsún et al. 2003).

Integrating diagnosis of N requirements and recommendations for N application into simple models might be useful for improving N use efficiency and therefore crop profitability. In Río Cuarto, Argentina, Anselin et al. (2004) estimated corn crop response to variations between topographic positions within the field with a quadratic function of N fertilizer applied. However, as Liu et al. (2006) stated, this model has limitations because it does not consider soil mineral N availability and soil available water content at sowing (SAW) at sowing and the interaction of these variables with applied N, because the model assumes that these variables are inherent to the landscape. Therefore, variability in N and SAW supply between MZ would be included in the error term. Agronomic fertilization efficiency in a given environment depends on available soil mineral N and SAW, which affect soil N use, crop growth and N dynamics (Ruffo and Parsons 2004; Liu et al. 2006; Miao et al. 2006).

In semi-arid regions, the model developed by Anselin et al. (2004) could be modified by incorporating site-specific variables with the aim of improving accuracy of the diagnosis of N availability and recommendation of variable rates of N fertilizer (VRF). For example, Liu et al. (2006) proposed the explicit inclusion of two categories of site-specific variables related to N supply and demand for dryland corn crops in sandy loam and loam soils in Michigan (USA). The former group includes the variables that affect N availability (i.e., soil organic matter (SOM) content and cation exchange capacity) and the latter includes variables related to N demand (e.g., radiation). Moreover, in regions with low and variable rainfall, water stored in the soil profile at sowing might modify the attainable grain yields and therefore crop management decisions. Under such conditions, the amount of SAW can sometimes be more important than rainfall during growing season in determining crop yields (Moeller et al. 2009).

Recent studies evaluating corn N fertilization models have not included soil N and SAW, nor discriminated between MZ or used analytical methods that consider spatial structure of geo-referenced data. The aim of this study was to develop a model for diagnosis of N availability and recommendation of N fertilizer rates adjusted to MZ for dryland corn crops growing in Haplustolls. This model includes soil N and SAW and uses spatial statistical analysis.

## Materials and methods

### Experimental sites and general characterization of the study area

The study was performed at four sites located in the semi-arid Pampas region of Argentina: Site I: 63°42′ W, 31°51′ S, Site II: 63°41′ W, 31°22′ S, Site III: 63°43′ W, 31°53′1.8″ S and Site IV: 64°20′ W, 31°34′ S. Crops at sites I and II were sown in the 2004–2005 crop season; and at sites III and IV, in the 2005–2006 season. The climate in

**Table 1** Summary of rainfall and temperatures recorded during the crop cycle in each site

| Sites | SAW | Dates | | | Planting—flowering | | Flowering—phys. mat | | Planting—phys. mat. | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Planting | Flowering | Physiological maturity | pp | T° | pp | T° | pp | T° |
| I | 75.25 | 14/10/04 | 29/12/04 | 01/03/05 | 222 | 19.7 | 318 | 21 | 540 | 20.35 |
| II | 140.73 | 14/09/04 | 05/12/04 | 01/02/05 | 249 | 19.9 | 175 | 23 | 424 | 21.3 |
| III | 181.63 | 20/10/05 | 08/01/06 | 17/03/06 | 284 | 20.9 | 322 | 21.15 | 606 | 21.02 |
| IV | 242.65 | 14/11/05 | 15/01/06 | 31/03/06 | 356 | 22.8 | 274 | 22.4 | 630 | 22.6 |

*SAW* soil available water (mm), *pp* precipitation (mm), *T*° average temperature in °C the region is mesothermal, with a mean annual rainfall of 750 mm and monsoon-type distribution (93% of the rainfall events occur between September and April). A summary of rainfall and temperatures recorded during the crop cycle is shown in Table 1. The main soil types are Typic Haplustolls with silty loam texture (16% of clay, 68% of silt and 16% of sand) and with moderate to low SOM content (1.25–3.0%). The soil type of all MZ in the four sites was classified as Typic Haplustoll of the Oncativo series (Jarsún et al. 2003).

## Management zones delimitation

In each site, MZ were delimited based on the analysis of digital elevation maps, which provide background information about the productivity and soil properties, both influenced by climate and topography (Moore et al. 1993; Vieira et al. 2006). Yield maps were available from the sites I and II and they were also taken into account for the delimitation of the MZ. The MZ were identified using the software Management Zone Analyst (Mizzou-ARS 2000). Management Zone Analyst (MZA) is a decision-aid for creating within-field management zones based on quantitative field information. It mathematically breaks up a field into natural clusters or zones based on the classification parameters which allows unsupervised fuzzy clustering of information. The procedure was unsupervised because it does not require prior knowledge of the classification variables but it produces natural groupings of data. It is also fuzzy because it allows the classification of data belonging to different groups. The software, after pooling the data, estimates two performance indices in order to guide the decision as to which is the best number of groups or MZ. These indices are the “normal rate of entropy (NCE)”, which accounts for the disruption created by grouping the data into zones and the “fuzzy performance index (FPI)”, which reports the number of members shared between classes. The best data grouping is the size of area where both indices have their minimum value (Fridgen et al. 2004).

In each of the sites, in order to identify the MZ, ground elevation was surveyed by collecting positioning data (latitude and longitude) and elevation (m) with a Trimble® GPS model 4600LS during the winter fallow prior to planting crops. The recording equipment was placed on a vehicle, which traversed the site in equi-distant transects every 10 m and an elevation map was made by interpolation to a regular grid of 5 m by the method of equi-distance kriging. Elevation was represented in contour maps of curves using the software Surfer version 8.4 (Surface Mapping System, copyright 1993–2003, Golden Software, Inc., USA). Then these elevation logs, processed with the available yield maps, were entered into the MZA software for classification into homogeneous groups according to the performance indices described. From this procedure, the following zones were identified: (i) a high productivity (HP) area, located in a zone of lower than average elevation, and (ii) a low productivity (LP) zone located at higher than average elevation (Fig. 1). In site IV, three MZ were identified because they represented different topographic attributes: (i) a HP MZ located on a plateau higher than the field mean elevation, with almost no slope (0.9%), (ii) a medium productivity (MP) area with an elevation below the field mean value and with a slope of 1%, and (iii) a LP area with an elevation lower than the field mean value, and with a steep slope of 9%.

