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Delineation of management zones with soil apparent electrical conductivity to improve nutrient management ☆

Nahuel Raúl Peralta [a,c,*], José Luis Costa [b,c]

[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), Unidad Integrada Balcarce, C.C.276, 7620 Balcarce, Buenos Aires, Argentina

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ABSTRACT

Site-specific management demands the identification of subfield regions with homogeneous characteristics (management zones). However, determining subfield areas is difficult because of complex correlations and the spatial variability of soil properties and nutrient concentrations, responsible for variations in crop yields within the field. We evaluated whether apparent electrical conductivity (EC_a) is a potential estimator of soil properties and nutrients, and a tool for the delimitation of homogeneous zones. Two field sites with several soil series were studied in southeastern Cordoba Province, Argentina. Soil properties and nutrient concentrations were compared with EC_a using principal components (PC)-stepwise regression and ANOVA. The PC-stepwise regression showed that soil properties (pH, $EC_{1:2.5}$, CEC, SOM) and nutrients (Na^{+2}, Mg^{+2}, Mn^{+2}, Cu^{+2}, Ca^{+2}, Zn^{+2}, Fe^{+2}) are key loading factors to explain the EC_a ($R^2 > 0.90$). In contrast, K^+, P, NO_3^-—N and SO_4^{-2}—S), content were not able to explain the EC_a. The ANOVA showed that EC_a measurements successfully delimited two homogeneous soil zones associated with the spatial distribution of soil properties and some nutrients (Na^{+2}, Mg^{+2}, Mn^{+2}, Cu^{+2}, Ca^{+2}, Zn^{+2}, Fe^{+2}). These results suggest that field-scale EC_a maps have the potential to design sampling zones to implement site-specific management strategies.

1. Introduction

The Cordoba Province of Argentina is a vast plain with approximately 7.794 (miles ha) of cropland. This province is the largest producer of soybeans and corn in Argentina, producing 12,750 (‘000 ton) and 8749 (‘000 ton), respectively (SAGPyA, 2009), and is composed mainly of (I) excessively drained soils, developed on sandy materials related to higher areas of land with a use capacity (usability) limited by low moisture retention (Instituto Nacional de Tecnología Agropecuaria (INTA), 1986) and (II) moderately drained to imperfect soils, moderately saline-alkali in depth, developed on sandy-loam to loam materials, related to depressed areas of land. Its usability is restrained by the presence of salts, which limits grain production. Soils vary widely in their nutrient contents and in their ability to supply sufficient micronutrients for optimal crop production. The spatial variability of soil nutrients may be affected by soil type, land forms, vegetation, climate, and anthropogenic activities. Therefore, it is not surprising that the content, distribution, and availability of soil nutrients can vary widely among soils both within and between fields (Corwin and Lesch, 2003).

Uniform management of fields does not take into account the spatial variability; therefore, it is not the most effective management strategy (Moral et al., 2010). Precision agriculture is considered the most viable approach for achieving sustainable agriculture (Kravchenko and Bullock, 2002; Bullock et al., 2007). In particular, site-specific management (SSM) is a form of precision agriculture whereby decisions on resource application and agronomic practices are improved to better match soil and crop requirements as they vary in the field. SSM enables the identification of regions (management zones) within the area delimited by field boundaries. These subfield regions constitute areas of the field that have similar permanent characteristics, such as topography and nutrient levels (Kitchen et al., 2005; Moral et al., 2011).

Efficient techniques to accurately measure within-field variations in soil properties are very important for homogeneous management zones (HMZ) (Peralta et al., 2013). Traditional soil sampling is costly and labor-intensive. This traditional method is not viable from an HMZ 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 EC_a

* Corresponding author at: Facultad de Ciencias Agrarias-UNMdP (Universidad Nacional de Mar del Plata), Unidad Integrada Balcarce, C.C.276, 7620 Balcarce, Buenos Aires, Argentina. Tel.: +54 2266 439100; fax: +54 02266 439101.

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

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is an efficient ground-based sensing technology that is helping to take HMZ from concept to reality (Corwin and Lesch, 2003). EC_a can be intensively recorded in an easy and inexpensive way, and it is usually related to various physico-chemical properties across a wide range of soils (Sudduth et al., 2005), because it depends on the chemical composition of the soil solution and soil exchangeable ions, clay content, and the interaction between non-exchangeable and exchangeable ions (Rhoades et al., 1989). This methodology can improve the characterization of the spatial pattern of edaphic properties that influence the nutrient content of the soil, which in turn can be used to define SSM units (Moral et al., 2010). However, the EC_a applications in HMZ showed weak and inconsistent relationships between EC_a and soil characteristics (Corwin and Lesch, 2003; Sudduth et al., 2005). These inconsistent relationships may be generated by the potentially complex interrelationships between EC_a and soil characteristics (soil properties and nutrient levels). The delimitation of HMZ with EC_a measurement to improve nutrient management has not been adequately described for excessively drained soils and moderately drained to imperfect soils (with salts present), which are characteristic of many agriculturally important soils in Argentina and throughout the world.

The main aims of this paper are to determine: (I) whether field-scale EC_a geospatial measurement is a potential estimator of soil properties ($EC_{1:2.5}$, pH, SOM and CEC) and nutrient levels (P, Zn^{+2}, Ca^{+2}, Mg^{+2}, Mn^{+2}, Na^{+}, K^{+}, Fe^{+2}, Cu^{+2}, NO_3–N and SO_4^{-2}—S) and (II) whether EC_a measurement can enable the delimitation of HMZ within the field of production. If EC_a could be used to produce accurate maps of zones with the differences in the soil properties and nutrient concentrations indicated, it could be a useful tool for variable-rate seeding and for fertilizer producers.

2. Materials and methods

2.1. Experimental sites

Soil EC_a mapping was carried out in July of 2009 and soil samples were taken prior to sowing winter crops (wheat, *Triticum aestivum*).

This study was conducted on two fields at La Unión, in southeastern Cordoba Province, Argentina (Fig. 1). The fields were 39 ha (F1) and 25 ha (F2) in size, cultivated under a no-tillage system since the year 2002 using a soybean–corn rotation system during the summer cropping seasons and with wheat as a cover crop during the winter season.

The soils in the two fields include a Canals series (coarse-loamy, mixed, thermic, Entic Haplustoll), an Aromos series (coarse-loamy, mixed, thermic, Typic Calciacuoll) and Medanitos series (coarse-loamy, mixed, thermic, Typic Natralboll). The Canals series is a well-drained soil, developed on sandy materials associated with hills. The Aromos and Medanitos series are moderate to imperfect-drainage soils, moderately saline-alkali in depth, developed on sandy-loam to loam materials linked to depressed levels. The climate of this region is characterized by a thermal regime with a mean annual temperature of 17 °C and a variation of 14 °C. Average annual rainfall is 871 mm and the seasonal distribution is a monsoon type (Ghida Daza and Sánchez, 2009).

