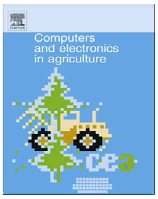
Computers and Electronics in Agriculture 110 (2015) 103–113

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag



Delineation of management zones to improve nitrogen management of wheat

Nahuel Raúl Peralta [a,c,*], José Luis Costa [b,c], Mónica Balzarini [a,d], Mauricio Castro Franco [a,c], Mariano Córdoba [a,d], Donald Bullock [e]

[a] *Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Av. Rivadavia 1917, CP C1033AAJ Buenos Aires, Argentina*
[b] *Estación Experimental Agropecuaria, INTA, Balcarce, C.C.276, 7620 Balcarce, Buenos Aires, Argentina*
[c] *Facultad de Ciencias Agrarias-UNMdP (Universidad Nacional de Mar del Plata), C.C.276, 7620 Balcarce, Buenos Aires, Argentina*
[d] *Facultad de Ciencias Agrarias-UNC (Universidad Nacional de Córdoba), Ciudad Universitaria, cc 509, 5000 Córdoba, Argentina*
[e] *Department of Crop Sciences, University of Illinois, Urbana-Champaign, Urbana, IL, USA*

ARTICLE INFO

Article history:
Received 9 May 2014
Received in revised form 15 October 2014
Accepted 21 October 2014

Keywords:
Management zones
Soil depth
Apparent soil electrical conductivity
Terrain attributes
Yield maps

ABSTRACT

Site-specific management of N (NSSM) is an attractive and intuitive approach to increasing N fertilizer use efficiency (NUE) of agricultural systems by adjusting fertilizer rates to the soil characteristics. The objective of this study is to assess: whether delineating of management zone (MZ) within fields improves NUE in wheat (*Triticum aestivum* L.). This research was carried out at 5 commercial fields (between 26 and 84 ha), located in the south-eastern portion of the Province of Buenos Aires, Argentina. The MZ were delineated by using georeferenced measurements of apparent soil electrical conductivity, terrain elevation and soil depth. Spatially referenced wheat yields were recorded with a yield monitor equipped with DGPS. The interaction effect was significant ($p < 0.05$) in most fields, thus indicating that the response to N fertilization is different among MZ. Also, NUE was significantly different ($p < 0.05$) among MZ. The detection of soil spatial variability and the delineation of MZ are now possible on a commercial scale. The delineation of MZ affords the opportunity of variable rate application of N fertilizers on Typic Argiudolls and Petrocalcic Paleudolls, and the minimization of pollution risk due to an excessive application of resources.

1. Introduction

Worldwide, the average efficiency of N fertilizer use in cereal crops is 33% (Raun and Johnson, 1999). The Argentine Humid Pampas region is one of the world's best regions for grain crop production (Satorre and Slafer, 1999). The major soil types that compose this region are Typic Argiudolls, with a loam texture at the surface layer, loam to clay loam at subsurface layers, and sandy loam below 110 cm deep, and Petrocalcic Paleudoll, which presents discontinuous layers of a petrocalcic horizon between 50 and 100 cm and greater clay contents at subsurface layers than Typic Argiudolls. Because of this, agricultural fields in south-eastern Pampas frequently have multiple soil map units within them, despite their sometimes relatively small size, and wide range of soil textures and properties, causing high soil spatial variability (Peralta et al., 2013a). As a result, spatial variability of the different soil processes that determine soil N supply and crop response to N fertilizer between and within fields (Ruffo et al., 2006; Jaynes et al., 2011) is generated. The dominant practice for farmers is to apply the same rate of N fertilizer over whole fields and even whole farms. In fields with spatially variable N needs, this practice leads to frequent mismatches between N fertilizer rate and crop N need. Over-application of N increases the probability of NO_3–N leaching below the root zone (Aparicio et al., 2008; Barbieri et al., 2008) while underfertilization limits yields and may restrict economic returns (Scharf and Lory, 2002). Efficient N fertilizer management is critical for profitable crop production and long-term soil and environmental quality. One of these is to use precision farming methods to apply N fertilizers at variable rates across a field rather than at a uniform rate (Raun and Schepers, 2008; Jaynes et al., 2011). Site-specific management of N (NSSM) is an attractive and intuitive approach to increasing fertilizer use efficiency of agricultural systems by adjusting fertilizer rates to the soil characteristics. Delineation of different management zones (MZ), i.e., zones that may differ in factors such as the type of soil, topography, water and nutrient availability (Bullock et al., 2009).

---

* Corresponding author at: Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Av. Rivadavia 1917, CP C1033AAJ, Buenos Aires, Argentina. Tel.: +54 2266 439100.

E-mail address: nperalta21@gmail.com (N.R. Peralta).

http://dx.doi.org/10.1016/j.compag.2014.10.017

Efficient techniques to accurately measure within-field variations in soil properties are very important to define an MZ (Peralta et al., 2013a). Traditional soil sampling is costly and labor-intensive. This traditional method is not viable from an MZ perspective, because it needs a large number of soil samples in order to achieve a good representation of soil properties and nutrient levels. The geospatial measurement of apparent electrical conductivity (ECa) is an efficient ground-based sensing technology that is helping to take MZ from concept to reality (Kitchen et al., 2003, 2005). ECa can be intensively recorded in an easy and inexpensive way, and provides an indirect measure of soil physical and chemical properties that can have a dominant influence on plant growth and yield (Kitchen et al., 2003; Peralta et al., 2013a). Terrain elevation, also provide useful information for to delineate MZ, because it plays an important role in the hydrological response of rainfall catchment and has a major impact on water availability for crop production in rainfed agriculture (Kitchen et al., 2003). In Pampean soils cultivated with grain crops, the depth of the petrocalcic horizon, is also a useful variable for MZ delineation (Peralta et al., 2013b; Córdoba et al., 2013). The delineation of management zones is an approach to the application of different N rates within the field (Ruffo et al., 2006; Bullock et al., 2009). In this regard, Wollenhaupt and Buchholz (1993) found a potential for improved profitability with NSSM, especially when applied to fields with contrasting texture, topography and soil depth. Mulla (1993) calculated the recommended N rates for three MZ for a winter wheat (*Triticum aestivum* L.) field in Washington based on soil organic matter content. He found that the recommended N rates for each MZ (37, 45, and 28 kg N ha^{-1}) were significantly different from the grower's uniform N rate of 73 kg N ha^{-1} in the year of the study. In contrast, Robert et al. (1996) developed MZ based on soil depth for winter wheat in France. They found yield components not to be significantly different between NSSM and a uniform rate. Bhatti et al. (1998) compared uniform N application on wheat with variable rate application based on crop productivity patterns and found no difference in grain yield, while the site-specific approach used less total N. These inconsistent results may be due to complex interrelationships between wheat and soil characteristics.

The NSSM in wheat has not been adequately described for regions with soils associations formed by h Typic Argiudolls and Petrocalcic Paleudoll, typical of many agriculturally important soils in Argentina and throughout the world. When ANOVA models do not take spatial autocorrelation structure into account estimated coefficients are biased and the variances can be inflated which in turn, affects the crops site-specific function responses such as profit analysis, leading to wrong conclusions (Bullock et al., 2009). This can be addressed by fitting ANOVA models under the Linear Mixed Model context which takes into account the correlation and heteroscedasticity problems encountered with soil and field variability. A proper model should accounts for within-trial spatial correlation, between-MZ heterogeneity, and includes random block effects or spatial correlations in the error terms (Casanoves et al., 2005).

The objective of this study is to assess whether delineating management zones with cluster analysis, using as input variable to ECa, topography and soil depth, improves N use efficiency (NUE) in wheat fields with multiple soil maps units within them.

2. Materials and methods

2.1. Experimental site

The study was performed, at five commercial production fields located in three experimental sites in the southeastern Pampas of the province of Buenos Aires, Argentina (Fig. 1). The five fields are composed of various soil series (Table 1), FA, FB and FE of the Tandil series (fine, mixed, thermic, Typic Argiudoll) and Azul series (fine, illitic, thermic Petrocalcic Paleudoll); F11, and F25 of the Semillero Buck series (fine, illitic, thermic Typic Argiudoll), Cinco Cerros series (fine, illitic, thermic, Lytic Argiudoll) and Azul series [Instituto Nacional de Tecnología Agropecuaria (INTA) 1970–1989]. These soils in surface and subsurface horizons present clay contents between 25% to 30% and 38% to 45%, respectively (Peralta et al., 2013a; INTA, 1989). Furthermore, these soils in surface and subsurface horizons present low values of electrical conductivity of the saturation extract (ECe) between 0.25 to 0.34 dS m^{-1} and 0.29 to 0.45 dS m^{-1}, respectively (Peralta et al., 2013a; INTA, 1989). Except for N fertilizer application rates, crop management and tillage practices varied between fields and were chosen by the farmer, but each farmer managing more than one field used the same practices on each field. Phosphorus fertilizer (Triple Super Phosphate, 0-46-0) was applied in all fields in the fall before wheat planting to avoid deficiencies. No-tillage (direct seeding) is widespread in the region and it was a feature common to all fields in this study.