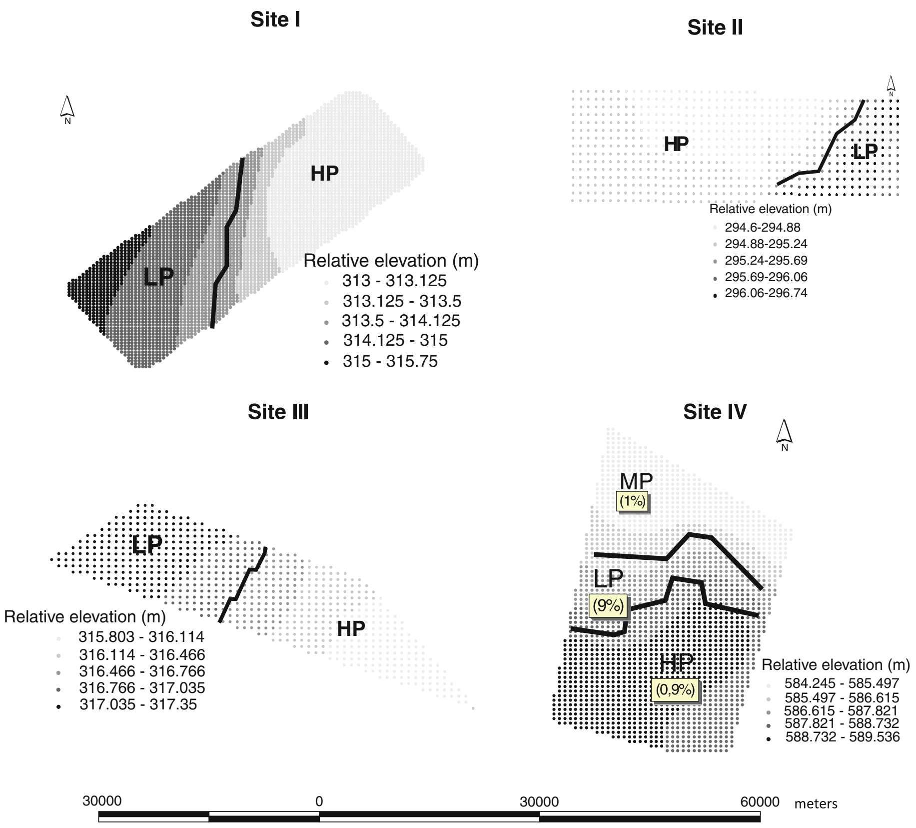


**Fig. 1** Maps of management zones (MZ) defined by analysis of digital elevation maps of each experimental site. Types of MZ: low productivity (LP), medium productivity (MP) and high productivity (HP)

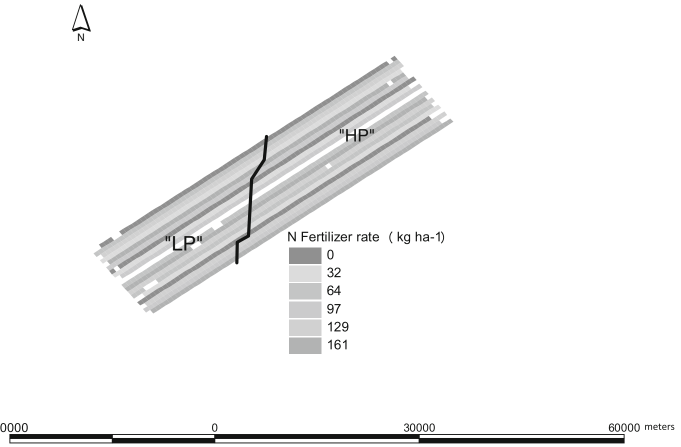


**Fig. 2** Experimental design in site I showing the N fertilizer rates (kg ha$^{-1}$) in each block (delineated by *dotted lines*), between areas of low (LP) and high (HP) productivity

## Experimental design and treatments

In each site, the experimental design consisted of three randomized complete blocks with different N fertilizer rates (0, 32, 64, 96, 129 and 161 kg N ha$^{-1}$) arranged in continuous strips crossing each MZ (Broud and Nielsen 2000). The width of the strips was that of the combine harvester (6.3 m) and strip length was plot length (approximately 400 m). Figure 2 illustrates the allocation of the fertilizer strips in one of the experimental sites. The fertilizer applied was urea (46-0-0) broadcaste at sowing.

## Evaluation method

In each MZ, three geo-referenced soil samples composed of seven geo-referenced subsamples were taken before sowing (Fig. 3). Samples were collected from the 0–0.20 m layer, air-dried and sieved. The following soil properties were determined: SOM content using the wet combustion or Walkley and Black method (Nelson and Sommers 1996), total nitrogen (TN) according to Kjeldahl (Bremmer 1996), Bray and Kurtz 1 soil extractable phosphorus (P) (Kuo 1996), water pH and electrical conductivity (EC) by potentiometry. Soil bulk density (BD) was measured before sowing using undisturbed soil samples and the cylinder method (Blake and Hartge 1986).

Soil extractable N-NO$_3$ content of the following layers: 0–0.2, 0.2–0.4, 0.4–0.8, 0.8–1.4, and 1.4–2 m were determined using the method described by Mulvaney (1996). N-NO$_3$ content was expressed as kg ha$^{-1}$ using the BD values determined in this study for the upper soil layers and the values provided by Martellotto et al. (2004) for this type of soil at deeper layers.