2.2. Soil EC_a and elevation data collection

Soil EC_a measurements were made using the Veris 3100® (Veris 3100, Division of Geoprobe Systems, Salina, KS) (Fig. 2b). The device comprises six disc-shaped metal electrodes (coulter), which penetrate approximately 6 cm into the soil. One pair of electrodes passes electrical current into the soil, while the other two pairs measure the voltage drop. The measurement depth is based on the distance between the emitting and receiving coulter-electrodes. The system is set up to work in configuration A (0–30 cm) and B (0–90 cm) (Fig. 2a). Configuration A comprises the inside coulters (2, 3, 4, 5) and voltage is measured between the innermost ones (3 and 4). In configuration B, the four outside coulters (1, 2, 5, 6) include the 0–90 cm deep measurement, and the voltage gradient is measured between coulters 2 and 5 (Fig. 2a). Output from the Veris data logger reflects the conversion of resistance to conductivity (1/resistance = conductivity). In this paper, we are working with an EC_a measurement to 0–90 cm because it is more stable over time than the EC_a to 0–30 cm (Veris Technologies, 2001; Sudduth et al., 2003). The Veris 3100 sensor was pulled across each field behind a pick-up truck, taking simultaneous and geo-referenced EC_a measurements in real-time with a differential GPS (Trimble 132, Trimble Navigation Limited, USA) (Fig. 2), with sub-meter measurement accuracy and configured to take a satellite position once per second. On average, travel speeds through the field mapping ranged between 7 and 11 km h^{-1}, corresponding to about 2–3 m spacing between measurements in the direction of travel. For ease of maneuvering, the field was traversed in the direction of crop rows in a series of parallel transects spaced at 15- to 30-m intervals, because a spacing greater than 30 m generates measurement errors and information loss (Farahani and Flynn, 2007). Elevation dates were collected at the same times that EC_a data, using a differential GPS (vertical accuracy of 3–5 cm).

2.3. Electrical conductivity zones and determination of sampling points

Previous research on various soils suggested that using more than three zones does not increase the available information (Peralta et al., 2013). Therefore, soil sampling was carried out by zones, based on three EC_a classes. Soil EC_a values and amplitude were classified by equal area quantiles using the Geostatistical Analyst in ArcGIS 9.3.1 (Environmental System Research Institute, Redlands, CA). Three representative geo-referenced soil-sampling points were selected within each of the three EC_a classes identified at each field (Fig. 3). Soil sample data were matched to the EC_a measurements taken using the Veris 3100 by averaging all EC_a measurements from the portion of the transect within a 20-m radius of the center-point location from which the soil cores were collected. This resulted in an average of eight to ten EC_a measurements matched to each soil sample taken.

2.4. Soil sampling and analysis

Soil samples were collected in plastic bags. Upon arrival at the laboratory, they were air-dried and analyzed for soil organic matter (SOM) by dichromate oxidation (Walkley and Black, 1934). Cation exchange capacity (CEC) was measured using the neutral ammonium acetate method; pH in a 1:2.5 (soil:water) suspension and the electrical conductivity of saturation extract ($EC_{1:2.5}$) was measured using the electrometric method (Chapman, 1965). The NO_3^-—N content was determined with the colorimetric method of acid 2,4 phenoldisulfonic (Bremner, 1965). P, Zn^{+2}, Ca^{+2}, Mg^{+2}, Mn^{+2}, Na^{+}, K^{+}, Fe^{+2}, Cu^{+2}, SO_4^{-2} were quantified by extracting the soil solution with Mehlich-3 extractant (Mehlich, 1984) and analyzing the elements with a PerkinElmer Plasma System (PerkinElmer, Wellesley, MA).

2.5. Spatial variability of EC_a and elevation

The spatial dependence of EC_a and the elevation were quantified using semivariograms which characterize and determine distribution patterns such as randomness, uniformity and spatial trend.

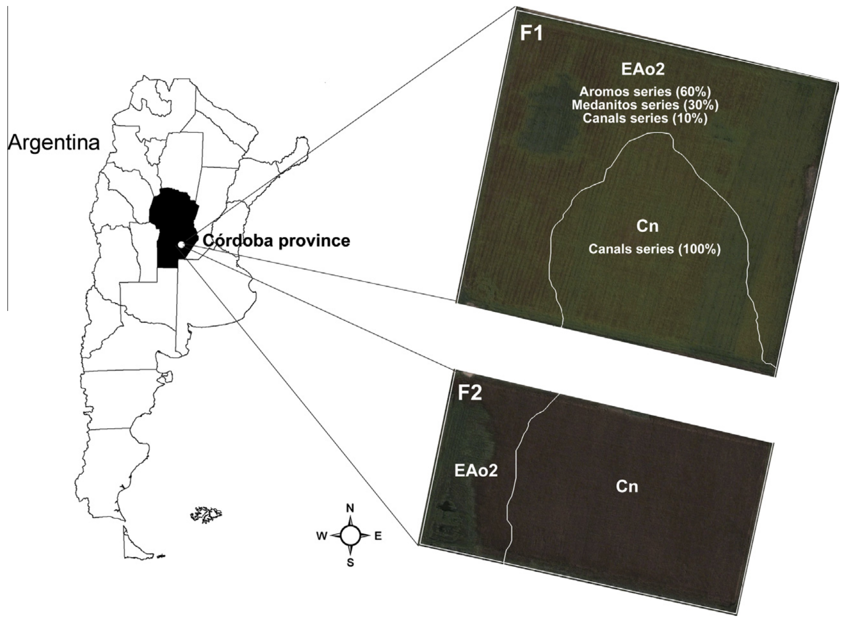

Fig. 1. Soil series for the two fields, situated in southeastern Cordoba Province, Argentina.

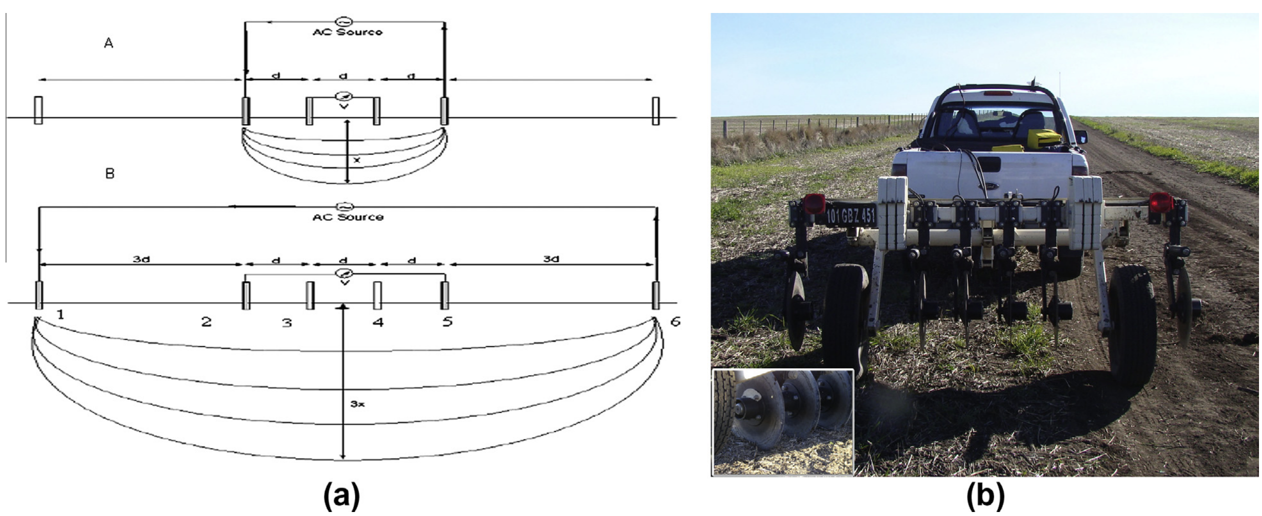

Fig. 2. (a) The system components of veris soil ec mapping-model: Veris 3100. Schematic of Configuration A-Shallow < 30 cm (top) and B-Deep < 90 cm (below). (b) The Veris 3100 Mapping System mounted behind truck.