2.2. Soil sampling, analysis and precipitation data

The precipitation data (monthly precipitation for June–December) were obtained from weather stations located at each farm. For all the experiments and MZ, a water balance was calculated according to Della Maggiora et al. (2002). Maximum and actual crop evapotranspiration (MET and AET) were estimated using crop coefficients as reported by Allen et al. (1998). The effective depth of the soil ranged from 132.2 and 59.6 cm, total soil wáter storage capacity (mm cm^{-1}) and available soil water (mm cm^{-1}) were calculated using the model of Travasso and Suero (1994). Maximum water storage limit and available water content were estimated as the product of soil depth by total storage capacity and available water, respectively (Travasso and Suero, 1994). Soil water content at the lower limit was 54% of total water content; actual soil water was determined by the balance between rainfall and AET. The physiological threshold was assumed as 50% of available water (Doorenbos and Kassam, 1979). When actual soil water content fell below this threshold, AET was less than the MET, and water deficit was estimated as the difference between MET and AET.

Soil sampling at sowing was done by randomly collecting eight 2-cm-diameter cores from each replication; samples were taken to 0- to 60-cm soil depth in 20-cm depth increments. Soils were oven dried (30 °C). Determinations of soil NO_3–N content (0–60 cm) was done by microdistilation (Bremner and Keeney, 1966).

2.3. Measurements to generate management zones

The following variables were recorded: georeferenced measurements of apparent electrical conductivity (ECa) taken at two depths: 0–30 (ECa30) and 0–90 cm (ECa90), elevation and soil depth. All variables were measured between April and June, prior to sowing winter crops (wheat, *T. aestivum*).

Soil ECa measurements were taken using Veris 3100® (Veris 3100, Division of Geoprobe Systems, Salina, KS). The sensor was pulled across the field in a series of parallel transects spaced at 15–20 m intervals, the appropriate spacing to avoid measurement errors and information loss (Farahani and Flynn, 2007). ECa was simultaneously measured and georeferenced with a Differential Global Positioning System (DGPS) (Trimble R3, Trimble Navigation Limited, USA) with sub-metric measurement accuracy and set up to record position once per second. Terrain elevation data were processed to obtain a vertical accuracy of about 3–5 cm. The soil depth was measured using a hydraulic penetrometer (Giddings

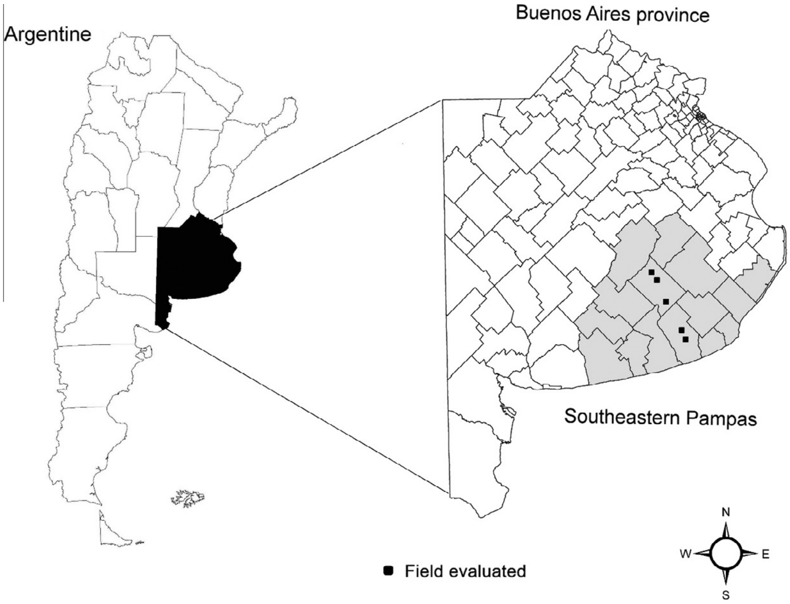


Fig. 1. The field evaluated located in southeastern Pampas, Buenos Aires province, Argentina.

Table 1
Experimental sites and soil classifications (INTA, 1970, INTA, 1989).

Experimental site	Fields	Surface (ha)	$N–NO_3$[**]	Soil type			Horizons	
			(kg ha^{-1})	U.M.[*]	Soil series	Soil classification	Topsoil	Subsoil
Tandil	FA	45	80	Ta19	Tandil (70%) Azul (30%)	Typic Argiudoll Petrocalcic Paleudoll	Loam Clay-loam	Loam-clay Clayey
	FB	26	84	Ta19	Tandil (70%) Azul (30%)	Typic Argiudoll Petrocalcic Paleudoll	Loam Clay-loam	Loam-clay Clayey
La Numancia	FE	33	80	Ta19	Tandil (70%) Azul (30%)	Typic Argiudoll Petrocalcic Paleudoll	Loam Clay-loam	Loam-clay Clayey
Loberia	F11	75	87	AZ26	Azul (60%) Semillero Buck (30%) Cinco Cerros (10%)	Petrocalcic Paleudoll Typic Argiudoll Lytic Argiudoll	Clay-loam Loam Clay-loam	Clayey Loam-clay Clayey
	F25	84	83	AZ26	Azul (60%) Semillero Buck (30%) Cinco Cerros (10%)	Petrocalcic Paleudoll Typic Argiudoll Lytic Argiudoll	Clay-loam Loam Clay-loam	Clayey Loam-clay Clayey

[*] U.M.: mapping unit.
[**] Nitrate concentration at sowing (0–60 cm).

Machine Co., Windsor, CO) from a 30-m rectangular grid until reaching the depth of petrocalcic horizon. Wheat grain yield was measured and recorded using calibrated commercial yield monitors mounted on combines equipped with DGPS.

2.4. Spatial variability of ECa, elevation, soil depth and grain yield

The spatial dependence of ECa (ECa30 and ECa90), elevation, soil depth and yield were quantified using semivariograms which characterize and determine distribution patterns such as randomness, uniformity and spatial trend. The semivariogram was estimated using the following equation (Isaaks and Srivastava, 1989):

$$\gamma^*(h) = \frac{1}{2N(h)}\sum_{i=1}^{N(h)}(z(x_i) - z(x_i + h))^2 \qquad (1)$$

where $\gamma^*(h)$ is the experimental semivariance value at the lag or distance interval h; $z(x_i)$ is the measured sample value at sample points x_i, in which there are data at x_i; and $x_i + h$; $N(h)$ is the total number of sample pairs within the distance interval h. The semivariogram shows the spatial correlation between two points in space as separation as the lag changes. The semivariogram for each field were used to interpolate the ECa, soil depth and elevation by means of ordinary kriging after checking for common geo-statistical assumptions (Isaaks and Srivastava, 1989). All geostatistical work was conducted with the ArcGIS Geospatial Analyst (ArcGIS v9.3.1, Environmental System Research Institute Inc. (ESRI), Redlands, CA, USA). A final 10 m × 10 m grid cell size was chosen because it reflects the scale of variability associated with the ECa measurements, elevation, soil depth and yield (Kitchen et al., 2003; Peralta and Costa, 2013).

2.5. Grain yield evaluation

Wheat 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 of 10.6 m. Grain yield data were corrected to 14% 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 editer* (Sudduth and Drummond, 2007).

2.6. Management zone delineation

For MZ determination based on soil and terrain variables the methodology described by Córdoba et al., 2013 was used. This algorithm takes the spatial principal components (sPC) of soil and terrain variables obtained through MULTISPATI-PCA analysis, as inputs for fuzzy k-means cluster analysis (Bezdek, 1981). MULTISPATI-PCA (Dray et al., 2008) is an extension of Principal Component Analysis that uses spatial information in the data for forming the principal components. The imposed restriction by spatial data is incorporated through the Moran Index, which measures correlation between observations for a given sampling point and the average of observations for nearby points. In this work, a net of neighborhoods was defined in terms of Euclidean distance, considering neighboring points as those located between 0 and 20 m apart. The sPC with eigenvalues $\geqslant 1$ were selected as input for the cluster fuzzy k-means (CFK) analysis. To implement MULTISPATI-PCA, the functions "ade4" (Chessel et al., 2004) and "spdep" (Bivand, 2012) in the R (R Development Core Team, 2013) software were used. The CFK analysis was carried out based on the first two sPC (sPC1 y sPC2) of soil and terrain variables, using Management Zone Analyst 1.0.1 (MZA) software (Fridgen et al., 2004). Because the sPC presented dissimilar variances, a diagonal distance matrix was used for clustering. Other configuration options of MZA were: maximum number of iterations = 300, convergence criterion = 0.0001, minimal zone number = 2, and maximum zone number = 6. The fuzziness exponent in the CFK method was set in 1.30 (Odeh et al., 1992). To determine the number of MZ within the field, two indexes were used: Normalized Classification Entropy (NCE) and Fuzziness Performance Index (FPI) (Odeh et al., 1992). The selected number of MZ was determined when both NCE and FPI reached a minimum, which represents a lower level of overlap (FPI) or a higher level of organization among clusters (NCE) (Fridgen et al., 2004). From this procedure, the following management zones were identified: (I) high productivity (HP), located in terrains presenting low elevation, (II) low productivity (LP), located in terrains presenting high elevation, and (III) average productivity (MP) located in transition areas between LP and HP.