Total soil water content was determined before planting using the technique down to 2 m at the same three geo-referenced sampling sites. The values were expressed in volumetric water content (mm$^3$ mm$^{-3}$) using the same BD values as for N-NO$_3$ content. The drained upper limit of available water was field-measured following the procedures reported by Ratcliff et al. (1983). The permanent wilting point was determined on

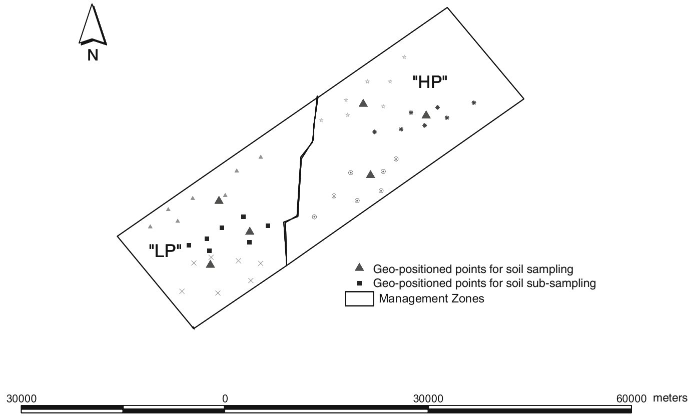


**Fig. 3** Geo-positioned points for soil samples (three) and subsamples (seven) in each management zone in site I

disturbed samples with a −1.5 MPa suction pressure membrane (Richards 1947). SAW was calculated as the difference between the observed soil water content and that corresponding to permanent wilting point for each soil layer down to 2 m. Soil properties of the MZ within each site were compared with ANOVA, using InfoStat statistical software (Infostat 2007).

Because the spatial density of the soil sampling was much lower than grain yield data, it was necessary to adjust the density of data; thus interpolated soil data were obtained using the nearest neighbor method following the approach proposed by Griffin et al. (2005). As explained by these authors, the nearest neighbor interpolation was created by surrounding each input point by an area such that any location within that area is closer to the original point than any other point. In this work, depending on the size of a site and the distribution of soil sampling, each soil sample spanned from 14 to 18% of the total yield data for each site.

## Grain yield evaluation

Yield data were collected with a standard AgLeader™ yield monitor, a geo-positioned device located on the combine harvester that measures and records crop yields on-the-go. Combine speed and GPS were monitored during yield data collection. Grain yield data were spatially located and analyzed with SSToolbox GIS software (SST 2006). 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. Finally, the remaining data were filtered using GeoDa software (Anselin 2004).

To normalize the distance of the observations within and between the strips, the pooled data from each site (2 111, 1 771, 1 341 and 939 observations at sites I, II, III and IV, respectively) were arranged in a 6.3 m × 6.3 m grid averaging the observations within each polygon. From the resulting square (1 297; 1 049; 1 012 and 588 at sites I, II, III and IV, respectively), a matrix of spatial weights, weighting the data according to the proximity between observations, was calculated.

## Data analysis

Spatial statistical analysis (Anselin 1988) was performed using the Geoda software (Anselin 2004). The analysis involved two steps. First the feasibility of integrating each experimental site into a single response function was determined estimating whether the response to available Nitrogen (soil available N-$NO_3$ at planting + applied N) (Nd) was dependent on geographical location or only on MZ, regardless of the experimental site. This analysis was based on the following model:

$$\Upsilon_{ij} = \alpha + \beta_1 Nd + \beta_2 Nd^2 + \gamma_1 SAW + \gamma_2 SAW^2 + \delta C + \phi Nd * C + \kappa SAW * C + \nu Nd * SAW * C + \varepsilon_{ij} \tag{1}$$

where $Y_{ij}$ is the maize grain yield (kg ha$^{-1}$) in each experimental site “C” ($i$) and each geo-referenced location ($j$), $\delta C_i$ is a dummy variable for the sites, $\alpha$, $\beta_1$, $\beta_2$, $\gamma_1$, $\gamma_2$, $\delta$, $\omega$, $\kappa$ and $\nu$ are the parameters of the regression equation, and $\varepsilon_{ij}$ is the error term of the regression. If $\delta C_i$ was not significantly different between experimental sites, then it was feasible to perform the second step of the analysis to obtain a unique equation able to predict grain yield response to Nd and SAW at sowing:

$$\Upsilon_j = \alpha + \beta_1 Nd_j + \beta_2 Nd_j^2 + \gamma_1 SAW_j + \gamma_2 SAW_j^2 + \delta Nd_j * SAW_j + \varepsilon_j \tag{2}$$

In both steps, the space error model (Anselin 2004) was used with a spatial weight matrix of "Queen" (eight structure neighbors with common edges and corners).

Goodness of fit was tested by using adjusted $R^2$, likelihood Log, Akaike information criterion and Schwarz criterion.

### Mathematical models

Nd amount for the maximum attainable grain yield or agronomically-optimum N rate (AON) were estimated for each site once dY/dNd was equal to zero in Eq. 3, by using Eq. 4:

$$\frac{dY}{dNd} = \beta_1 + 2\beta_2 Nd + \delta SAW = 0 \tag{3}$$

$$Nd = \frac{-(\beta_1 + \delta SAW)}{(2\beta_2)} \tag{4}$$

When prices of maize grain and Nd were considered, economically-optimum N rate (EON) was estimated by calculating the economic return ($\pi$):

$$\pi = P_m \times \left(\alpha + \beta_1 Nd + \beta_2 Nd^2 + \gamma_1 SAW + \gamma_2 SAW^2 + \delta Nd \times SAW\right) - P_n \times Nd \tag{5}$$

where $\pi$ is the economic return of the use of N in US\$ ha$^{-1}$, $P_m$ is the price of corn in the harvest month (March) in US\$, minus 15% due to hauling and tax expenses, and $P_n$ is the price of fertilizer N in the form of urea and during the month of sowing, plus 6 months of interest at a 15% annual rate. Because of the temporal variation in the input/output price relationship over the study period an historical value (Márgenes Agropecuarios 2006) was considered, with the aim of evaluating the method used regardless of the immediate results, which should be analyzed individually for each specific situation. The mean values between 2001 and 2006 were US\$ 0.23 kg$^{-1}$ for corn and US\$ 2.30 kg$^{-1}$ for N. According to Costanza et al. (1997), "the environmental services or flows of materials, energy and information generated by natural capital, when combined with goods and other services produce welfare". Because of the lack of markets for the exchange of these services, in many situations its value is not properly considered when making decisions for the allocation of resources. However, these services contribute to the sustainability of human life and are valuable for the society and it is important to consider its marginal value (Pretty et al. 2000; Prabhu et al. 2007). Thus, in our study the same value as the price of the N fertilizer was attributed to soil available N because it was considered an environmental service (Viglizzo 2005).