The semivariogram was estimated using the equation (Isaaks and Srivastava, 1989):

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

where $\gamma^*(h)$ is the experimental semivariance value at 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 decrease of spatial correlation between two points in space when the separation distance increases. The semivariograms adjusted for each field were used to interpolate the EC_a and elevation by means of ordinary kriging after checking geo-statistical common assumptions (Isaaks and Srivastava, 1989), using 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 EC_a measurements and elevation (Kitchen et al., 2003).

2.6. Statistical analysis

Principal-components analysis was used to examine the relationship between the soil properties ($EC_{1:2.5}$, pH, MOS and CEC) and nutrient levels measured in this study (P, Zn^{+2}, Ca^{+2}, Mg^{+2}, Mn^{+2}, Na^{+}, K^{+}, Fe^{+2}, Cu^{+2}, NO_3–N and SO_4^{-2}—S), and to determine which soil properties and nutrients were important influences on EC_a.

Due to the colinearity of the independent variables, correlation analysis could not be used to directly relate multiple soil properties to EC_a. Principal components analysis puts identified, correlated variables into groups. These groups (PCs) become new, independent, random variables that could then be used to identify which soil properties influenced EC_a. In this study, the objectives of using the PC-stepwise regression analysis were to identify the key soil

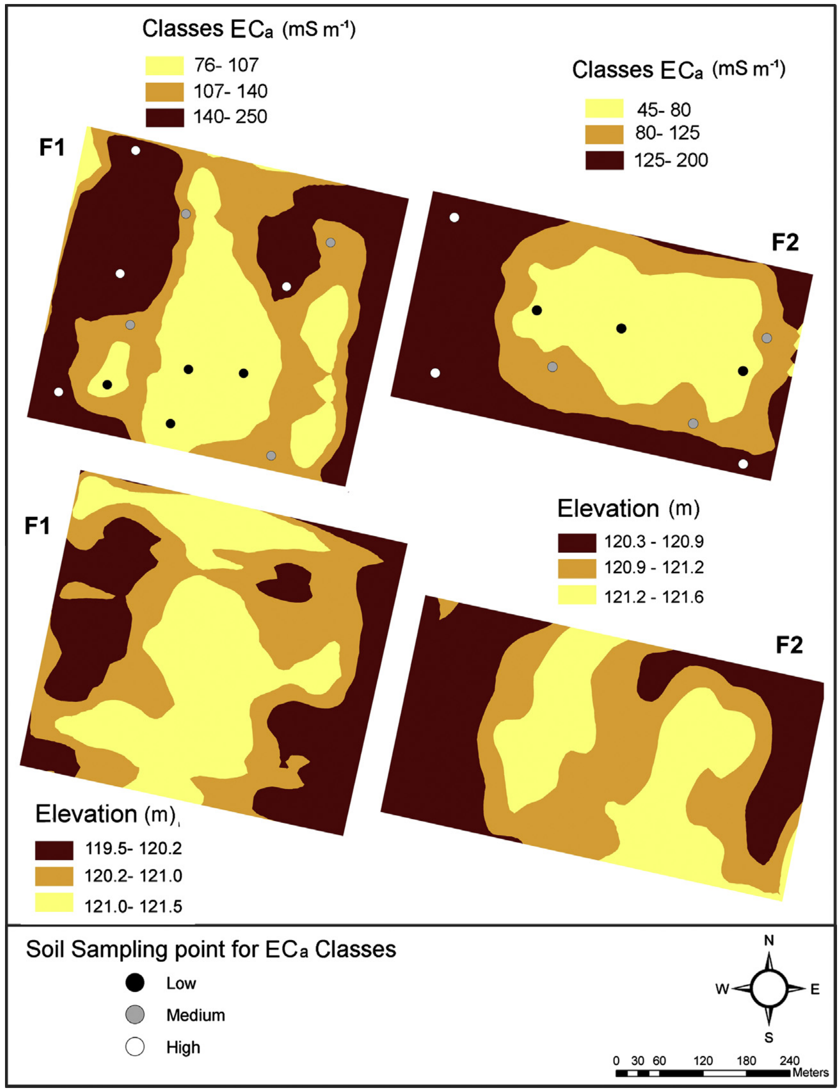

Fig. 3. Apparent electrical conductivity (EC_a) and elevation map for the two fields with three electrical conductivity classes (zones). Variations in color, from light to dark, correspond to increasing conductivity.

properties and nutrients that had significant relationships with EC_a; determine the strength of that relationship; and determine the influence and role of each soil property and nutrient in the relationship.

The PCs were identified from the correlation matrix using the COMP procedure in SAS (SAS Institute, 2002). Any PCs with an eigenvalue greater than 1 was selected because it explained a significant amount of the variance present in the soil properties and nutrients at each field. The PCs with eigenvalues >1 were then used in a stepwise-regression procedure (SAS Institute, 2002) to determine if there was a significant relationship between the PCs and EC_a. The stepwise-regression procedure repeatedly alters the model by adding or removing predictor PCs until the only remaining PCs are above the 0.15 significance level. The regression therefore effectively evaluates the result of the PCA. When the PCs remaining in the regression model accounted for >50% of the variability in the EC_a measurement, the eigenvectors (loading factors) were examined and the soil properties–nutrients in the PCs ranked according to the amount of variability explained by the PCs. For instance, a soil property and nutrient that was a component of the PCs that accounted for most of the variability in the regression model and had the highest loading factor in that PC group was ranked first. Soil properties and nutrients with loading factors <0.4 were not considered key latent variables and were not included in the ranking because they did not substantially influence the relationship between the PC groups and the nutrient concentration being examined. The ranking of the soil properties and nutrients, strength of the loading factor, and sign (positive or negative) of the loading factor were used to determine the influence and role that each soil property and nutrient had in explaining the variability in the EC_a.

