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

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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

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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.