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Autoregressive state spatial modeling of soil bulk density and organic carbon in fields under different tillage system

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ABSTRACT

Uncontrolled transit operations could be responsible of repetitive patterns of soil properties. Cyclic spatial structure patterns of soil bulk density (BD), soil organic carbon (OC) and water content (WC) in farm fields were assessed with spectra and cross spectra analysis in a 100 m-long transect sampled at 1 m apart, on Vertic and Typic Argiudol soils under no tillage (NT) from a commercial farm in San Antonio de Areco, 34° 15′32.42″ S, 59°25′19.93″ W, Ondulate pampa region, Argentina. Although spectrum and cospectrum analysis showed several cyclic locations, only sites at approximately 2.6 m, 4 m and 9 m were significant ($p < 0.05$). These distances are clearly related with tractors axles and combine harvester paths, thus suggesting the importance of those operations on soil variables. An autoregressive state space modeling approach was used to integrate the spatial information and to model BD, WC and OC in different transects at 10 m and 30 m apart. With the spatial relationship between BD and OC we create predictive models that explain 63% of the OC data and 54% of the BD data over a 2740 m-long transect. However, it was not possible to predict WC, despite the spatial correlation observed among the soil variables. The low importance of WC in the modeling process of BD and OC, and the large dominance of the autoregressive part in the final model are pointing out that an important surrogate variable is missing, which could be the key for modeling soil variables at different scale.

1. Introduction

Agricultural activities always determine several alterations of soil ecosystem because it is necessary to modify their natural condition. In strict sense, all farm machineries operations have adverse effects on soil properties. Tractors towing seeder, self-propeller sprayers, and combine harvester with grain carts moving around when harvesting impose a variety of stress loads over the soil. Note that depending on the vehicle, the distance between tires can vary from 1.2 m in tractors to 4 m in a combine harvester. In addition, contractors can use dual or triple tires in the front axle. They also can use different tire pressure or to add loads, depending on the need for sustentation in wet condition (Botta et al., 2012; Seehusen et al., 2014). Despite the size of the equipment and frequency of harvesting procedure, these operations are not often considered in soil degradation studies. However, it becomes evident that the tillage, the terrestrial equipment and the harvesting practices can affect soil properties dynamically in space and time. This evidence is increasing the need to apply spatial and temporal analyses to gain knowledge of the soil use and its behavior, especially in farmer's fields (Strudley et al., 2008). Knowing the spatial distribution of soil properties and their alteration could allow improving soil management practices or assessing their effect on soil quality (Cambardella et al., 1994). Additionally, spatial techniques could define the soil sampling intensity or to improve the sampling scheme for detecting adverse effects on soil functioning (Webster and Oliver, 2001). The alteration of soil properties even under controlled equipment traffic may fluctuate because a variation in landscape features and because the temporal variability could masked the wheel-track effects. Spatial and temporal variability often overshadows specific management effects. Differences in temporal variability depend on spatial locations between rows, within fields at different landscape positions, and between sites with different climates and soil types. Tillage practices have pronounced effects on soil properties but the duration of those effects could vary substantially (Strudley et al., 2008). The reason could be the resilience of the soil properties, as well as the effect of the root system and crop residue on the soil structure (De Varennes and Torres, 2011; Strudley et al., 2008; Abiven et al., 2007). Being the most common soil variables used for tillage comparison, soil bulk density (BD), water content (WC) and soil organic carbon content (OC), received special attention in soil

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studies. Despite all data available, the reviewers still found inconsistent responses about what happens with BD or WC when comparing different tillage practices (Strudley et al., 2008;). For example, Franzluebbers and Arshad (1996) found that tillage-induced BD exhibited large seasonal dynamics similar to WC. On the contrary, Cresswell et al. (1993) demonstrated insensitivity of tillage to WC in a silt loam in New Zealand. Thus, the evidence for changes in WC under tillage has not been generalized, but probably due to the temporal scale is more important than the spatial scale of variability of WC. The scale of variability is an important feature of soil properties, because depend on the soil variable under study. Cambardella et al. (1994) found that BD was moderately spatial-dependent while OC was strongly spatial dependent under tillage systems, conventional tillage and No tillage in central Iowa. They concluded that due to the spatial dependence, is not possible to extrapolate information from one field to another. Soil properties also can exhibit a repetitive or quasi cyclic behavior that could depend on tillage operations (Perfect and Caron, 2002) or cultivation practices (VanWesenbeeck et al., 1988; Nielsen and Alemi, 1989). The cyclic behavior of soil properties or periodicity in the spatial variation can be quantified from the spectral analysis, which approximates a spatial data series by a sum of sine and cosine functions (Nielsen and Wendroth, 2003; Biswas and Si, 2011). The squared amplitude at a given frequency is equal to the contribution of that frequency component to the total variance in the spatial series (Webster, 1977; Shumway, 1988). Frequency domain analysis or spectral analysis (Nielsen and Alemi, 1989) was successfully used for several researchers in soil science to analyze soil properties responsible for water and solute transport (Yang and Wendroth, 2014), effects of land use on leaching (Schwen et al., 2012) or bulk density and gravimetric water content (Perfect and Caron, 2002). In addition, soil data varying along transects can be described as multivariate autoregressive systems in state-space models (Wendroth et al., 1992, 2001). Those models have allowed a better understanding of processes in the field that influence the soils variability. In addition, state-space models were useful in identifying the underlying process that caused different soil function, as well as the yield spatial variability (Li et al., 2002; Wendroth et al., 2003, 2013). Being able to identify soil variables that are related spatially or temporarily allows greater opportunity to understand the mechanisms that create the spatial variation (Morkoc et al., 1985). The goal of this work was to identify the presence of cyclic patterns of selected soil variables (BD, WC and OC) induced for transit operations under NT by using a spectral-cospectral spatial approach. The intention is to assess the cyclic pattern produced by tillage and harvesting operation and to use the spatial relationship to describe and predict soil variables under contrasting tillage system with an autoregressive state space model.