In order to determine whether the EC_a measurements allow delimitation of homogeneous zones within the fields, the differences in the averages of the soil properties (SOM, CEC, $EC_{1:2.5}$, pH_s) and the amount of nutrients (P, Zn^{+2}, Ca^{+2}, Mg^{+2}, Mn^{+2}, Na^{+}, K^{+}, Fe^{+2}, Cu^{+2}, NO_3^{-}—N and SO_4^{-2}) were compared among the various EC_a classes (zones) using a mixed ANOVA model from PROC MIXED (SAS Institute, 2002). They were compared using the LSMEANS procedure of PROC MIXED (SAS Institute 2002), with a significance level of 0.05. Descriptive statistics and simple correlations between the soil properties–nutrients and EC_a were calculated using the SAS MEANS and CORR procedures (SAS Institute 2002). Significant results with a high Pearson correlation coefficient (>0.60) indicate situations where the CE_a measured could be used to estimate soil properties and the concentration of a particular element in the soil (Heiniger et al., 2003).

3. Result and discussion

3.1. Exploratory analysis of EC_a, soil properties and nutrient concentrations

Maps of EC_a and elevation are shown for F1 and F2 (Fig. 3), and the associated descriptive statistics are summarized in Table 1. EC_a measurements showed substantial spatial variability with CV varying from 38.97% to 53.63% across the two studied fields. Mean EC_a measurements for F1 were notably greater than for F2. These differences in mean EC_a might be caused by the greater proportion of Aromos and Medanitos series within F1. These series had higher salt content values (higher $EC_{1:2.5}$) and clay content than the Canals series. In the model proposed by Rhoades et al. (1989), they identified that the major factors that influence EC_a are: (I) the electrical conductivity of the soil solution associated with continuous and discontinuous pores; (II) the volumetric content of soil particles; (III) the electrical conductivity of the soil particles and; (IV) the volumetric water content in the soil. The first, second and third factor are influenced and increased by soil salinity (Malicki and Walczak, 1999), clay content (Rhoades and Corwin, 1990), and CEC (Shainberg et al., 1980), respectively. With respect to the fourth factor, the conduction of electricity in soils takes place through moisture-filled pores between soil particles; soils with high clay content generally have more continuous water-filled pores that tend to conduct electricity more easily than sandy soils (Rhoades et al., 1989).

Table 1
Summary statistics of apparent electrical conductivity (EC_a), elevation, soil properties and nutrient concentrations in each field. Average values (mean), coefficient of variation (CV), minimum (min), maximum (max) and range.

Fields	Variables	Mean	CV	Min	Max	Range
F1	EC_a (mS m^{-1})	139.27	38.97	76	250	174
	Elevation (m)	120.63	0.26	119.50	121	1.50
	SOM (%)	2.69	23.58	1.66	2.86	1.20
	P (mg kg^{-1})	9.88	33.81	5.68	15.00	9.32
	K^+ (cmol kg^{-1})	2.41	9.96	2.04	2.81	0.77
	Mg^{++} (cmol kg^{-1})	2.97	23.23	2.46	3.47	1.01
	Ca^{+2} (cmol kg^{-1})	6.95	19.42	5.83	8.32	2.49
	Na^{+2} (cmol kg^{-1})	0.15	58.82	0.07	0.28	0.21
	pH	6.72	2.15	6.06	7.00	0.94
	CEC (cmol kg^{-1})	16.84	20.13	14.17	19.26	5.09
	NO_3–N (mg kg^{-1})	48.07	12.48	38.90	61.33	22.43
	SO_4^{-2}–S (mg kg^{-1})	9.91	11.10	4.75	14.29	9.54
	Zn^{+2} (mg kg^{-1})	0.94	21.28	0.67	1.00	0.33
	Mn^{+2} (mg kg^{-1})	47.26	19.21	34.09	63.69	29.60
	Fe^{+2} (mg kg^{-1})	122.27	10.43	99.12	149.53	50.41
	Cu^{+2} (mg kg^{-1})	1.10	10.91	0.79	1.41	0.62
	$EC_{1:2.5}$ (dS m^{-1})	1.27	38.46	0.80	2.00	1.20
F2	EC_a (mS m^{-1})	104.05	53.63	45	200	155
	Elevation (m)	121.12	0.24	120.30	121.60	1.30
	SOM (%)	2.91	20.27	2.31	3.65	1.34
	P (mg kg^{-1})	15.75	68.19	7.36	32.67	25.31
	K^+ (cmol kg^{-1})	2.24	14.23	1.71	3.37	1.66
	Mg^{++} (cmol kg^{-1})	2.74	6.57	2.57	3.01	0.44
	Ca^{+2} (cmol kg^{-1})	7.16	10.06	5.70	8.10	2.40
	Na^{+2} (cmol kg^{-1})	0.12	40.00	0.07	0.19	0.12
	pH	6.83	3.81	6.14	7.15	1.01
	CEC (cmol kg^{-1})	16.19	17.91	14.95	17.18	2.23
	NO_3^-–N (mg kg^{-1})	66.62	10.51	52.89	83.99	31.10
	SO_4^{-2}–S (mg kg^{-1})	15.37	1.69	15.00	15.88	0.88
	Zn^{+2} (mg kg^{-1})	1.54	38.96	0.77	2.54	1.77
	Mn^{+2} (mg kg^{-1})	42.78	38.38	20.00	70.21	50.21
	Fe^{+2} (mg kg^{-1})	108.42	7.68	95.00	122.06	27.06
	Cu^{+2} (mg kg^{-1})	1.03	11.65	0.68	1.24	0.56
	$EC_{1:2.5}$ (dS m^{-1})	0.96	33.33	0.70	1.75	1.05

SOM: soil organic matter, CEC: cation exchange capacity, $EC_{1:2.5}$: laboratory-measured electrical conductivity.

Standard criteria suggested by Wilding et al. (1994) were used to characterize the magnitude of variability of soil properties and nutrient levels; with CV from 0% to 15%, 15% to 35%, and 35% to 100% characterizing low, medium, and high variability, respectively. Soil SOM for both fields ranged from 1.20% to 1.34% with whole field CV ranging from 23.58% to 20.57%, which showed medium variability (Table 1). Soil CEC, Ca^{+2}, Mg^{+2}, Zn^{+2}, and Mn^{+2} contents had medium variability among fields, while the concentration of K^+, NO_3^-—N, SO_4^{-2}—S, Fe^{+2} and Cu^{+2} and pH had low variability. However, P, Na^+ and $EC_{1:2.5}$ showed higher variability (Table 1). The higher mean of Na^+ content and $EC_{1:2.5}$ in F1 was probably due to the predominance of Aromos and Medanitos series, while the Canals series prevailed in F2. CVs for soil properties indicated high spatial variability and suggested the convenience of defining different management zones. High spatial variability in soil properties is the consequence of the interaction of (i) soil formation processes, (ii) meteorological processes, and (iii) anthropogenic influences. Soil formation processes are the result of complex interactions between biological, physical, and chemical mechanisms acting on a parent material over time and influenced by topography (Moral et al., 2010).