When $d\pi$/dNd was equal to zero (Eq. 6), EON was calculated using Eq. 7. AON and EON estimates were based on a traditional optimization model (Dillon and Anderson 1990):

$$\frac{d\pi}{dNd} = P_m \times (\beta_1 + 2\beta_2 Nd + \delta SAW) - P_n = 0 \tag{6}$$

$$Nd = \left(\left(\frac{P_n}{P_m}\right) - \beta_1 - \delta SAW\right) \times \left(\frac{1}{2\beta_2}\right) \tag{7}$$

For each MZ, data of SAW replications were used to calculate AON and EON. Mean values obtained were compared between MZ within each site using ANOVA.

The response curves of corn grain yield to Nd used in each MZ were estimated with Eq. 2 using the SAW average value from each MZ. In each site and MZ, Agronomic fertilizer N-use efficiency (NUEf) was calculated from the difference between corn grain yield at AON and without N fertilizer, using the following equation (Eq. 8)

$$NUEf = (Y_{AON} - Y_{Nf0})/Nf_{AON} \tag{8}$$

where, $Y_{AON}$ is the yield at AON, $Y_{Nf0}$ is the yield without N fertilizer and $Nf_{AON}$ is the N fertilizer rate at AON.

At each site, the apparent contribution of variable N fertilizer rates between MZ was compared against uniform N fertilizer using the average of Nd and SAW information without discriminating between MZ. Finally, ANOVA and LSD-T analysis were performed for the comparison between both fertilizer strategies with four replicates (each of the sites).

## Results and discussion

### Soil properties at the sites

Mean values of soil P, SOM and TN content in the 0–0.2 m soil layer and total SAW in the 0–2 m soil profile at planting were highest in the HP MZ of each site (Table 2) with statistically significant differences only in some cases. Moreover, N-$NO_3$ content in the upper 0.6 m layer was similar between MZ, except in site I and II, where SAW differences between MZ were the greatest (Table 2). The differences in soil properties found between MZ agree with previous reports. Zubillaga et al. (2006), based on grid sampling of Typic and Entic Hapludolls from Buenos Aires province (Argentina), observed that the spatial distribution of some soil properties was not random. Furthermore, they observed that areas with high crop productivity also showed greater soil TN and greater SAW than LP areas. The soil properties observed in this study are within the normal range of cropped soils of the semi-arid Pampas region. Kravchenko and Bullock (2000) used a regression analysis in Haplaquolls and Argiudolls from central Illinois (USA) and eastern Indiana (USA) and concluded that differences in the topography explained 30% of the variability in SOM content and in extractable soil P and K. Likewise, Dharmakeerthi et al. (2005) reported that more soil N was available in a Typic Hapludalf from Ontario (Canada) at lower positions in the landscape. The present study agrees with these results, most soil N-$NO_3$ at sowing was available in the HP MZ, usually at low positions in the field (Table 2).

Distribution of soil water content down the profile (0–2 m in depth) at sowing showed similar patterns in all MZ of each site (Fig. 4), but the accumulated content differed between MZ (Table 2), showing a close relationship with the differences in crop productivity between MZ (Fig. 6). SAW in LP MZ was 42, 12, 18 and 34 less than in the HP MZ, in sites I, II, III and IV, respectively. For the same sites, yields were 9, 10, 7, and 26% larger in HP MZ than in LP ones. According to Moore et al. (1993) and Vieira et al. (2006), the differences described in SAW amount are associated with a greater water recharge during fallow in HP MZ due to topographic characteristics. Different soil N and SAW

**Table 2** Mean values and standard error (SE) of soil properties (0–0.2 m layer) and soil available water content (SAW, 0–2 m) at planting in management zones (MZ) of low productivity (LP), medium productivity (MP) and high productivity (HP) of four experimental sites from the semi-arid Pampas

| MZ | Experimental site | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Site I | | Site II | | Site III | | Site IV | | |
| | LP | HP | LP | HP | LP | HP | LP | MP | HP |
| TN (g $kg^{-1}$) | 1.17 ± 0.05 | 1.26 ± 0.03 | 1.13 ± 0.08 | 1.61 ± 0.08 | 1.34 ± 0.08 | 1.42 ± 0.03 | 0.96 ± 0.04 | 1.07 ± 0.02 | 1.47 ± 0.23 |
| Water pH | 6.9 ± 0.1 | 7.1 ± 0.1 | 8.0 ± 0.1 a | 6.9 ± 0.2 b | 6.7 ± 0.2 a | 7.3 ± 0.1 b | 7.1 ± 0.2 | 6.6 ± 0.2 | 6.8 ± 0.1 |
| EC ($dSm^{-1}$) | 0.77 ± 0.03 | 0.98 ± 0.06 | 1.23 ± 0.12 | 1.11 ± 0.04 | 0.83 ± 0.03 | 0.93 ± 0.12 | 0.67 ± 0.03 | 0.63 ± 0.09 | 0.83 ± 0.03 |
| SOM (%) | 2.0 ± 0.1 | 2.75 ± 0.5 | 1.92 ± 0.1 | 3.28 ± 0.5 | 2.48 ± 0.1 | 2.99 ± 0.2 | 1.48 ± 0.1a | 1.71 ± 0.0 a | 3.13 ± 0.1 B |
| P (mg $kg^{-1}$) | 15.2 ± 2.4 | 31.7 ± 13.4 | 8.5 ± 0.3 a | 56.3 ± 9.9 b | 36.7 ± 6.6 | 52.7 ± 5.4 | 4.3 ± 0.3 | 17.0 ± 5.5 | 26.0 ± 4.6 |
| N-$NO_3$ (Kg $ha^{-1}$) | 20.94 ± 1.19 a | 26.34 ± 0.85 B | 29.98 ± 3.64 a | 42.44 ± 0.92 b | 86.06 ± 5.18 | 69.15 ± 9.37 | 57.64 ± 4.77 | 68.40 ± 4.03 | 58.53 ± 8.16 |
| SAW (mm) | 55.5 ± 7.2 a | 95.0 ± 11.4 b | 131.4 ± 3.5 a | 149.5 ± 1.2 b | 164.7 ± 6.2 a | 198.6 ± 4.6 b | 167.4 ± 7.9 a | 223.7 ± 2.6 b | 261.5 ± 9.5 c |