2. Material and methods

The study was performed in San Antonio de Areco, 34°15′32.42″S, 59°25′19.93″W, NE of Buenos Aires province, Argentina. The landscape is lightly undulate with moderate to gently slopes, and it was intensively cultivated from more than 80 years. The weather condition is temperate, humid with mean annual temperature of 17 °C and 1000 mm yr^{-1} total precipitation (decade1995-2005). Two soil series are found in the area, Portela silt loam vertic Argiudol and Rio Tala silt loam typic Argiudol (Soil Survey, 1999). Both soils are well-drained and originated on loess material. They are characterized by high fertility, moderate low acidity (pH 6.5), high cation exchange capacity (CEC), high base saturation and large amounts of exchangeable calcium. A typical crop rotation in this region consists of double cropping wheat (*Triticum aestivum* L.) and soybean (*Glycine max* L. Merr.) followed by corn (*Zea mays* L.)-fallow-soybean (*Glycine max* L. Merr.). Sometimes the double cropping wheat/soybean is repeated several times before rotate with corn. The predominant tillage systems in the area are usually no tillage (NT) and even a combination of NT following wheat under moldboard plowing with disc tillage (MT). Usually this situation occurs when crop rotations include pasture for several years. Three different data sets were used in this study; (a) a 100 m long transect in a field under NT with samples taken every 1 m ($\text{NT}_{1\text{m}}$); (b) a 500 m long transect with samples taken every 10- m, in a NT field ($\text{NT}_{10\text{m}}$); (c) a 2740 m long transect across different adjacent farms. The soil samples were spaced every 30-m along this transect ($\text{NT}_{30\text{m}}$) and included one out of third sampled data taken from the $\text{NT}_{10\text{m}}$ for predictive purposes. The sampling scheme was displayed in Figs. 1 and 2(a–c) show the soil bulk density (BD), volumetric water content (WC) and soil organic carbon content (OC) data as was found in the different transect. The soil bulk density was determined by the core method (Blake and Hartge, 1986) using undisturbed soil core samples with a volume of a 310 cm^3 and a length of 7.5 cm. The gravimetric water content was determined from these soil cores after dried in oven at 105 °C and converted to volumetric water content with the corresponding BD values. A second set of soil samples were taken in the same location for measuring the OC, which was determined with Walkey Black procedure (Nelson and Sommers, 1982) (Table 1).

In order to apply a frequency domain analysis of variance components, i.e., spectral and cross-spectral analysis (Shumway, 1988; Nielsen and Wendroth, 2003), only data from $\text{NT}_{1\text{m}}$ transect was used. The frequency domain analysis transforms data to a finite Fourier series that are uncorrelated and have variances equal to the power spectrum. In this way, the presence of multi-collinearity common in soil variables as illustrated in Manns and Berg (2014) is avoided. The power spectrum is the analogue to the analysis of variance, where it is necessary to define the oscillation rate of a time (space) series in terms of its frequency. The total variance in the series is the sum of the variance contributions evaluated at different frequencies (Shumway, 1988). The spectrum formula is as follows:

$$S_{(f)} = 2\int_{0}^{\infty} r(h)\cos(2\pi f h)dh \tag{1}$$

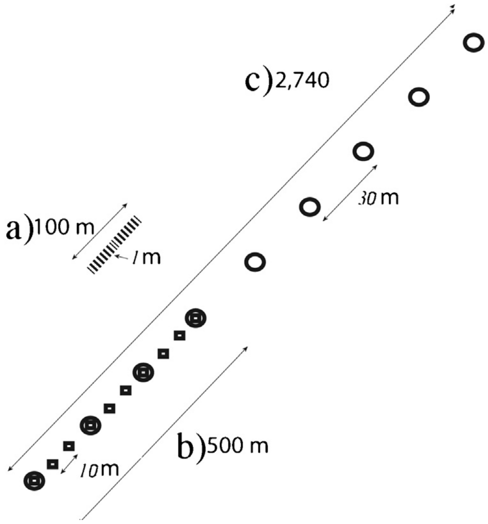

Fig. 1. Sampling scheme of the different transects used in the spatial analysis. (a) 100 m long transect sampled every 1 m; (b) 500 m long transect sampled at 10 m; (c): 2740 m long transect with soil samples taken at 30 m. The scheme is not in scale.