3.2. Relationships among EC_a with soil properties and nutrient concentrations

Table 2 shows all PCs with an eigenvalue greater than 1, which were selected because they explained a significant amount of the variance present in the soil properties and nutrient levels at each field. In both cases, PCs had a cumulative variance of more than 80%. In both fields, the first PC (PC1) explained >60% of the total variance and was strongly influenced by all soil properties and Zn^{+2}, Ca^{+2}, Mg^{+2}, Mn^{+2}, Na^+, Fe^{+2} and Cu^{+2}. The second PC (PC2) and third PC (PC3) showed a more intense relationship with P, K^+ and NO_3^-—N, SO_4^{-2}—S, respectively.

For both fields, the PC-stepwise regression analysis only retained PC1 (Table 3). $EC_{1:2.5}$, pH, CEC, Ca^{+2}, Mg^{+2} and Na^+ contents had the highest positive loading factors and were positively related to EC_a, which was associated with lower areas of the fields. In contrast, SOM, Zn^{+2}, Mn^{+2}, Fe^{+2}, Cu^{+2} had the highest negative loading factors and were negatively related to EC_a.

The correlation between elevation and EC_a was significant and negative (Table 4). The higher EC_a values are observed in lower areas (formed mainly by Aromos and Medanitos series) (Figs. 1 and 3), where salts, pH, Na^+ and CEC levels were higher than in higher areas (formed mainly by the Canals series) (Table 5 and Fig. 4). Surface topography plays a significant role in influencing spatial EC_a variation (Kravchenko and Bullock, 2002). Slope and aspect will determine the level and location of run-off and infiltration, which will influence the variation in water content and salinity. Areas where the slope is steep tend to have lower water content than areas where a depression occurs (Marques da Silva and Silva, 2008). The influence of surface topography on salinity distribution coincides with the influence of surface topography on water-flow gradients, which results in salt transport (Corwin and Lesch, 2005).

Three variables ($EC_{1:2.5}$, pH and Na^+) were highly correlated with EC_a and presented values $r > 0.67$ for both fields. This high correlation is expected because it reflects the influence of salts on the EC_a reading and because these properties are highly correlated (Kaffka et al., 2005). Salts and Na^+ concentrations increased soil solution conductivity (Rhoades et al., 1989) and is consistent with findings in previous studies (Kaffka et al., 2005).

The EC_a showed a positive correlation with CEC, Ca^{+2} and Mg^{+2} (Table 4). This indicates that changes in Ca^{+2} and Mg^{+2}

Table 2
Regression model resulting from the principal component (PC) – stepwise regression analysis of the relationship between apparent electrical conductivity (EC_a) and soil properties–nutrients.

Fields	Key PCs	Eigenvalue	Cumulative σ^2	Parameter														
				SOM	P	K^+	Mg^{+2}	Ca^{+2}	Na^{+2}	pH	CEC	NO_3–N	SO_4^{-2}–S	Zn^{+2}	Mn^{+2}	Fe^{+2}	Cu^{+2}	$EC_{1:2.5}$
F1	CP 1	8.7	0.61	−**0.4**	−0.19	0.26	**0.44**	**0.42**	**0.46**	**0.46**	**0.45**	0.15	−0.26	−**0.41**	−**0.44**	−**0.41**	−**0.43**	**0.47**
	CP 2	2.1	0.73	0.14	**0.54**	**0.53**	0.15	0.29	−0.01	−0.01	0.11	0.13	0.44	−0.14	0.03	−0.01	0.15	−0.19
	CP 3	1.4	0.82	−0.03	−0.11	0.23	−0.02	−0.12	0.09	0.12	0.1	**0.78**	−0.11	0.32	−0.01	0.37	−0.05	0.15
F2	CP 1	9.57	0.64	−**0.43**	0.18	0.21	**0.45**	**0.44**	**0.42**	**0.45**	**0.41**	0.29	−0.33	−**0.45**	−**0.45**	−**0.44**	−**0.44**	**0.46**
	CP 2	2.57	0.81	−0.14	**0.61**	**0.57**	−0.02	0.15	−0.09	0.06	0.15	-0.02	**0.45**	0.06	0.19	0.18	−0.16	−0.02
	CP 3	1.59	0.92	−0.26	−0.13	−0.27	0.17	0.04	−0.21	−0.25	0.18	**0.53**	**0.38**	−0.1	0.1	0.05	0.22	−0.21

SOM: soil organic matter, CEC: cation exchange capacity, $EC_{1:2.5}$: laboratory-measured electrical conductivity. Bold values indicate significant loading factors > 0.4.

Table 3
Key principal components (PCs) (eigenvalues > 1.0), cumulative variance and loading factors for each soil property and nutrient.

Fields	Regression model	R^2	RMS	*p*	Key latent variables (loading factors > 0.4) (listed in order of importance)	
					Soil properties	Nutrients
F1	139.25 + 18.20* PC1	0.94	0.61	0.0001	pH, $EC_{1:2.5}$, CEC, SOM	Na^{+2}, Mg^{+2}, Mn^{+2}, Cu^{+2}, Ca^{+2}, Zn^{+2}, Fe^{+2}
F2	101.76 + 17.37* PC1	0.91	0.64	0.0071	pH, $EC_{1:2.5,}$ SOM, CEC	Mg^{+2}, Zn^{+2}, Mn^{+2}, Ca^{+2}, Fe^{+2}, Cu^{+2}, Na^{+2}

SOM: soil organic matter, CEC: cation exchange capacity, $EC_{1:2.5}$: laboratory-measured electrical conductivity, RMS: root mean square.

concentrations associated with changes in the CEC across the fields were influencing EC_a. Increases in the CEC contributed to the raised concentration of Ca^{+2} and Mg^{+2} in the soil solution and to increasing the electrical conductivity of soil particles, which increased the EC_a (Shainberg et al., 1980). The CEC might be linked to clay content, because the highest values were found in the sampling points on the Aromos series (loam). In contrast, the lowest values of CEC (and hence Ca^{+2}, Mg^{+2}) were associated with the Canals series (sandy loam). Heiniger et al. (2003) reported that sand was negatively related to Ca^{+2} and Mg^{+2} levels, while silt and clay were positively related. It is clear that the CEC, Ca^{+2} and Mg^{+2} concentrations affected the EC_a measurements, due to the influence on the electrical conductivity of the soil particles. However, the common assumption is that in soils with salinity problems, salts have a greater influence on the EC_a variability (Rhoades et al., 1989), either by affecting the electrical conductivity of the soil solution associated with discontinuous pores or by the electrical conductivity of the mobile soil solution associated with large, continuous pores (Shainberg et al., 1980; Malicki and Walczak, 1999).

Moreover, the EC_a showed a negative correlation with SOM, and between SOM and $EC_{1:2.5}$ (Table 4). High concentrations of salt in soils influence soil organic matter (SOM) content. Salinity has been found to have a negative influence on the activity of soil microbial biomass and biochemical processes essential for the maintenance of soil organic matter (Tripathi et al., 2006). In agricultural fields without salts present, high EC_a was associated with the highest values of SOM (Heiniger et al., 2003; Peralta et al., 2013). Also, the EC_a showed a negative correlation with Zn^{+2}, Mn^{+2}, Fe^{+2} and Cu^{+2} concentrations (Table 4).