Different letters indicate significant differences ($p < 0.05$) between MZ within each experimental site

*TN* total soil nitrogen, *EC* soil electrical conductivity, *SOM* soil organic matter and *P* soil extractable phosphorus. *N-NO*$_3$ down to 0.6 m

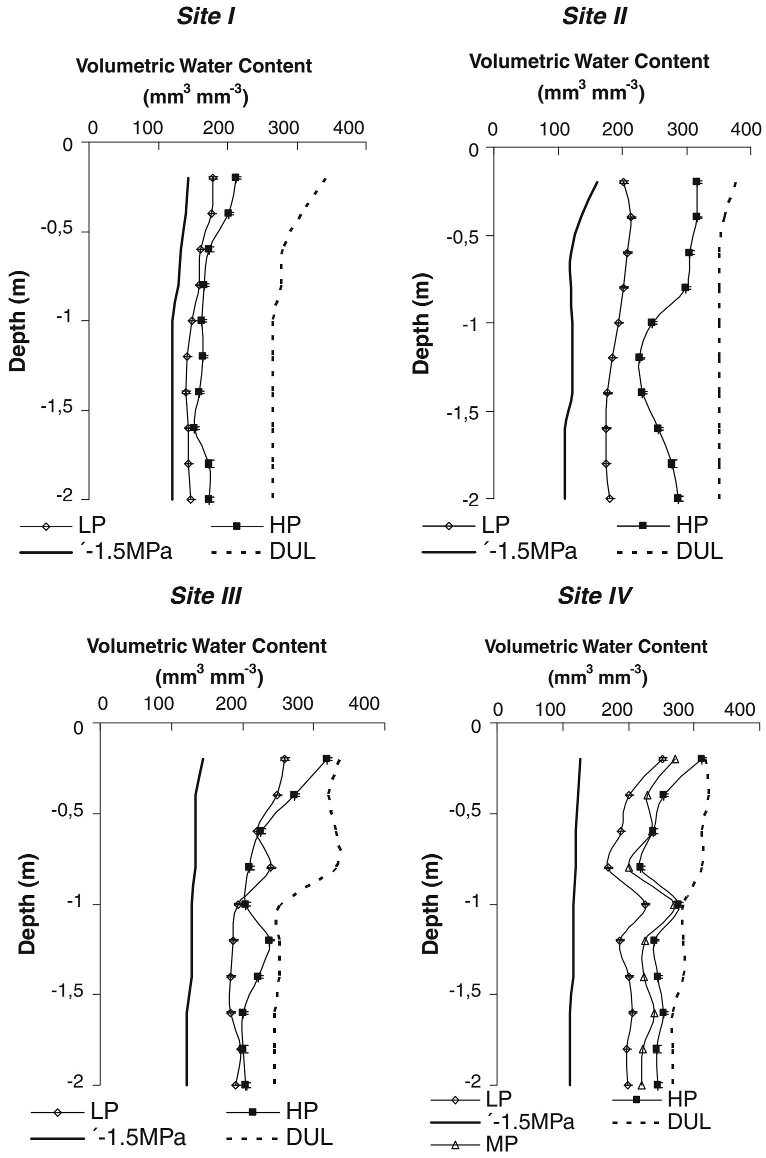
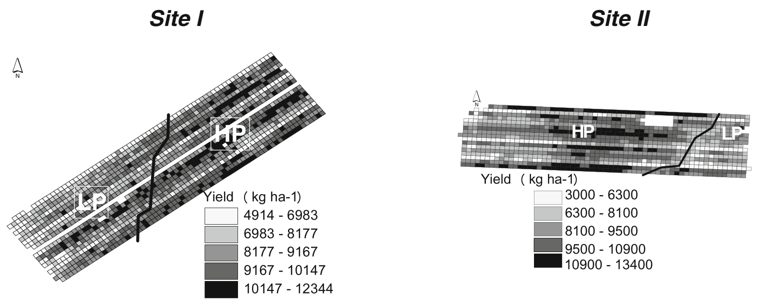


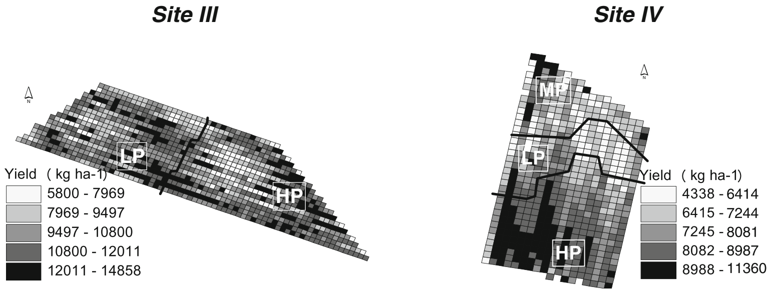
**Fig. 4** Volumetric soil water content (0–2 m depth) at planting in management zones of low (LP), medium (MP) and high (HP) productivity of four sites from the semi-arid Pampas. The *dashed lines* indicate the volumetric soil water content at the drained upper limit (DUL) and the *solid lines* indicate the volumetric soil water content measured in the laboratory at −1.5 MPa water potential. The *horizontal bars* show the standard errors of the mean

combinations determined different environments for maize production. In Typic Fragiochrepts from the state of New York (USA), Timlin et al. (1998) found that soil water availability, either in excess or deficit is a source of corn grain variability.