To characterize MZ, the mixed linear model (MLM) for elevation, ECa30, ECa90 and soil depth was fitted using a "nlme" (Pinheiro et al., 2013) package of the R statistical software (R Core Team, 2013).

$$y_{ij} = \mu + Z_i + \varepsilon_{ij} \tag{2}$$

where y_{ij} represents the observed value of the variable in management zone i at the site j; μ represents the general mean of the variable; Z_i is the effect of the management zone with $i = 1,\ldots,z$; and ε_{ij} is the random error which is assumed to be spatially correlated through an exponential model.

2.7. Experimental design and application rates

We used a randomized complete block experimental design with between 5 and 12 replications in each MZ (Fig. 2). Different number of replications was used in each management zone within a field, depending on field and MZ shapes and sizes. Plot dimensions varied slightly among fields, according with farming equipment, but each was at least 70 m long and 30 m wide. Each plot received one N fertilizer rate, control (0 N), above, or equal to a benchmark rate.

In south-eastern Buenos Aires province, the benchmark or common N fertilizer rate (Nf) that most farmers use is Nf = CT − x, where Nf = N fertilizer, CT = critical threshold of N available at sowing (125 kg N ha^{-1} for yields <4500 kg ha^{-1}; 170 kg N ha^{-1} for yields of about 6000–7000 kg ha^{-1}) (Calviño et al., 2002; Barbieri et al., 2012) and x is the N-nitrates availability at 0–60 cm of sowing depth. The N fertilizer rates applied were a control (0 N), 125 − x (the traditional benchmark) and 170 − x.

For each MZ and N rate, wheat NUE (kg of grain kg of applied N^{-1}) was calculated as the difference between the yield of fertilized crops (YieldN) and that of the control (YieldC) divided by the applied rate ([YieldN − YieldC]/N rate). The GIS spatial design of the experiments (i.e. the plot plan) was developed with the ArcGIS. The randomization of rates to each experimental unit was performed with the PLAN procedure of SAS (SAS Institute, 2003). At least 20 m were left as buffer between the field headlands and the start of the experiment in order to improve fertilizer application and yield monitor performance. The digital plot plan of each field was transferred to each producer and the N rates were applied with commercial variable rate applicators equipped with differential global positioning system (DGPS). Applied N fertilizer and wheat yield were imported into ArcGIS. Only the two central passes of the combine and the applicator pass closest to these passes were retained for further analysis. Yield and applied N fertilizer points at a distance shorter than 7.5 m from either the start or end of the plot were discarded. Mean wheat yield and mean applied N fertilizer were calculated with ArcGIS for each experimental unit.

2.8. Statistical model for treatment evaluation

In order to compare treatments within each MZ including N rate × MZ interaction, a MLM of ANAVA was adjusted for plot yields from the basic model:

$$y_{ijk} = \mu + T_i + Z_j + B(Z)_{k(j)} + TZ_{(ij)} + \varepsilon_{ijk} \tag{3}$$

where y_{ijk} represents the observed yield with the N fertilizer rate i, in MZ j, block k; μ represents the overall mean; T_i is the fixed effect of N fertilizer rate with $i = 1,..,t$; Z_j is the fixed effect of the MZ with $j = 1,\ldots,z$; $B(Z)_{k(j)}$ is the random effect of blocks within the management zone with $k = 1,\ldots,b$; $TZ_{(ij)}$ is the effect of interaction between N rate and MZ and ε_{ijk} is the random error which is potentially correlated under two covariance models: a random block (RB) model, and then a random block model plus spatial correlation of plot errors (RB + SP). For the RB + SP models, exponential, gaussian and spherical correlation functions without nugget effect were evaluated using a "nlme" (Pinheiro et al., 2013) package of the R statistical software (R Core Team, 2013). These models (RB, RB + SP(Exp), RB + SP(Gau), RB + SP(Sph)) were adjusted with homogenous and heterogeneous variances for the different MZ. Model selection for the correlation structure was done following the Akaike information criteria (AIC). When comparing homoscedastic and heteroscedastic models, Likelihood Ratio Test (LRT) was used (West et al., 2007). Moreover, the interaction between N availability (soil available N–NO_3 at planting + applied N) and M was studied for all the fields together.

3. Results and discussion

3.1. Climatic conditions

Accumulated rainfall during growing seasons ranged from 257 mm to 317 mm. Median historic rainfall (over the last 80 years)

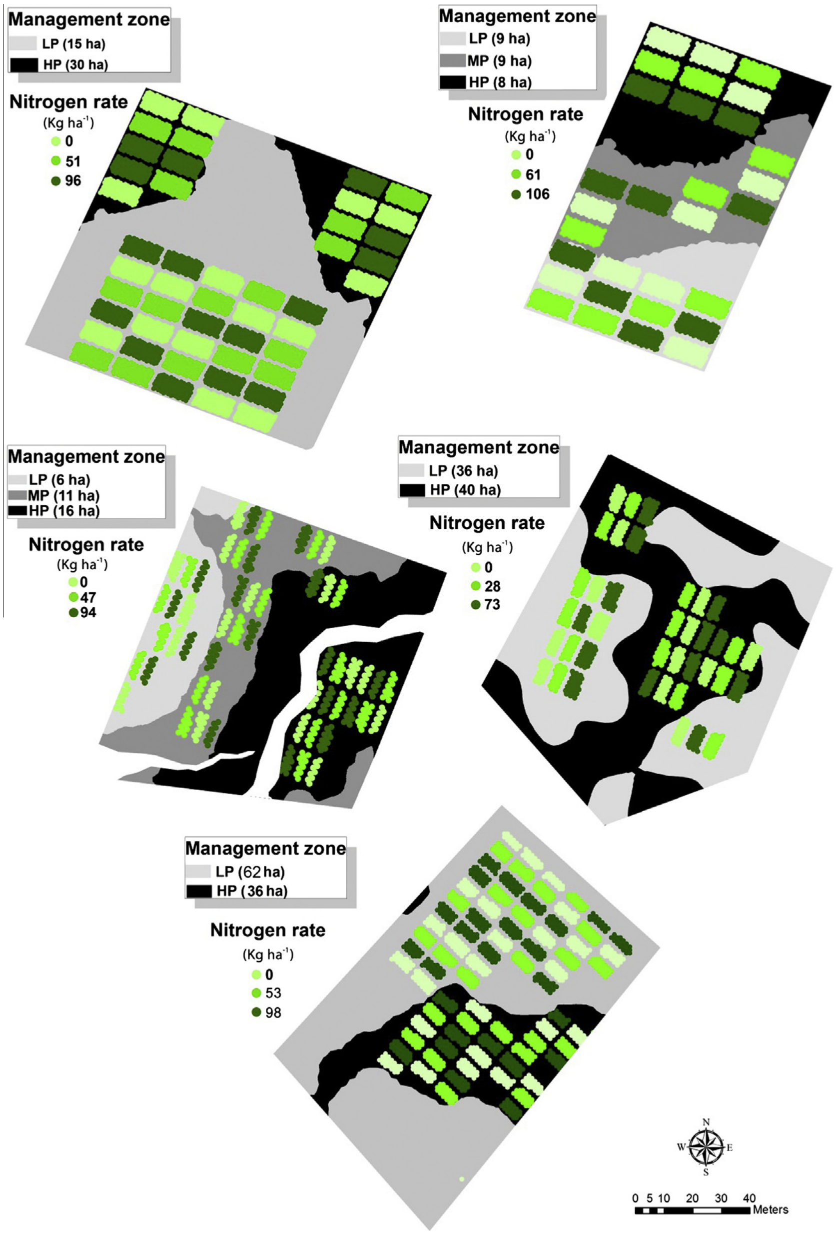


Fig. 2. Experimental fields with delimited management zones and plots with different N rates.