Conversely, PC2 and PC3 showed a more intense relationship with P, K^+, NO_3–N and SO_4^{-2}–S), (Table 2). PC2 and PC3 were not retained in the PC-regression model in both fields (Table 3). These variables showed no significant correlation with the EC_a (Table 4) because the variation was very low (CVs < 15%, Table 1), except for P (CVs were >30%). The low association between EC_a and P is probably due to the fact that equivalent conductances of common inorganic P ions in soils (e.g. $H_2PO_4^-$ and HPO_4^{-2}) are generally lower than ionic species (e.g. Ca^{+2} and Mg^{+2}) (Motavalli et al., 2013). Furthermore, Jung et al. (2005) mentioned that the low association between EC_a and P is attributable to the influence of fertilization form (band application) and tillage system (direct drilling, without soil removal). The available N and S levels were not related to the variability of the EC_a, this may be explained by variation and low concentrations of these anions, without influence on the electrical conductivity of the mobile soil solution. Corwin et al. (2006) found a very strong correlation between EC_a with NO_3^-—N and SO_4^{-2}—S), contents working in fields with higher concentrations and variations.

Identification of regression models that were able to account for a large portion (50%) of the variability in soil EC_a would indicate situations where EC_a could be used successfully to measure soil properties and nutrient levels (Heiniger et al., 2003). As can be seen, the EC_a was strongly linked to soil properties, mainly $EC_{1:2.5}$ and pH (higher loading factors). It was also correlated with some exchange cations such as Zn^{+2}, Ca^{+2}, Mg^{+2}, Mn^{+2}, Na^+, Fe^{+2} and Cu^{+2}; there were no correlations with K^+, P, NO_3^-—N and SO_4^{-2}—S), indicating that EC_a measurements in these fields were driven primarily by salinity.

3.3. Delineation of homogeneous management zones

While the PCA revealed which soil properties and nutrients explained the major total variance, and the PC-stepwise regression determined which soil properties and nutrients were more associated with EC_a, neither of these two techniques can determine significant differences among EC_a classes. Therefore, to assess whether EC_a can be used to determine HMZ, a mixed ANOVA model was fitted (Table 5).

The soil properties ($EC_{1:2.5}$, pH, CEC and SOM) had the greater significant differences among EC_a classes in each field (Table 5), which is consistent with the results of the PCA. These soil properties were considered key latent variables (loading factors > 0.4) because they substantially influence the relationship between PC1 and the EC_a (Table 3). The $EC_{1:2.5}$ and pH exhibited significant differences between two EC_a classes (Table 5). The delimitation of areas with different values of $EC_{1:2.5}$ and pH is very important for SSM because soil salinity refers to the presence of major dissolved inorganic solutes in the soil aqueous phase. These consist of soluble and readily dissolvable salts including charged species, non-ionic solutes, and ions that combine to form ion pairs (Corwin and Lesch, 2005). Salinity limits water uptake by plants because it reduces the osmotic potential, making it more difficult for the plant

Table 4
Correlations between apparent electrical conductivity (EC_a), elevation, soil properties and nutrient concentrations in each field.

Fields	Variables	EC_a	Elevation	SOM	P	K^+	Mg^{++}	Ca^{+2}	Na^{+2}	pH	CEC	NO_3^-—N	SO_4^{-2}—S	Zn^{+2}	Mn^{+2}	Fe^{+2}	Cu^{+2}	$EC_{1:2.5}$
	EC_a	1	–***	–**	ns	ns	–**	–***	–***	–***	–***	ns	ns	–***	–***	–***	–***	–***
	Elevation	−0.91	1	–**	ns	ns	–***	–***	–***	–***	–***	ns	ns	–**	–***	–*	–*	–***
	SOM	−0.72	0.71	1	ns	ns	–*	–*	–*	–*	ns	ns	ns	ns	–***	ns	–***	–**
	P	−0.11	0.23	0.3	1	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	K^+	0.34	−0.44	−0.14	0.45	1	ns	–**	ns	ns	ns	ns	ns	–*	ns	ns	ns	ns
	Mg^{++}	0.76	−0.89	−0.66	−0.14	0.42	1	–***	–***	–**	–***	ns	ns	–***	–***	–**	–*	–*
F1	Ca^{+2}	0.84	−0.84	−0.57	0.11	0.59	0.9	1	–**	–**	–***	ns	ns	–**	–***	–*	–*	–*
	Na^{+2}	0.67	−0.77	−0.64	−0.04	0.28	0.78	0.71	1	–*	–***	ns	ns	–**	–***	–***	–***	–*
	pH	0.93	−0.76	−0.64	0.00	0.36	0.7	0.7	0.67	1	–***	ns	ns	–*	–**	–**	–***	–***
	CEC	0.89	−0.9	−0.25	−0.13	0.46	0.92	0.89	0.59	0.55	1	ns	ns	–*	–***	–*	–**	–***
	NO_3^-—N	−0.05	0.1	0.05	0.03	0.29	0.08	−0.06	0.18	0.14	0.13	1	ns	ns	ns	ns	ns	ns
	SO_4^{-2}—S	−0.58	0.55	0.41	0.54	0.09	−0.29	−0.15	−0.57	−0.59	−0.4	0.04	1	ns	ns	ns	–*	–***
	Zn^{+2}	−0.80	0.72	0.43	−0.01	−0.39	−0.76	−0.78	−0.71	−0.67	−0.66	0.24	0.38	1	–**	–***	–*	ns
	Mn^{+2}	−0.83	0.75	0.77	0.34	−0.2	−0.87	−0.75	−0.76	−0.69	−0.83	−0.1	0.35	0.71	1	–**	–**	–*
	Fe^{+2}	−0.63	0.67	0.52	−0.07	−0.05	−0.71	−0.64	−0.81	−0.72	−0.61	0.28	0.37	0.81	0.68	1	–**	–*
	Cu^{+2}	−0.77	0.64	0.72	0.11	−0.13	−0.57	−0.56	−0.88	−0.89	−0.69	−0.05	0.64	0.6	0.72	0.72	1	–***
	$EC_{1:2.5}$	0.90	−0.8	−0.73	−0.24	0.16	0.68	0.59	0.61	0.92	0.76	0.1	−0.77	−0.53	−0.66	−0.66	−0.88	1
	EC_a	1	–*	–*	ns	ns	–***	–**	–***	–***	–***	ns	ns	–***	–***	–**	–***	–***
	Elevation	−0.70	1	ns	ns	ns	–*	ns	–*	ns	ns	ns	ns	–**	–*	ns	ns	–**
	SOM	−0.71	0.52	1	ns	ns	–***	–*	–*	–*	ns	ns	ns	–**	–*	–*	–**	–*
	P	0.03	0.08	−0.25	1	–***	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	K^+	0.15	0.01	−0.26	0.98	1	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	Mg^{++}	0.67	−0.73	−0.88	0.01	0.07	1	–***	–**	–***	–**	ns	ns	–***	–***	–**	–**	–**
	Ca^{+2}	0.72	−0.57	−0.76	0.28	0.34	0.91	1	–**	–***	–**	ns	ns	–**	–*	–*	–*	–*
	Na^{+2}	0.70	−0.64	−0.70	0.19	0.33	0.83	0.83	1	–***	–**	ns	ns	–**	–***	–*	–***	–*
F2	pH	0.95	−0.56	−0.72	0.22	0.34	0.84	0.87	0.66	1	–*	ns	ns	–**	–***	–**	–***	–***
	CEC	0.78	−0.47	−0.29	−0.12	−0.05	0.79	0.78	0.52	0.66	1	ns	ns	–***	–**	–*	–*	–**
	NO_3^-—N	−0.38	−0.42	−0.89	−0.04	−0.08	0.81	0.63	0.42	0.44	0.46	1	ns	ns	ns	–*	ns	ns
	SO_4^{-2}—S	−0.32	0.42	0.24	0.42	0.22	−0.48	−0.35	−0.62	−0.59	−0.49	−0.14	1	ns	–**	–**	ns	–*
	Zn^{+2}	−0.81	0.77	0.77	0.07	0.02	−0.92	−0.81	−0.80	−0.83	−0.88	−0.65	0.41	1	–***	–**	–*	–***
	Mn^{+2}	−0.82	0.69	0.73	0.19	0.06	−0.87	−0.72	−0.85	−0.86	−0.78	−0.59	0.79	0.85	1	–***	–**	–***
	Fe^{+2}	−0.73	0.56	0.76	0.18	0.05	−0.83	−0.67	−0.77	−0.81	−0.70	−0.65	0.77	0.77	0.97	1	–**	–*
	Cu^{+2}	−0.67	0.54	0.80	−0.38	−0.50	−0.77	−0.77	−0.91	−0.92	−0.65	−0.48	0.52	0.72	0.82	0.81	1	–***
	$EC_{1:2.5}$	0.96	−0.81	−0.65	0.06	0.18	0.82	0.76	0.55	0.90	0.81	0.39	−0.61	−0.87	−0.87	−0.74	−0.84	1

