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Apparent electrical conductivity and multivariate analysis of soil properties to assess soil constraints in orchards affected by previous parcelling

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ABSTRACT

Fruit production is relevant to the European agricultural sector. However, orchards in semi-arid areas of southern Europe may contain soils with constraints for tree development. This is the case of soils with high $CaCO_3$ content or limiting layers at variable depth. To assess spatial and in-depth variation of these soil constraints, an apparent electrical conductivity (ECa) survey was conducted in an orchard by using a galvanic contact soil sensor (Veris 3100). Different soil properties were randomly sampled at two depths (topsoil and subsoil) in 20 different sampling points within the plot. ECa raster maps were obtained for shallow (0–30 cm) and deep (0–90 cm) soil profile depths. In addition, an inversion modelling software was used to obtain horizontal ECa slices corresponding to 10 cm thick soil layers from 0–10 cm to 80–90 cm in depth. Concordance analysis of ECa slices allowed the soil profile to be segmented into four homogeneous horizons with different spatial conductivity pattern. Then, a multivariate analysis of variance (MANOVA) was key, i) to better interpret the specific soil properties that mainly contributed to the spatial variation of ECa ($CaCO_3$ and organic matter (OM) contents), and ii) to delimit the soil layer and the specific spatial pattern of ECa that allows potential management areas to be delineated by presenting the same trend in $CaCO_3$ and OM for topsoil and subsoil simultaneously. Moreover, assessing 3D variation of ECa made it possible to identify different soil areas that, linked to previous earthworks to optimize the parcelling of the farm, are the main cause of spatial variability within the orchard.

1. Introduction

Fruit production and quality are affected to some extent by soil properties given the plant-soil interaction (Pedrera-Parrilla et al., 2014; Unamunzaga et al., 2014; Khan et al., 2016). As soil can vary spatially and at different scales, knowledge of spatial patterns within the plots could help farmers to make better management decisions based on the delimitation of areas with different soil conditions and agronomic needs (Ping et al., 2005; Vitharana et al., 2008; Pedrera-Parrilla et al., 2014; Córdoba et al., 2016). This is particularly relevant in semi-arid fruit growing areas of southern Europe. Soils in these areas are characterized by a high and spatially variable content of carbonates with a clear incidence in nutritional deficiencies and chlorosis that affect growth and the normal foliar development. Accordingly, orchards usually show spatial variability in the canopy volume within the plot. In addition, this lack of homogeneity is particularly remarkable in plots that have been affected by successive earthworks over the years to reshape and optimize the parcelling of the farm. Fruit growers are therefore especially interested in locating and delimiting areas within the orchards that can be a major constraint for management (Fulton et al., 2011).

Soil sensors for mapping the apparent soil electrical conductivity (ECa in mS/m) are increasingly used to understand and evaluate how soil varies spatially (Corwin and Lesch, 2003; Abdu et al., 2008; Fulton et al., 2011) to delineate ECa-based management zones (Moral et al., 2010; Peralta and Costa, 2013). At present, it begins to be applied as a key sensing system in the framework of precision fruticulture (Käthner and Zude-Sasse, 2015). As ECa varies on a similar spatial scale as many soil physico-chemical properties (Sudduth et al., 2003; Carroll and Oliver, 2005), these soil monitoring systems have been widely accepted. Specifically, good correlations with soil salinity, soil water content and soil texture have been widely documented (Corwin and Lesch, 2005; Heil and Schmidhalter, 2012). Even, other soil properties affecting conductivity may be the organic C (Sudduth et al., 2003; Martinez et al., 2009), the cation exchange capacity (Sudduth et al., 2005) and the $CaCO_3$ content (Kühn et al., 2009). However, despite these good predictive characteristics, there are few studies that refer the use of such sensors in horticulture and, more specifically, in fruit orchards located in Mediterranean latitudes. One reason could be the

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small size of many fruit orchards. This induces farmers to think that tree plantations are rather homogeneous, and spatial variability is not enough to justify investing in this technology. By contrast, Käthner and Zude-Sasse (2015) show that even in small orchards there may be differences in soil properties that relate to tree growth and fruit size. Two soil sensing systems are commonly used in agriculture (Corwin and Lesch, 2005). In both cases (galvanic contact with the soil and electromagnetic induction), sensors measure the ECa on a soil volume basis including both topsoil and subsoil. This is very interesting since soil influences fruit trees at least to the depth covered by the roots, and ECa measurements should cover the same depth. Depending on the system, soil sensors provide with several electrical signals corresponding to several explored depths. When two signals are provided, they are known as shallow and deep ECa, and may correspond to the topsoil and whole profile depending on the sensor range. Farmers can get maps of both signals to evaluate the spatial variation of ECa, and indirectly the spatial pattern of soil related properties. Moreover, by overlapping maps, they can also assess whether the soil is uniform or varies in depth. The problem occurs when the interest is to determine exact depths at which changes in the soil profile are produced (e.g. petrocalcic horizons) using such averaging procedures that encompass all or part of the soil profile (Heege, 2013).