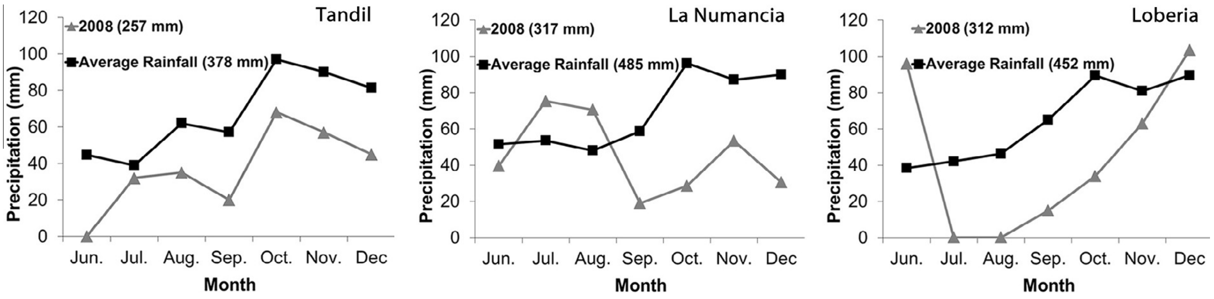


Fig. 3. Rainfall during the wheat-growing seasons (June–December) at Tandil. La Numancia and Loberia.

Table 2
Summary statistics of apparent electrical conductivity (ECa30 and ECa90); elevation, depth soil and yield in each evaluated field. Average values (mean), coefficient of variation (CV), minimum (min) and maximum (max).

Site	Field	Variables	Mean	CV	Min	Max
Tandil	FA	ECa30 (mS m^{-1})	19.6	12.7	14.5	26.1
		ECa90 (mS m^{-1})	19.5	23.7	8.0	33.4
		Elevation (m)	195.2	1.1	191.0	200.0
		Depth soil (cm)	89.7	16.3	55.0	101.1
		Yield (t ha^{-1})	3.7	6.9	2.7	4.5
	FB	ECa30 (mS m^{-1})	18.5	9.0	15.3	22.4
		ECa90 (mS m^{-1})	19.4	12.0	16.3	27.4
		Elevation (m)	198.9	2.1	191.0	207.9
		Depth soil (cm)	85.1	18.6	49.7	120.4
		Yield (t ha^{-1})	3.7	19.8	2.7	4.3
La Numancia	FE	ECa30 (mS m^{-1})	17.7	20.9	11.0	27.0
		ECa90 (mS m^{-1})	18.4	21.8	9.5	31.2
		Elevation (m)	258.6	3.4	245.5	282.0
		Depth soil (cm)	110.9	22.4	60.0	153.6
		Yield (tn ha^{-1})	3.9	22.8	2.4	4.8
Loberia	F11	ECa30 (mS m^{-1})	25.9	19.0	12.6	41.0
		ECa90 (mS m^{-1})	27.1	17.1	11.5	41.0
		Elevation (m)	152.3	0.4	149.0	153.3
		Depth soil (cm)	60.9	13.5	40.0	90.2
		Yield (t ha^{-1})	3.1	9.2	2.0	4.2
	F25	ECa30 (mS m^{-1})	22.9	11.3	16.6	26.7
		ECa90 (mS m^{-1})	26.2	8.3	21.2	31.0
		Elevation (m)	146.8	0.9	144.0	149.5
		Depth soil (cm)	82.2	18.5	72.8	134.1
		Yield (t ha^{-1})	3.5	25.3	2.6	4.3

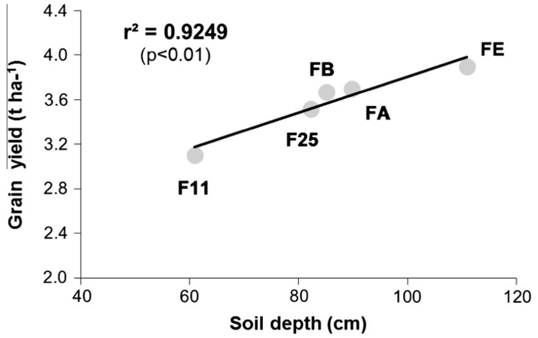


Fig. 4. Relationship between wheat yield (*Y*) in commercial fields and soil depth (*x*).

from June to December for the southeastern pampas is 438 mm, which was not surpassed at any of the experimental sites (Fig. 3). Water deficit in the growing period was inversely related to wheat grain yield ($r^2 = 0.47$) due to a reduction in the number of kernels per unit area (Abbate et al., 1995; Calviño and Sadras, 2002).

3.2. Descriptive analysis of soil properties and wheat yields

The ECa30 and ECa90 averages for all fields were 20.92 and 22.13 (mS m^{-1}) respectively. At Lobería, the averages for ECa30 and ECa90 were 24.39 and 26.68 mS m^{-1}, respectively, which are higher than the remaining fields (18.62 and 19.11 mS m^{-1}). Those differences can be attributed to a dissimilar distribution of soil particle size among fields, as described by Peralta et al., 2013a.

Due to soil type, at the Lobería fields the average soil depth is considerably less than at the other fields (71 cm) (Table 2). The Lobería soils belong mainly to the Azul series, formed by Petrocalcic Paleudols (70–100 cm). In contrast, at the remaining fields, the prevailing soil type is the Tandil series, formed by Typic Argiudolls (>150 cm). In these fields, the average soil depth is 95 cm.

The fields at Lobería have the lowest elevations (Table 2). Some areas within these fields do not have adequate surface drainage and are prone to water accumulation and ponding.

Wheat grain production varied among locations (Table 2). Average yield varied between 3.1 and 3.9 t ha^{-1} with a CV from 6.9% to 25.3%. The lowest average yields were recorded in the fields at Lobería (Fig. 4 and Table 2). These fields have the lowest soil depth (F11 and F25) and thus lower water availability for the crop affecting yield (Sadras and Calviño, 2001). The field at La Numancia (FE), in contrast, showed the greatest yield and the deepest soils.

3.3. Management zones

Soil depth and elevation had the highest loadings for the first spatial principal component (sPC1) (Table 3). The variation in sPC2 was mainly caused by ECa30 in the fields of Tandil (FA and FB) and F25. While for FE and F11 the most important variable was ECa90 and grain yield, respectively (Table 3).

In Fig. 5, the values for FPI and NCE for each field are shown. The optimal number of MZ for a given field is determined when the FPI and NCE each reach a minimum value (Fridgen et al., 2004). The fields FA and F11 produced two MZ, whereas the fields FB and FE produced three MZ. For the field F25, the number of MZ suggested by the FPI criterion (4 clusters) differs from the optimal number of

Table 3
Eigenvectors in the analysis of spatial principal components (sPC). The most relevant coefficients were highlighted.

Site	Field	Synthetic variables	ECa30	ECa90	Elevation	Soil depth	Grain yield
Tandil	FA	sPC1	−0.10	−0.28	**−0.63**	**0.64**	0.33
		sPC2	**0.77**	0.46	−0.26	0.22	−0.30
		sPC3	−0.04	**0.52**	0.47	0.39	**0.60**
	FB	sPC1	−0.26	**−0.37**	**0.62**	**−0.58**	0.28
		sPC2	**0.76**	0.34	0.25	−0.42	−0.26
		sPC3	−0.22	−0.33	0.07	−0.06	**−0.91**
La Numancia	FE	sPC1	**0.42**	−0.14	**0.58**	**−0.56**	−0.39
		sPC2	−0.21	**−0.85**	0.04	−0.20	**0.44**
		sPC3	−0.15	−0.45	−0.27	0.28	−0.79
Lobería	F11	sPC1	0.04	−0.49	0.20	**−0.73**	−0.43
		sPC2	−0.04	**0.53**	−0.20	0.07	**−0.82**
		sPC3	−0.03	**0.57**	**−0.26**	**−0.68**	0.37
	F25	sPC1	0.10	**−0.56**	0.46	**0.60**	0.33
		sPC2	0.62	−0.15	**0.47**	−0.32	−0.52
		sPC3	**0.71**	−0.02	−0.41	−0.12	**0.55**