SOM: soil organic matter, CEC: cation exchange capacity, $EC_{1:2.5}$: laboratory-measured electrical conductivity.
ns, not significant.
* Significant at the $\alpha = 0.05$ error level.
** Significant at the $\alpha = 0.01$ error level.
*** Significant at the $\alpha = 0.001$ error level.

to extract water. Salinity may also cause specific ion toxicity or upset the nutritional balance of plants, reducing crop yields (Corwin and Lesch, 2005). Also, pH controls the nutrient availability for plants and soil microbial activity (Serrano et al., 2010). The SOM and CEC exhibited significant differences among two EC_a classes, but with an inverse pattern (Table 5). Bearing in mind that CEC and SOM are relatively static over time (Shaner et al., 2008), and that they affect crop growth and development (Groenigen et al., 2000), it would be useful and necessary to classify fields into homogeneous zones. The classes of high EC_a showed lower values of SOM. In a previous study published by Gambaudo et al. (2008), it was observed that in medium–low zones of EC_a, the SOM increased. Also, the nutrients with high loading factors (Zn^{+2}, Ca^{+2}, Mg^{+2}, Mn^{+2}, Na^+, Fe^{+2} and Cu^{+2}) showed greater significant differences among the EC_a classes in each field. The micronutrient concentrations (Zn^{+2}, Mn^{+2}, Fe^{+2} and Cu^{+2}) exhibited significant differences among the two EC_a classes. In most cases, they showed no difference between the medium–high classes, except Cu^{+2} in F1 (Table 5). The high micronutrient concentrations in the low EC_a class were attributed to increasing soil acidification and relatively high SOM contents (Shuman, 1991; Shi et al., 2008; Eyherabide et al., 2012). The concentrations of Ca^{+2}, Mg^{+2} showed differences among two classes, while K^+ showed no significant differences among EC_a classes (Table 5), possibly because of the low CV exhibited in F1 and F2 (9.96% and 14.23%, respectively) (Table 1). The Na^{+2} concentrations showed differences among two EC_a classes (Table 5). Bosch Mayol et al. (2012), working in soils with a higher Na^{+2} content, found differences in three zones, concluding that the Na^{+2} spatial variability significantly affects EC_a.

However, the nutrients with low loading factors (K^+, P, NO_3^-—N and SO_4^{-2}—S), did not show significant differences among EC_a classes (Table 5). The NO_3^-—N and SO_4^{-2}—S), concentrations had low CVs, indicating that these variables showed little variation within the fields. Also, transformations in soil are controlled by soil water content, biological activity, cropping, composition and quantity of organic matter. These soil characteristics have an impact on the discordant processes of immobilization and leaching (losses) or mineralization (gains) that define NO_3^-—N and SO_4^{-2}—S), levels in soil (Eriksen, 1997). While P showed a high CV, it was not a variable that significantly affected the EC_a.

Geo-referenced EC_a measurements successfully delimited two homogeneous soil zones associated with spatial distribution of soil properties, such as salt concentration ($EC_{1:2.5}$), pH, CEC and SOM content. Two homogeneous soil zones were also delimited by micronutrients (Zn^{+2}, Mn^{+2}, Fe^{+2} and Cu^{+2}) strongly associated with soil pH and SOM (Table 4); and two zones by Na^+, Ca^{+2}, Mg^{+2}, which showed high correlations with CEC. However, the K^+, P, NO_3^-—N and SO_4^{-2}—S), content had few differences on average in the different EC_a zones, so it would not be advisable to make management zones based on these three nutrients. Soil properties such as pH, SOM and CEC showed high correlations with nutrient levels and, as they are relatively static over time, a model that included these measurements along with EC_a could be developed to predict soil nutrient content. Because EC_a is able to measure these soil proper-

Table 5
Soil properties and nutrient-concentrations means within three zones (classes) of apparent electrical conductivity (EC_a) in each field.