| MZ | Mean grain yield (kg/ha) ± SE |
|---|---|
| LP | 8,271 ± 53.7 |
| HP | 9,058 ± 49.7 |

| MZ | Mean grain yield (kg/ha) ± SE |
|---|---|
| LP | 8,366 ± 137.1 |
| HP | 9,215 ± 68.4 |



| MZ | Mean grain yield (kg/ha) ± SE |
|---|---|
| LP | 9,908 ± 76.4 |
| HP | 10,658 ± 69.5 |

| MZ | Mean grain yield (kg/ha) ± SE |
|---|---|
| LP | 6,630 ± 78.8 |
| MP | 7,460 ± 92.65 |
| HP | 8,389 ± 55.3 |

**Fig. 5** Polygons of mean corn grain yields in four experimental sites from the semi-arid Pampas estimated within management zones (MZ) of low (LP), medium (MP) and high (HP) productivity. The mean values ± standard error (SE) of each management zone (MZ) are displayed

## Spatial distribution of corn grain yields

Corn grain yields varied among sites and MZ within sites. In each site, the greatest corn grain yields were obtained in HP MZ, and variability was greater between MZ than within them (Fig. 5). Timlin et al. (1998) reported that large yields of rainfed corn crops in the states of New York and Minnesota (USA) were associated with low positions in the landscape, deep soils and high SOM content. In this study, the areas of HP showed greater TN, SOM and P content as well as greater SAW than less productive areas (Table 2).

The model performed well among MZ within sites. Goodness of fit tests (adjusted $R^2$, likelihood Log, Akaike information criterion and Schwarz criterion), were ($p < 0.05$). Thus, all MZs and site data sets were pooled and a unique model was tested. Table 3 summarizes the coefficients between yields and Nd amount, SAW and the dummy variables for each site estimated using the model fitted with Eq. 1. The coefficients of the

**Table 3** Summary of the coefficients and standard errors estimated to the response of soil available N (Nd) (soil available N-$NO_3$ + fertilizer N down to 0.6 m) and soil available water (SAW) down to 2 m, with dummy variables for all the management zones (MZ) within each experimental site (I, II, III and IV) in rainfed corn crops, during 2004–2005 and 2005–2006, in the semi-arid Pampas

| Variable | Coefficient | SE | *p* |
|---|---|---|---|
| Constant | 8 417.65 | 5 775.3 | NS |
| Nd | 33.93 | 1.9 | 0.001 |
| $Nd^2$ | −0.07 | 0 | 0.001 |
| SAW | −25.43 | 82.2 | NS |
| $SAW^2$ | 0.06 | 0.3 | NS |
| I | −4 482.31 | 5 806.7 | NS |
| II | −8 036.48 | – | – |
| III | 10 934.40 | 10 806.8 | NS |
| IV | 1 584.30 | 5 961.8 | NS |
| Nd × I | 0.64 | 3.2 | NS |
| Nd × II | 8.49 | – | – |
| Nd × III | 10.51 | 6.5 | 0.001 |
| Nd × IV | −19.65 | 5.1 | 0.001 |
| $Nd^2$ × I | −0.05 | 0 | 0.001 |
| $Nd^2$ × II | 0.04 | – | – |
| $Nd^2$ × III | 0.04 | 0 | 0.001 |
| $Nd^2$ × IV | 0.05 | 0 | 0.001 |
| SAW × I | 83.02 | 83.2 | NS |
| SAW × II | 62.83 | – | – |
| SAW × III | −122.2 | 135.2 | NS |
| SAW × IV | −23.65 | 82.6 | NS |
| $SAW^2$ × I | −0.42 | 0.3 | NS |
| $SAW^2$ × II | −0.1 | – | – |
| $SAW^2$ × III | 0.47 | 0.4 | NS |
| $SAW^2$ × IV | 0.07 | 0.3 | NS |
| Nd × SAW × I | 0.1 | 0 | 0.001 |
| Nd × SAW × II | 0.06 | – | – |
| Nd × SAW × III | −0.18 | 0 | 0.001 |
| Nd × SAW × IV | 0.01 | 0 | NS |
| $\lambda$ | 0.57 | 0 | *0.001* |
| Goodnes of fit measures | | | |
| Adjusted $R^2$ | | | 0.69 |
| Likelihood Log | | | −31 416.5 |
| Akaike information criterion (AIC) | | | 62 878.9 |
| Schwarz criterion (SC) | | | 63 022.3 |
| Test of the likelihood ratio | | | 926.8 |

Standard errors (SE) and significance probability levels ($p$) < 0.10 are displayed, *NS* non-significant ($p > 0.10$)

dummy variables were not statistically significant, suggesting that grain responses to Nd and SAW in any MZ were not different between sites. Then, under the conditions used in the present study, the site-specific variables (Nd and SAW) were equally related to yield, independent of the location of the sites.

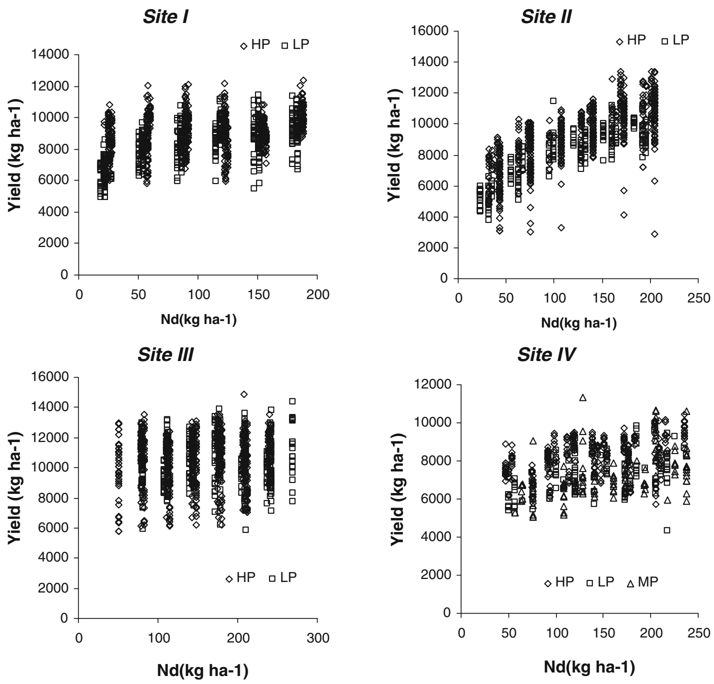
These results allowed the development of a unique model of grain response to the site-specific variables selected. All parameters selected for this regional model were significant ($p < 0.001$) (Table 4) and well predicted observed data for LP and HP MZs (Fig. 6). Also, this model predicted increased AON and EON amount for HP in three of the four sites (Fig. 7) with significant differences.