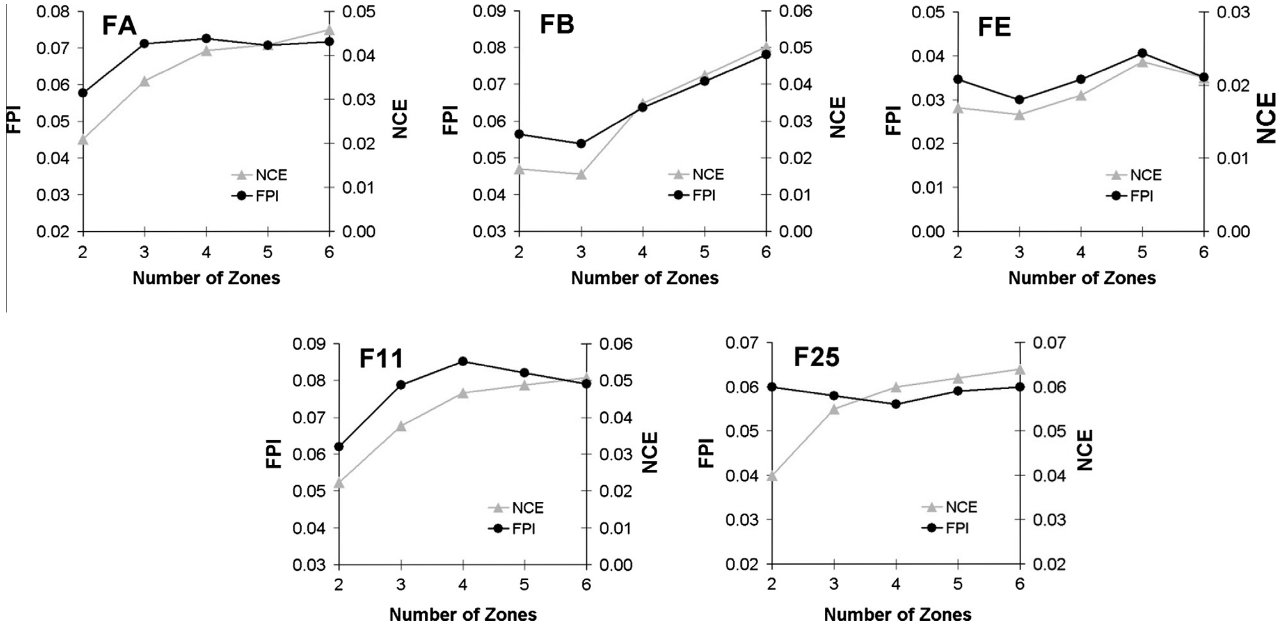


Fig. 5. Fuzziness Performance Index (FPI) and Normalized Classification Entropy (NCE) used to evaluate the optimum number of management zones at five fields (FA, FB, FE, F11, and F25).

Table 4
Apparent electrical conductivity (ECa30 and ECa90), elevation, depth soil and yield means within zones (classes) in each field.

Site	Field	Zone	ECa30 (mS m^{-1})	ECa90 (mS m^{-1})	Elevation (m)	Soil depth (cm)	Yield (t ha^{-1})
Tandil	FA	LP	19.9 a*	20.7 a	197.2 a	80.6 b	3.64 b
		HP	19.6 a	21.1 a	192.5 b	90.5 a	3.92 a
	FB	LP	18.4 a	19.2	204.0 a	60.1 c	3.5b
		MP	18.0 a	19.5	198.7 b	75.4 b	3.7 ab
		HP	18.1 a	19.0	193.2 c	85.8 a	3.9 a
La Numancia	FE	LP	20.7 a	21.8 a	276.2 a	69.9 c	3.5 b
		MP	16.4 b	16.8 b	261.7 b	93.4 b	3.7 b
		HP	17.1 b	16.8 b	250.7 c	132.2 a	4.2 a
Loberia	F11	LP	27.1 a	27.8 a	152.3 a	67.2 a	2.9 a
		HP	25.5 a	26.6 a	152.2 a	59.6 a	3.0 a
	F25	LP	24.1 a	27.3 a	160.7 a	80.8 b	3.3 b
		HP	19.2 b	23.7 b	161.2 a	98.1 a	3.8 a

LP: low productivity; HP: high productivity; MP: average productivity.

* Different letters indicate statistically significant differences ($P < 0.05$) among management zone for each field.

Table 5
Akaike Information Criteria (AIC) for model selection.

Field	Models							
	RB	RB_H	RB + SP(Exp)	RB + SP(Exp)_H	RB + SP(Gau)	RB + SP(Gau)_H	RB + SP(Esf)	RB + SP(Sph)_H
FA	3.43†	5.33† (0.756)‡	5.43	7.33	5.43	7.33	5.4	7.31
FB	19.46	21.38 (−0.354)	21.46	23.38	21.46	23.38	21.46	23.38
FE	−19.9	−23.15 (−0.026)	−17.9	−21.15	−17.9	−21.15	−17.9	−21.15
F11	20.68	22.67 (−0.917)	22.68	24.67	22.68	24.67	22.68	24.68
F25	220.59	213.28 (−0.002)	222.59	215.28	222.59	215.28	222.59	215.28

RB: random block model.

RB + SP: random block model plus spatial correlation of plot errors (exponential – Exp, Gaussian – Gau and Spherical – Sph correlation functions).

† A lower AIC value indicates a better model accuracy.

‡ In parenthesis, p-value for Likelihood Ratio Test comparing the heteroscedastic model against the same correlation model with homogeneous variance between management zone.

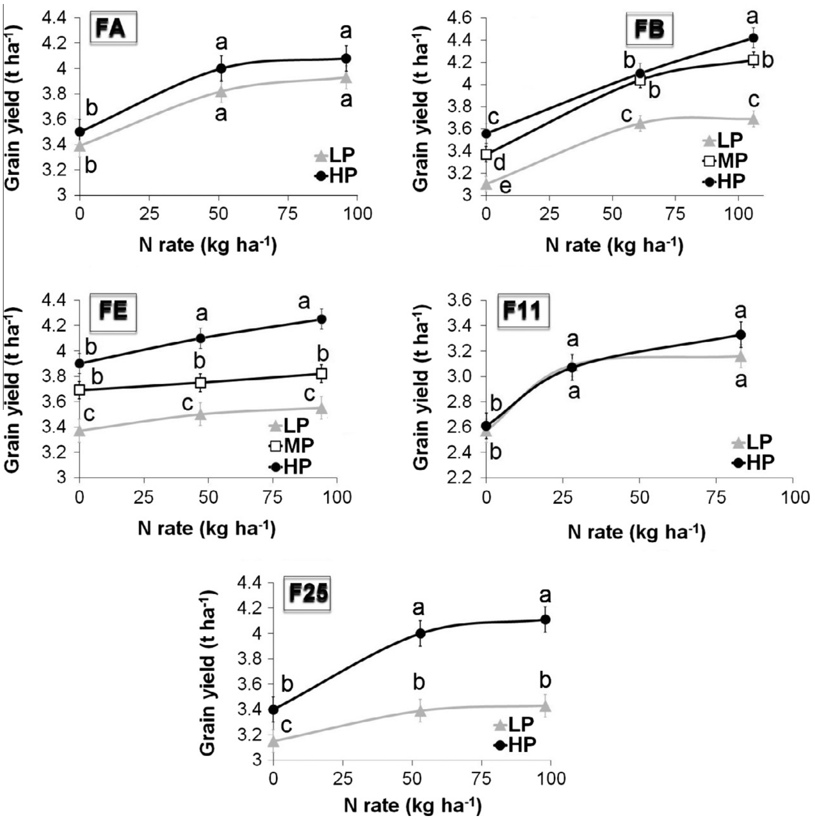


Fig. 6. Average yields for different N rates and management zones. Different letters indicate statistically significant differences ($p < 0.05$). Vertical bars indicate standar error of mean for each management zone.

classes obtained through NCE (2 clusters). Since the optimal number of clusters differs for the two indices (FPI and NCE), we selected the smaller (Lark and Stafford, 1997).

In most fields elevation and soil depth presented significant differences between MZ (Table 4). The high potential management zone (HP) was associated with lower elevation and deeper soils (Table 4). In contrast, the low potential zone (LP) was associated to higher elevation and shallower soils. In the fields FE and F25, ECa30 and ECa90 showed significant differences among MZ, whereas for the remaining fields those did not present significant differences (Table 4). HP was related to areas with lower ECa and vice versa. Previous studies (Sudduth et al., 1995; Fraisse et al., 2001) have reported that zones with higher ECa values correspond to shallower soils where the clay horizon (Bt) is near the soil surface, and lower ECa values correspond to deeper soils where the Bt horizon is also deeper. Cabria and Culot (1994) reported that shallow calcareous layers generally lead to the presence of a Bt horizon with higher clay content. Soils with high clay content also have close particle–particle contact and a greater number of small pores which retain water better and longer and, thus, conduct electricity better (Rhoades et al., 1989) than soils with larger sand contents (Williams and Hoey, 1987; Farahani and Flynn, 2007).

Table 6
Average water deficit at the wheat growing season.