Fields	EC_a Zones	EL[a]	SOM (%)	P (mg kg^{-1})	K^+ (cmol kg^{-1})	Mg^{+2} (cmol kg^{-1})	Ca^{+2} (cmol kg^{-1})	Na^{+2} (cmol kg^{-1})	pH	CEC (cmol kg^{-1})	NO_3^-—N (mg kg^{-1})	SO_4^{-2}—S (mg kg^{-1})	Zn^{+2} (mg kg^{-1})	Mn^{+2} (mg kg^{-1})	Fe^{+2} (mg kg^{-1})	Cu^{+2} (mg kg^{-1})	$EC_{1:2.5}$ (dS m^{-1})
	Low	120.98	2.91 a	9.79	2.34	2.51 b	5.93 b	0.09 b	6.26 b	14.51 b	50.56	10.5	1.18 a	65.12 a	145.52 a	1.11 a	0.8 b
F1	Medium	120.63	2.57 a	8.03	2.31	3.17 b	6.9 a	0.12 b	6.27 b	16.88 b	42.91	8.46	0.84 b	46.78 b	124.25 b	1.11 a	0.8 b
	High	120.12	1.96 b	8.44	2.55	3.49 a	7.54 a	0.23 a	6.78 a	19.95 a	50.74	10.78	0.73 b	34.48 b	114.56 b	0.82 b	1.5 a
	Low	121.29	3.19 a	21.42	2.50	2.55 b	7.28 b	0.07 b	6.17 b	15.72 b	60.53	15.19	2.0 a	63.94 a	119.67 a	1.15 a	0.6 b
F2	Medium	120.98	2.99 a	10.37	1.93	2.71 b	7.65 ab	0.08 b	6.3 b	17.06 b	67.38	15.34	1.24 b	45.7 b	107.54 b	1.09 b	0.7 b
	High	120.56	2.25 b	15.44	2.30	3.05 a	8.95 a	0.18 a	6.75 a	20.83 a	71.96	15.59	1.12 b	38.71 b	101.39 b	0.89 b	1.18 a

SOM: soil organic matter, CEC: cation exchange capacity, $EC_{1:2.5}$: laboratory-measured electrical conductivity.
a–b The same letters indicate no significant differences ($P \leqslant 0.05$) for each site.
[a] EL: Average elevation for each EC_a zone.

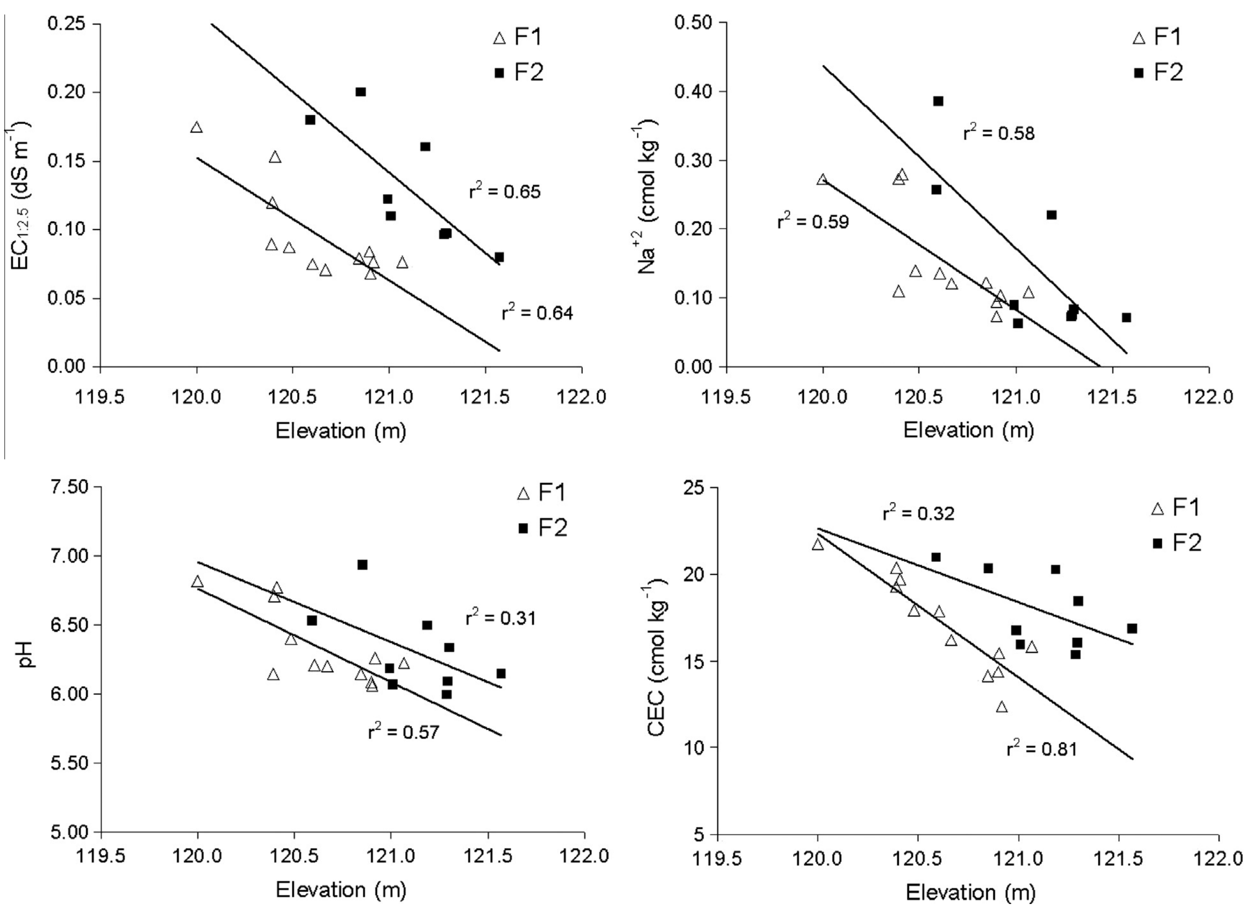

Fig. 4. Elevation vs. $EC_{1:2.5}$, Na^{+2}, pH and CEC in each field. The coefficient of determination (r^2) is given for simple linear regressions.

ties directly, it has the potential to identify HMZ with differing productivity and nutrient requirements.

4. Conclusions

The results of this study indicate that for both fields, the PC-stepwise regression analysis was able to account for >50% of the variability in the EC_a. Principal-component groups consisting of all soil properties (mainly $EC_{1:2.5}$ and pH) and some exchange cations (Zn^{+2}, Ca^{+2}, Mg^{+2}, Mn^{+2}, Na^+, Fe^{+2} and Cu^{+2}) were able to consistently account for the spatial variability of the EC_a. In contrast, the PC-stepwise regression analysis was not able to consistently identify models that accounted for other soil nutrients (K^+, P, NO_3^-—N and SO_4^{-2}—S). >This does not mean that EC_a has no value in determining nutrient levels in the soil. Instead, this study shows that EC_a could be a valuable tool when used in conjunction with multivariate statistical procedures in identifying some soil properties and nutrient content.

The K^+, P, NO_3^-—N and SO_4^{-2}—S), content had low values and few differences in average in the different classes of EC_a, so it would not be advisable to create management zones based on these nutrients. However, EC_a measurements successfully delimited two homogeneous soil zones associated with the spatial distribution of all soil properties and Zn^{+2}, Ca^{+2}, Mg^{+2}, Mn^{+2}, Na^+, Fe^{+2} and Cu^{+2} concentrations.

Considering that CEC, SOM content and pH_s values are static over time and are used to determine soil fertility, these results suggest that EC_a field-scale maps in areas with well-drained soil (Entic Haplustoll) and moderate to imperfect-drainage soil, moderately saline-alkali in depth (Typic Calciacuoll, Typic Natralboll), can delimit two zones which are homogeneous enough to serve as meaningful zones for management and sampling purposes, without sacrificing soil spatial variability information.

In the next few years, some studies will be conducted to evaluate these subfield management zones, using yield maps to better understand the agronomic significance of this classification.

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