Using a quadratic relationship between corn grain yield and soil N availability at sowing in the province of Córdoba (Argentina), Bianchini et al. (2004) found N availability values similar to those in this study, although they did not discriminate between MZ. Those authors determined that 130 kg ha$^{-1}$ of N-NO$_3$ supply (0–0.6 m-depth) at sowing was necessary to achieve 10 000 kg ha$^{-1}$ yield. Similar results were found by Ruffo (2003) in a study conducted in southern and central Illinois (USA) using a single model for two locations, but including other site-specific variables, some of them related to topography (e.g., topographic and runoff energy indices), N availability and rainfall.

Although differences between MZ were not large, the analysis of the apparent contribution of VRF over a single N fertilizer rate for each MZ in each site was performed with the available information, without discriminating between MZ, i.e., using the average of SAW and Nd. N fertilizer rate and corn yield were estimated for each site according to the unique model described in Eq. 2 and considering Nd and SAW down to 0.6–2 m, respectively. NUEf was calculated as the difference between yield obtained at AON and yield obtained without Nf (Eq. 8), i.e., yield obtained with only soil nitrogen, with respect to Nf (Table 5).

**Table 4** Summary of the estimated coefficients and standard errors (SE) and significance probability levels ($p$) < 0.1, of the response to soil available N (Nd) (soil available N-NO$_3$ + fertilizer N down to 0.6 m) and soil available water (SAW) down to 2 m using Eq. 2 for all the management zones (MZ) within each site (I, II, III and IV) in rainfed corn crops, during 2004–2005 and 2005–2006, in the semi-arid Pampas

| Variable | Coefficient | SE | $p$ |
|---|---|---|---|
| Constant | 4 860 | 307.94 | 0.001 |
| Nd | 39.69 | 1.23 | 0.001 |
| Nd$^2$ | −0.099 | 0.005 | 0.001 |
| SAW | 16.18 | 4.07 | 0.001 |
| SAW$^2$ | −0.06 | 0.013 | 0.001 |
| Nd × SAW | 0.013 | 0.0063 | 0.001 |
| $\lambda$ | 0.74 | 0.0014 | 0.001 |
| Goodnes of fit measures | | | |
| Adjusted $R^2$ | | | 0.63 |
| Likelihood Log | | | −31 834.6 |
| Akaike information criterion (AIC) | | | 63 681.3 |
| Schwarz criterion (SC) | | | 63 718.7 |
| Test of the likelihood ratio | | | 2 079.0 |



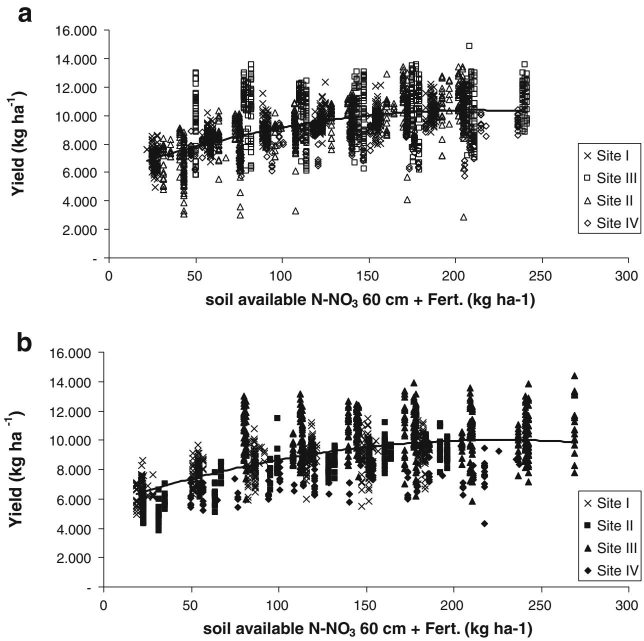
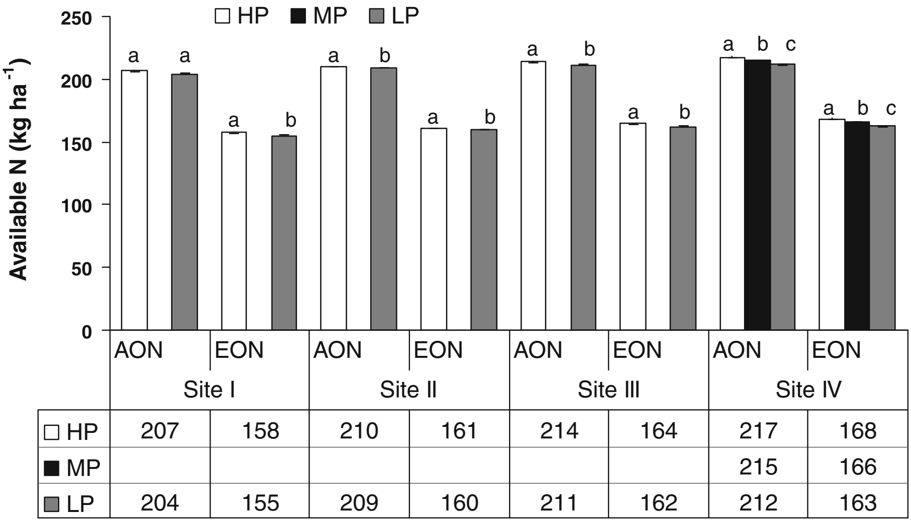