Site	Field	Zone	Water déficit (mm)*
Tandil	FA	LP	164
		HP	156
		LP	172
	FB	MP	166
		HP	162
La Numancia		LP	168
	FE	MP	158
		HP	141
Loberia	F11	LP	176
		HP	180
	F25	LP	159
		HP	127

* Water deficit during the most critical period for grain yield determination in wheat. The most critical periods were defined as follows: between 30 d before anthesis in wheat Fischer (1985).

In all fields (except for F11), grain yield was significant different among the MZ (Table 4). At the FB and FE fields, grain yield differed for the HP and LP zones. At the FA and F25 fields, grain yield significantly differed between the HP and LP zones. The HP zone was associated with lower elevation and deeper soils (Table 4) and greater yield (Peralta et al., 2013b). In these areas, there was possibly an accumulation of eroded material (Buschiazzo, 1986) and higher water accumulation and soil moisture (Kravchenko and Bullock, 2000; Kaspar et al., 2003, 2004).

In contrast, lower wheat grain yield was associated with greater elevation and shallower soils. For the F11 field however, yield did not differ significantly between MZ. That was probably due to the small difference in elevation and soil depth and thus small differences in water accumulation and ponding for the different MZ.

3.4. Management zones and nitrogen rate

In all fields the model with randomized blocks was sufficient to account for spatial correlation. This indicates that the blocks were relatively homogenous. However, for the fields FE and F25, it was necessary to differentiate residual variances within each MZ; i.e. the heterogeneous residual variance models were more accurate

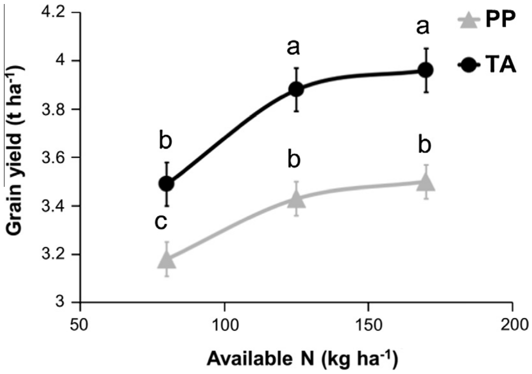


Fig. 7. Average yields for N available (soil available N–NO_3 60 cm + Fert.) and soil type (Typic Argiudolls, TA and Petrocalcic Paleudoll, PP). Different letters indicate statistically significant differences ($p < 0.05$). Vertical bars indicate standar error of mean for each management zone.

than those which assume variance homogeneity of fields of each MZ (Table 5). The effects of N rate, MZ and the N rate × MZ interaction were assessed through the selected models. For the fields FB, FE and F25, N rate × MZ interaction were all significant ($p < 0.05$) (results not shown), thus indicating that the response to fertilization differs for the MZ (Fig. 6). Therefore, in the following years, a variable rate application of N by MZ should be carried out. This practice leads to adjust frequent mismatches between N fertilizer rate and N crop needs. By analyzing the three cases (FB, FE and F25) where site-specific management could be beneficial (i.e. where N rate × MZ interaction was significant), it was observed that in the FB field, the LP zone, the N rates (61 and 106 kg N ha^{-1}) did not produce significantly different yields, but both did produce significantly greater yields than the 0 N (control) treatment. In the MP and HP zones, N rate did produce significantly different grain yields. In the LP zone, the N rates (61 and 106 kg N ha^{-1}) showed a yield response of 549 kg ha^{-1} (18%) and 580 kg ha^{-1} (16%), respectively. In the MP zone, the yields were 670 kg ha^{-1} (20%) and 850 kg ha^{-1} (23%), respectively. In the HP zone, the yield increased by 543 kg ha^{-1} (17%) and 864 kg ha^{-1} (24%) respectively. At FE field, in the LP and MP zones, N addition did not increase yield significantly, whereas in the HP zone, N addition did significantly increase yield. In the LP zone, the N rates (47 and 94 kg N ha^{-1}) showed a yield response of 130 kg ha^{-1} (3.85%) and 180 kg ha^{-1} (5%), respectively. In the MP zone, the yield increased 60 kg ha^{-1} (1%) and 130 kg ha^{-1} (4%), respectively. In the HP zone, however, the increase in yield was 200 kg ha^{-1} (5%) and 410 kg ha^{-1} (10%), respectively. At F25, in the LP and HP zones, the N rates (53 and 98 kg N ha^{-1}) did not produce significantly greater yield, but the N rates did differ from the control (0 N). In the LP zone, the N rates (53 and 98 kg N ha^{-1}) showed a yield response of 240 kg ha^{-1} (8%) and 280 kg ha^{-1} (9%), respectively. The HP zone, however, produced an increase in yield of 600 kg ha^{-1} (18%) and 700 kg ha^{-1} (20%), respectively. At these three sites, the HP zone demonstrated the most sensitive response to N

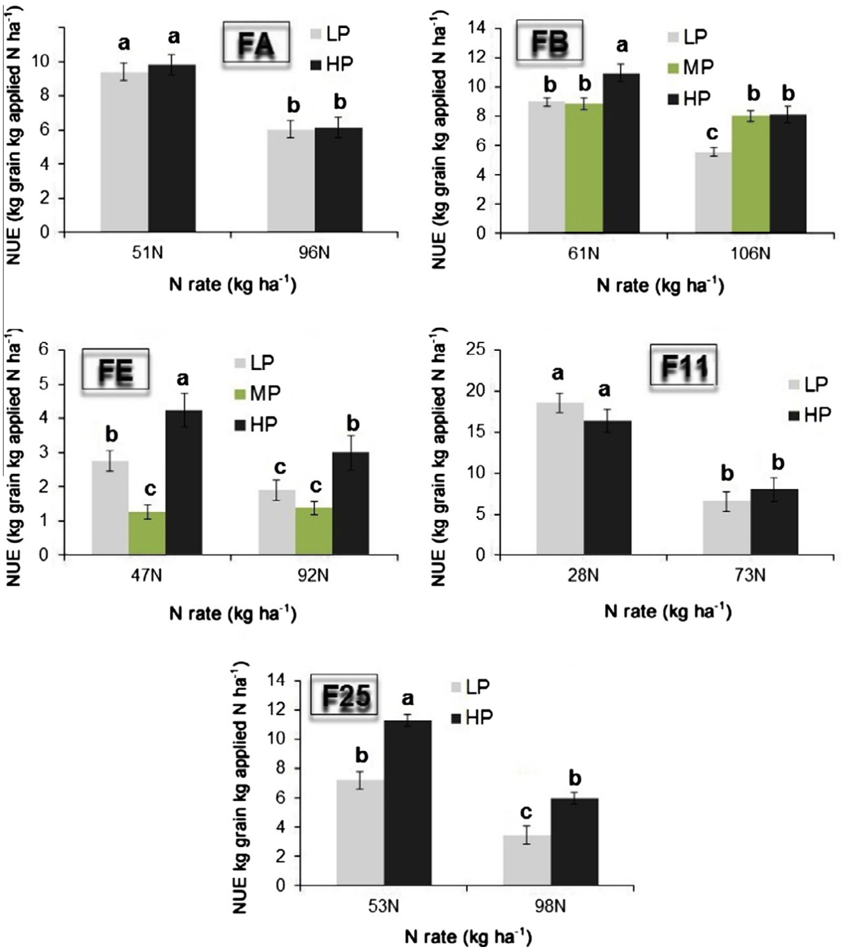


Fig. 8. Average fertilizer use efficiency depending on N rate and management zone. Different letters indicate statistically significant differences ($p < 0.05$). Vertical bars indicate typical mean error for each management zone.

fertilization (Fig. 6). HP zone were associated with lower elevation and deeper soils (Table 4), which may have allowed for water accumulation and better moisture conditions (Kravchenko and Bullock, 2000). Less water stress, as a consequence of water accumulation, does afford a better crop response to N fertilization (Calviño et al., 2002). In contrast, LP zone was associated with higher elevation and shallower soils, lower water availability and higher water stress (Table 6). Presumably that limited crop response to N fertilization (Delin, 2004). During the same experimental year and also in the south-eastern portion of Buenos Aires province, with the same soil types, Typic Argiudolls and Petrocalcic Paleudolls, Peralta et al. (2014) found a significant interaction between N availability and MZ for barley (*Hordeum vulgare*), thus indicating that crop response to fertilization does vary with MZ. In the F11 and FA fields, the N rate × MZ interaction was not statistically significant (Fig. 6). At F11, N rate did not produce significantly different grain yield either between MZ or within MZ. The absence of significant differences between MZ and N rate could be due to a minimal difference in soil depth and water availability among MZ (Table 4).