Mapping the thickness or depth to a contrasting textural layer using ECa has been also referenced in several studies to detect clay horizons (Doolittle et al., 1994; Saey et al., 2009), or estimate topsoil depth explored by roots (Khan et al., 2016). Depth estimates may be based on empirical equations (using a single ECa signal that integrates the relative contribution of soil at each depth) or by combining data from multiple ECa sensors in both two- and three-layer models (Sudduth et al., 2010, 2013). Electromagnetic conductivity imaging (EMCI) of soil is another option that has been recently investigated (Triantafilis et al., 2013). Combining conductivity data and an inversion modelling software, a two-dimensional model of the ECa can be generated to assess soil variation (i.e. horizons) at discrete depth intervals (Triantafilis and Monteiro Santos, 2013). Researchers can take advantage of this additional information regarding the signal variation probably caused by layers of different thickness and composition. In short, soil properties sampled at varying depths may be better interpreted if a model indicating the variation of ECa with soil depth is available.

The main objective of the present research was to analyse the capacity of a galvanic contact soil sensor (Veris 3100) to be used as a diagnostic tool in fruit growing areas with high calcium carbonate content, and plots affected by previous parcelling works. Special attention was devoted to assess the spatial variability of physico-chemical soil properties to properly define differential management zones within an orchard. For that, we focused our research on: i) evaluating the sensing system and its signal mapping, ii) inverting the ECa signal to obtain electrical imaging of ECa variation with soil profile, and iii) applying not conventional statistical methods i.e. multivariate analysis of variance (MANOVA) for a better interpretation of ECa and soil data.

2. Materials and methods

2.1. Study area

The study was carried out at the IRTA Experimental Station (Lon. 0.392017, Lat. 41.654413, Datum WGS84), located in Gimenells, 24 km west from Lleida (Catalonia, Spain). The research was focused on a 0.65 ha plot that was planted in 2011 with peach trees (*Prunus persica* L. Stokes var. platycarpa) according to a 5 × 2.80 m plantation pattern (Fig. 1). Soil was classified as Petrocalcic Calcixerept (Soil Survey Staff, 2014), and it is a well-drained soil without salinity problems. The climate, typical of semi-arid areas of the Mediterranean region, is characterized by strong seasonal temperature variations (cold winters and hot summers), and an annual precipitation that is usually below 400 mm, although with significant interannual variability.

However, the most important feature of the plot was the presence of a petrocalcic horizon at a variable depth from 40 cm to 80 cm. This spatial variation in depth could be explained by the successive earthworks made in recent years in order to improve or adapt the parcelling of the farm. Probably, the petrocalcic layer was broken over time due to soil tillage and now appears even at shallow depths in certain areas. In fact, the history of transformation and land uses of this plot has been relatively complex as shown in Fig. 1. Since 1946, when the Experimental Station was created, the plot has been cultivated with different crops and was modified in shape and size in several occasions (at least, the plot undergone a minimum of four major transformations in recent years, Fig. 1).

2.2. Soil sampling

A simple random soil sampling was carried out in 20 different points within the plot (Fig. 2). Soil was sampled on March 15th, 2015. Samples were collected with the aid of a manual auger-hole at three different depths (0–30, 30–60, 60–90 cm). It is necessary to clarify that only in 4 of these sampling points it was possible to take a sample of the deepest layer, since the soil was shallow at most of the sampled sites. Sample locations were also georeferenced with submetric precision using a Trimble GPS Geo XH receiver and SBAS differential correction based on EGNOS. Soil samples were air-dried and sieved, and different physicochemical properties were analysed in the laboratory according to the standard procedures. Specifically, data were obtained on the following properties: calcium carbonate content ($CaCO_3$), cation exchange capacity (CEC), electrical conductivity in a 1:5 soil-water solution ($EC_{1:5}$), organic matter (OM), pH measured in a 1:2.5 soil-water ratio, soil texture, total nitrogen (TN) in soil, and water holding capacity (WHC).

In addition to manual soil sampling, an ECa survey was conducted by using the Soil EC Surveyor Veris 3100 (Veris Technologies, Inc., Salina, KS, USA). The Veris 3100 implement is a simple and effective tool to acquire on-the-go information on soil bulk electrical conductivity for subsequent mapping. Its advantage lies in using two electrical arrays that allows ECa readings to be obtained at two different soil depths simultaneously and free of metal interference. Equipped with six heavy-duty coulter-electrodes, a pair of electrodes injects electrical current into the soil while the other two pairs measure the voltage drop. The penetration of the electrical current into the soil and, by extension, the volume of soil explored increases as the inter-electrode spacing increases. In our case, the array configuration allowed 0–30 cm (shallow ECa lecture) and 0–90 cm (deep ECa lecture) soil depths to be explored.

The ECa survey was carried out on March 23rd, 2015. For that, the Veris 3100 system was pulled by a 4-wheel drive vehicle passing along all the alleyways of the peach orchard. As tree rows were spaced 5 m, parallel ECa measurements were spaced this same distance. On the other hand, the soil sensor was connected to a Trimble AgGPS332 receiver for georeferencing purposes, and SBAS differential correction based on EGNOS was used. Regarding the spatial sampling resolution, data were recorded every second providing a total of 644 georeferenced ECa readings within the orchard (990 sampling points per hectare).

2.3. Apparent electrical conductivity maps and quasi-3D inversion modelling

Both ECa values (shallow and deep) were mapped by ordinary kriging. Maps were obtained after checking the normality of the acquired data and having removed extreme outliers from the analysis. Regarding the latter, ECa values lower than $Q_1 - 3 \times IQR$ or greater than $Q_3 + 3 \times IQR$ were not considered in the spatial interpolation (Q_1 and Q_3 were the first and third quartiles, and IQR was the interquartile range of the distribution). ArcMap 10.4.1 Geostatistical Analyst (Environmental Systems Research Institute, Redlands, CA, USA) was then used to finally interpolate shallow and deep ECa values by kriging