**Fig. 6** Corn grain yields in each site. (**a**) low and (**b**) high productivity management zones, as functions of available N level with different symbols for each site. The *solid lines* show the fitted regional model using Eq. 2 (See text for details)



| | Site I AON | Site I EON | Site II AON | Site II EON | Site III AON | Site III EON | Site IV AON | Site IV EON |
|---|---|---|---|---|---|---|---|---|
| ☐ HP | 207 | 158 | 210 | 161 | 214 | 164 | 217 | 168 |
| ■ MP | | | | | | | 215 | 166 |
| ▨ LP | 204 | 155 | 209 | 160 | 211 | 162 | 212 | 163 |

**Fig. 7** Estimated agronomic (AON) and economic (EON) optimum N availability for corn grain production in management zones (MZ) of low (LP), medium (MP) and high (HP) productivity from four experimental sites of the semi-arid Pampas region. *Different letters* at the top of each column for each site indicate significant differences ($p < 0.05$) between MZ

Maximum yield estimated using data obtained from each MZ varied between 9 853 and 10 246 kg ha$^{-1}$. The corresponding AON would be achieved at fertilizer rates between 137 and 182 kg Nf ha$^{-1}$. Similar results were obtained when yield was estimated using average values of Nd and SAW for each site (Table 5). NUEf ranged between 13 and 18 kg of grain (kg of applied N) considering both the relative contribution of each MZ and a single recommendation per location. Similar results were obtained if EON was applied. Ruffo (2003) found similar results evaluating the variable N fertilizer rate recommended for corn crops in Illinois (USA). Furthermore, the differences found in the EON between variable and uniform N fertilizer rates were only 0.4 kg ha$^{-1}$, even smaller than those calculated by us (Table 5). It can be justified because the MZ defined in this study presented similar soil types with moderate differences in their properties (Table 2).

## Conclusions

The lack of differences among sites in grain responses to Nd and SAW in any MZ allowed the fitting of a regional model whose parameters (Nd, Nd$^2$, SAW, SAW$^2$) contributed significantly ($p < 0.001$) to yield prediction. The differences in Nd and SAW were not enough to recommend variable rates of N fertilizer between the MZ within the fields. Therefore, the hypothesis of a general need for variable N fertilizer rate for the production of corn crops in Haplustoll soil with contrasting MZ, was rejected. This hypothesis could be true if there are greater differences in soil available water contents between MZ than those described in this research.

**Table 5** Nitrogen fertilizer rate, corn grain yield and agronomic fertilizer N use efficiency (NUEf) at the agronomic (AON) and the economic (EON) optimal amount at four sites from the semi-arid Pampas for two fertilizer strategies: mean or uniform and variable rate

| Fertilizer strategy | | | Experimental site | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Site I | | Site II | | Site III | | Site IV | | | Mean (SE) | *p*-Value |
| | | | LP | HP | LP | HP | LP | HP | BP | MP | HP | | |
| Ns a 0.6 m (kg N ha$^{-1}$): | | | 21 | 26 | 30 | 43 | 88 | 63 | 61 | 70 | 57 | | |
| Ratio MZs (%): | | | 56 | 44 | 21 | 79 | 51 | 49 | 23 | 24 | 53 | | |
| AON | | | | | | | | | | | | | |
| N fertilizer rate (kg ha$^{-1}$) | Each MZ | | 183 | 180 | 179 | 167 | 123 | 150 | 154 | 157 | 160 | | |
| | Uniform rate | | 182 | | 173 | | 137 | | 157 | | | 161 (10.2) | 0.972 |
| | Variable rate | WA | 182 | | 170 | | 137 | | 158 | | | 162 (9.59) | NS |
| Grain yield (kg ha$^{-1}$) | Each MZ | | 9 688 | 10,06 | 10 229 | 10 251 | 10 238 | 10 107 | 10 233 | 10 021 | 10 105 | | |
| | Uniform rate | | 9 898 | | 10 245 | | 10 190 | | 9 721 | | | 10 013 (123.8) | 0.601 |
| | Variable rate | WA | 9 853 | | 10 246 | | 10 173 | | 10 114 | | | 10 097 (85.5) | NS |
| NUEf (kg grain kg N$^{-1}$) | Each MZ | | 18,13 | 17,85 | 17,73 | 16,56 | 12,2 | 14,89 | 15,29 | 16,04 | 15,8 | | |
| | Uniform rate | | 18.0 | | 17.1 | | 13.5 | | 15.8 | | | 16.0 (0.9) | 0.944 |
| | Variable rate | WA | 18.0 | | 16.8 | | 13.5 | | 15.7 | | | 16.1 (0.95) | NS |
| EON | | | | | | | | | | | | | |
| N fertilizer rate (kg ha$^{-1}$) | Each MZ | | 134 | 131 | 130 | 118 | 74 | 101 | 101 | 96 | 111 | | |
| | Uniform rate | | 133 | | 124 | | 88 | | 103 | | | 112 (10.2) | 0.672 |
| | Variable rate | WA | 131 | | 119 | | 86 | | 127 | | | 117(9.59) | NS |
| Grain yield (kg ha$^{-1}$) | Uniform rate | | 9 448 | | 9 982 | | 9 997 | | 10 012 | | | 9 859 (137.4) | 0.377 |
| | Variable rate | WA | 9 447 | | 9 986 | | 9 997 | | 9 869 | | | 9 824 (130.0) | NS |
| NUEf (kg grain kg N$^{-1}$) | Uniform rate | | 21.7 | | 22.1 | | 19.3 | | 23.2 | | | 22.0 (0.8) | 0.715 |
| | Variable rate | WA | 21.8 | | 21.7 | | 19.3 | | 24.7 | | | 23.0 (2.1) | NS |

*MZ* management zone, *SE* standard error, *p-value* probability of the value of F of the ANOVA, *NS* non-significant ($p > 0.05$), *WA* weighted average by ratio MZ′s

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