The interaction between N availability and MZ for all fields together is presented in Fig. 7. In this analysis, the low potential (LP) zone was associated with shallow soils (Petrocalcic Paleudoll-PP-; <100 cm). While the of high potential (HP) zone was associated with deep soils (Typic Argiudoll-TA-; >100 cm). For PP and TA, N availability × MZ interaction were significant ($p < 0.05$), thus indicating that the response to fertilization differs between soil types (Fig. 7). For PP and TA, the N availability (125 and 170 kg N ha^{-1}) did not produce significantly greater yields, but the N availability did differ from the control (80 kg N ha^{-1}). In the PP, the N availability (125 and 170 kg N ha^{-1}) showed a yield response of 250 kg ha^{-1} (8%) and 320 kg ha^{-1} (10%), respectively. Whereas in TA, the N availability produced an increase in yield of 390 kg ha^{-1} (11%) and 470 kg ha^{-1} (14%), respectively. These results demonstrate that, in years with low precipitation, the addition of N to the wheat crop had the lowest response in the Petrocalcic Paleudoll (PP; shallow soils) and the highest response in the Typic Argiudoll (TA; deep soils).

At the FA and F11 fields, the NUE did not differ among MZ (Fig. 8). In contrast, at FB, FE and F25 the NUE did differ significantly among MZ ($p < 0.05$) with greater NUE values in the HP zone (Fig. 8). This may be because in this zone there was greater water availability and less water stress during the growing season (Table 6) (Delin, 2004; Peralta et al., 2014). At the FB field, the NUE value for the 61 N rate was 9, 8.8 and 11 kg of grain per kg N applied for the LP, MP and HP zones, respectively. For the 106 N rates, the NUE value was 5.5, 8 and 8.2 kg of grain per kg N applied for the LP, MP and HP zones, respectively. At FE field, the NUE value for the 47 N rate was 2.7, 1.3 and 4.3 kg of grain per kg N applied for the LP, MP and HP zones, respectively. For the 92 N rate, the NUE was 2.1, 1.4 and 3 kg of grain per kg N applied for the LP, MP and HP zones, respectively. At F25, the NUE value for the 53 N rate was 7 and 11 kg of grain per kg N applied for the LP and HP zones, respectively. In contrast, for the 98 N rate, NUE was 3 and 6 kg of grain per kg N applied for the LP and HP zones, respectively. Peralta et al., 2014, found that NUE in similar field with barley crop varied between 1.3 and 18 kg of grain per kg N applied, which decreased as the applied N rate increased. Barbieri et al. (2008) and Velasco et al. (2012), found values similar to the present study, although they did not identify MZ. These authors mentioned that the low average values of NUE may be attributed to water stress during the growing season since in years without water stress, values of NUE were greater (see Fig. 8).

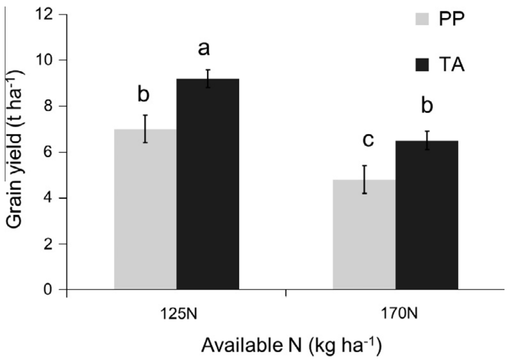


Fig. 9. Average fertilizer use efficiency depending on N available (soil available N–NO$_3$ 60 cm + Fert.) and soil type (Typic Argiudolls, TA and Petrocalcic Paleudoll, PP). Different letters indicate statistically significant differences ($p < 0.05$). Vertical bars indicate typical mean error for each management zone.

For all fields, the NUE did differ significantly among soil type ($p < 0.05$) with greater NUE values in TA (Typic Argiudoll) (Fig. 9). The NUE value for the 125 kg ha^{-1} N availability was 7 and 9 kg of grain per kg of N available for PP (Petrocalcic Paleudoll) and TA, respectively. In contrast, for the 170 kg ha N availability, NUE was 5 and 6.5 kg of grain per kg of N available for PP and TA, respectively.

Results show the relevance of identifying MZ and soil type for improving N management. The application of variable N rates in agreement with the potential of each soil type allows for greater efficiency in the use of this resource/fertilizer and so diminishes the risks of N losses and, in consequence, the probability of polluting the environment and increases production system sustainability. Similar results were reported by Delin, 2004.

4. Conclusions

In Typic Argiudolls and Petrocalcic Paleudolls, the application of precision farming allowed for the detection of soil spatial variability at a field scale. Optimal N fertilization rate varied among MZ and delimiting MZ improved the NUE. This justifies the application of variable fertilization N rates in order to minimize the environmental pollution risk provoked by overuse of resources.

Acknowledgements

We thank the farmers for their help in gathering the data on the fields where the study was conducted. The experiment was conducted with funding from the INTA Project, AEAI3722. At the same time, we would like express our appreciation to the CONICET (postgraduate fellowship program of National Council of Scientific and Technical Research).

References

Abbate, P.E., Andrade, F.H., Culot, J.P., 1995. The effects of radiation and nitrogen on number of grains in wheat. J. Agric. Sci. Camb. 124, 351–360.

Allen, R.G., Pereira, L.S., Raes, D., Smith, D., 1998. Crop Evapotranspiration. Guides for Computing Crop Water Requirements. FAO Irrig. Drain. No. 56. Rome, Italy, pp. 300.

Aparicio, V., Costa, J.L., Zamora, M., 2008. Nitrate leaching assessment in a long-term experiment under supplementary irrigation in humid Argentina. Agric. Water Manage. 95, 1361–1372.

Barbieri, P.A., Echeverría, H.E., Sainz Rozas, H.R., 2008. Time of nitrogen application affects nitrogen use efficiency of wheat in the humid pampas of Argentina. Can. J. Plant Sci. 88, 849–857.

Barbieri, P.A., Echeverría, H.E., Sainz Rozas, H.R., 2012. Alternatives for nitrogen diagnosis for wheat with different yield potentials in the humid pampas of Argentina. Commun. Soil Sci. Plant Anal. 43, 1–11.

Bezdek, J.C., 1981. Pattern Recognition with Fuzzy Objective Function Algorithms. Plenum Press, New York.

Bhatti, A.U., Ali, R., Ullah, F., Khan, 1998. Comparison of wheat yield under uniform and variable rates of fertilizer on spatially – M.J. eroded land. Comm. Soil Sci. Plant Anal. 29, 2855–2863.

Bivand, R.S., 2012. spdep: Spatial Dependence: Weighting Schemes, Statistics and Models. R package version 0.5-46, URL.

Blackmore, B.S., Moore, M., 1999. Remedial correction of yield map data. Precis. Agric. 1, 53–66.

Bremner, J., Keeney, D., 1966. Determination and isotope-ratio analysis of different forms of nitrogen in soil: 3. Exchangeable ammonium, nitrate and nitrite by extraction-distillation methods. Soil Sci. Soc. Am. Proc. 30, 577–582.

Bullock, D.S., Ruffo, M.L., Bullock, D.G., Bollero, G.A., 2009. The value of variable rate technology: an information-theoretical approach. Am. J. Agric. Econ. 21, 209–223.

Buschiazzo, D., 1986. Estudio sobre la tosca. Parte I: Evidencias de un movimiento descendente del carbonato en base a la interpretación de características macro y geomorfológicas. Ciencia del Suelo 4, 55–65.

Cabria, F., Culot, J., 1994. Selección y utilización de características edáficas para discriminar series de Argiudoles en el Sudeste Bonaerense. Ciencia del Suelo 12, 41–55.

Calviño, P.A., Sadras, V.O., 2002. On-farm assessment of constraints to wheat yield in the south-eastern Pampas. Field Crop Res. 74, 1–11.

Calviño, P.A., Echeverría, H.E., Redolatti, M., 2002. Diagnóstico de nitrógeno en trigo con antecesor soja bajo siembra directa en el sudeste Bonaerense. Ciencia del Suelo 20, 36–42.

Casanoves, F., Macchiavelli, R., Balzarini, M., 2005. Error variation in multienvironment peanut trails: within-trial spatial correlation and between-trial heterogeneity. Crop Sci. 45, 1927–1933.

Chessel, D., Dufour, A.B., Thioulouse, J., 2004. The ade4 package-I-one-table methods. R News 4, 5–10.

Córdoba, M., Bruno, C., Costa, J.L., Balzarini, M., 2013. Subfield management class delineation using cluster analysis from spatial principal components of soil variables. Comp. Electron. Agric. 97, 6–14.

Delin, S., 2004. Within-field variations in grain protein content – relationships to yield and soil nitrogen and consistency in maps between years. Precis. Agric. 5, 565–577.

Della Maggiora, A.I., Irigoyen, A.I., Gardiol, J.M., Caviglia, O., Echarte, L., 2002. Evaluación de un modelo de balance de agua en el suelo para el cultivo de maíz. Rev. Argent. Agrometeorol. 2, 167–176.

Doorenbos, J., Kassam, A., 1979. Yield Response to Water. FAO Irrig. and Drain. Paper No. 33. Rome, Italy. 193pp.

Dray, S., Saïd, S., Débias, F., 2008. Spatial ordination of vegetation data using a generalization of Wartenberg's multivariate spatial correlation. J. Veg. Sci. 19, 45–56.

Farahani, H.J., Flynn, R.L., 2007. Map quality and zone delineation as affected by width of parallel swaths of mobile agricultural sensors. Precis. Agric. 96, 151–159.

Fischer, R.A., 1985. Number of kernels in wheat crops and the influence of solar radiation and temperature. J. Agric. Sci. 105, 447–461.

Fraisse, C.W., Sudduth, K.A., Kitchen, N.R., 2001. Delineation of site-specific management zones by unsupervised classification of topographic attributes and soil electrical conductivity. Am. Soc. Agric. Eng. 44 (1), 155–166.

Fridgen, J.J., Kitchen, N.R., Sudduth, K.A., Drummond, S.T., Wiebold, W.J., Fraisse, C.W., 2004. Management zone analyst (MZA): software for subfield management zone delineation. Agron. J. 96, 100–108.

Instituto Nacional de Tecnologıa Agropecuaria. 1970. CIRN. Soil Institute. File – “3760_35 “Claraz””, PBA, Castelar: Soil Institute AICET. 1970. 72 p; 4 map photo; scale 1:50.000.

Instituto Nacional de Tecnologıa Agropecuaria. 1989. CIRN. Soil Institute. File – “3760_22 “Chillar””, PBA, Castelar: Soil Institute AICET. 1989. 50 pp; 4 map photo; scale 1:50.000.

Isaaks, E.H., Srivastava, R.M., 1989. An Introduction to Applied Geostatistics. Oxford University Press, New York, NY, 561pp.

Jaynes, D.B., Kaspar, T.C., Colvin, T.S., 2011. Economically optimal nitrogen rates of corn: management zones delineated from soil and terrain attributes. Agron. J. 103 (4), 1026–1035.

kaspar, T.C., Colvin, T.S., Jaynes, D.B., Karlen, D.L., James, D.E., Meek, D.W., 2003. Relationship between six years of corn yields & terrain attributes. Precision Agric. 4, 87–101.

Kaspar, T.C., Pulido, D.J., Fenton, T.E., Colvin, T.S., Karlen, D.L., Jaynes, D.L., Meek, D.W., 2004. Relationship of corn and soybean yield to soil and terrain properties. Agron. J. 95, 483–495.

Kitchen, N.R., Drummond, S.T., Lund, E.D., Sudduth, K., Buchleiter, K.A., 2003. Soil electrical conductivity and topography related to yield for three contrasting soil-crop systems. Agron. J. 95, 483–495.

Kitchen, N.R., Sudduth, K.A., Myersb, D.B., Drummonda, S.T., Hongc, S.Y., 2005. Delineating productivity zones on claypan soil fields using apparent soil electrical conductivity. Comput. Electr. Agric. 46, 285–308.

Kravchenko, A.N., Bullock, D.G., 2000. Correlation of grain yield with topography and soil properties. Agron. J. 92, 75–83.

Lark, R., Stafford, J., 1997. Classification as a first step in the interpretation of temporal and spatial variation of crop yield. Ann. Appl. Biol. 130, 111–121.

Mulla, D.J., 1993. Mapping and managing spatial patterns in soil fertility and crop yield. In: Robert, P.C. et al. (Eds.) Soil Specific Crop Management, Proceedings of a Workshop on Research and Development Issues, Minneapolis, Madison, USA, pp. 15–26.

Odeh, I.O., McBratney, A.B., Chittleborough, D.J., 1992. Soil pattern recognition with fuzzy c-means: application to classification and soil-landform interrelationship. Soil Sci. Soc. Am. J. 56, 505–516.

Peralta, N.R., Costa, J.L., 2013. Delineation of management zones with soil apparent electrical conductivity to improve nutrient management. Comput. Electr. Agric. 99, 218–226.

Peralta, N.R., Costa, J.L., Balzarini, M., Angelini, M., 2013a. Delineation of management zones with measurements of soil apparent electrical conductivity in the Southeastern Pampas. Can. J. Soil Sci. 93, 205–218.

Peralta, N.R., Costa, J.L., Balzarini, M., Castro Franco, M., 2013b. Delineation of management zones with digital elevation models and soil depth. J. Sci. Technol. Am. 38 (6), 1–7.

Peralta, N.R, Costa, J., Barbieri, P., Gowland, T., Aparicio, V., Castro Franco, M., 2014. Precision Agriculture: Variable Rate Nitrogen in Barley. XXIV Argentine Congress of Soil Science. Bahia Blanca, Buenos Aires, Argentina.

Pinheiro, J., Bates, D., DebRoy, S., Sarkar, D., 2013. nlme: Linear and Nonlinear Mixed Effects Models. R package version 3.1-107. 4.2.

R Development Core Team, 2013. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL <http://www.R-project.org>.

Raun, W.R., Johnson, G.V., 1999. Improving nitrogen use efficiency for cereal production. Agron. J., 91:357–363.

Raun, W.R., Schepers, J.S., 2008. Nitrogen management for improved use efficiency. In: Schepers, J.S., Raun, W.R. (Eds.), Nitrogen in agricultural systems. Agron. Monogr. 49. ASA, CSSA, and SSSA, Madison, WI, p. 675–693.

Rhoades, J.D., Manteghi, N.A., Shouse, P.J., Alves, W.J., 1989. Soil electrical conductivity and soil salinity: new formulations and calibrations. Soil Sci. Soc. Am. J. 53, 433–439.

Robert, M., Le Quintrec, A., Boisgontier, D., Grenier, G., 1996. Determination of field and cereal crop characteristics for spatially selective applications of nitrogen fertilizers. In: Robert, P.C. et al. (Eds.) Precision Agriculture – Proceedings of the 3rd International Conference, Minneapolis, Madison, USA, pp. 303–313.

Ruffo, M., Bollero, G., Bullock, D.S., Bullock, D.G., 2006. Site-specific production functions for variable rate corn nitrogen fertilization. Precis. Agric. 7, 327–342.

Sadras, V.O., Calviño, P.A., 2001. Quantification of grain yield response to soil depth in soybean, maize, sunflower and wheat. Agron. J. 93, 577–583.

SAS Institute, Inc. 2003. SAS User's Guide. SAS Institute, Inc., Cary, NC.

Satorre, E.H., Slafer, G.A., 1999. Wheat production systems of the Pampas. In: Wheat: Ecology and Physiology of Yield Determination. Food Products Press, New York, NY, pp. 333–348.

Scharf, P.C., Lory, J.A., 2002. Calibrating corn color from aerial photographs to predict sidedress N need. Agron. J. 94, 397–404.

Sudduth, K.A., Drummond, S.T., 2007. Yield editor: software for removing errors from crop yield maps. Agron. J. 99, 1471–1482.

Sudduth, K.A., Hughes, D.F., Drummond, S.T., 1995. Electromagnetic induction sensing as an indicator of productivity on claypan soils. In: Robert, P.C. et al. (Eds.), Proc. Int. Conf. on Site- Specific Management for Agricultural Systems, Minneapolis, Madison, USA, pp. 671–681.

Travasso, M.I., Suero, E.E. 1994. Estimación de la capacidad de almacenaje de agua en suelos del sudeste bonaerense. Boletín técnico No. 125, Estación Experimental agropecuaria INTA Balcarce. Buenos Aires, Argentina.

Velasco, J.L., Sainz Rozas, H., Echeverría, H., Barbieri, P., 2012. Optimizing fertilizer nitrogen use efficiency by intensively managed spring wheat in humid regions: effect of split application. Can. J. Plant Sci. 92, 1–10.

West, M.A.L., Kim, K., Kliebenstein, D.J., Van Leeuwen, H., Michelmore, R.W., Doerge, S., 2007. Global eQTL mapping reveals the complex genetic architecture of transcript-level variation in Arabidopsis. Genetics 175, 1441–1450.

Williams, B., Hoey, D., 1987. The use of electromagnetic induction to detect the spatial variability of the salt & clay content of soils. Aust. J. Soil Res. 25, 21–27.

Wollenhaupt, N.C., Buchholz, D.D., 1993. Profitability of farming by soils. In: Robert, P.C. et al. (Eds.), Soil Specific Crop Management, Proceedings of a Workshop on Research & Development Issues, Minneapolis, Madison, pp. 199–211.