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Short-range and regional spatial variability of soil chemical properties in an agro-ecosystem in eastern Croatia

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ABSTRACT

Spatial and temporal characterization of soil properties in agro-ecosystems is crucial for monitoring the evolution of soil functions and for understanding the main influential processes. Moreover, the objective mapping of soil properties in agro-ecosystems is urgently needed for regional planning purposes and the proper choice of land management practices. In this work, the geostatistical analysis of a dataset of soil properties, derived from 2411 soil samples collected in Vukovar-Srijem County (Croatia), highlighted the multiple benefits of a spatial-statistical approach. The main aim of this paper is to jointly examine short-range (i.e., within-field) and regional spatial variability of several soil chemical properties: soil pH, organic matter (OM), plant available phosphorus (AP) and potassium (AK). The available sampling network, characterized by a set of 2411 (0–30 cm depth) irregularly and field-clustered soil samples, allowed to derivate of two typologies of soil nutrient maps by means of ordinary block kriging: within-field high-resolution maps (block size 250 m) and regional low-resolution maps (block size 2000 m). Soil pH and OM had lower variability compared to AP and AK. The OM content and pH ranged from 1.24% to 5.25% and from 3.69 to 7.84, respectively. Almost 94% of all samples had an OM content below 3%, indicating the need for future adoption of environmentally friendly soil management in this county. The mean values of AP and AK were 173 mg kg^{-1} and 238 mg kg^{-1}, respectively, indicating a moderate supply of these nutrients. Geostatistical analysis revealed that the best-fit models were spherical for pH and AP, with moderate spatial dependency, and exponential for OM and AK, with strong spatial dependency. The within-field high-resolution soil property maps can be used as guidance for site-specific fertilization and liming. In addition, the regional maps derived for larger interpolation support provide quantitative information for regional planning and environmental monitoring and protection purposes. Consequently, the multi-resolution mapping of soil properties and the analysis of their spatial variability highlighted possible connections with influential factors and processes, including the relationships with different soil types. Finally, quantification of the spatial variability of soil properties by means of variogram models constitutes a basis for optimizing soil sample spacing for mapping purposes in the studied region.

1. Introduction

Soil is fundamental for life and biodiversity (Bot and Benites, 2005; Krogh, 2010) and plays a pivotal role in providing vital ecosystem services to support human well-being. Soils influence food availability, quality and security, as well as human contact with various chemicals and pathogens (Brevik and Sauer, 2015). From this perspective, chemical and physical characterization of soil is crucial for understanding the related key functions and potential interactions with the biosphere and anthroposphere. Unfortunately, the extensive characterization of soil properties is a difficult task because, as documented by numerous studies (e.g., Goovaerts, 1998; Hengl et al., 2004, 2007; Liu et al., 2009; Pilaš et al., 2013; Ceddia et al., 2015), soil properties vary in space and time across natural ecosystems. The spatial variability of soil properties in ecosystems is related to ecological, geo-environmental and anthropic forcings and is strictly linked to the five soil-forming factors: climate, organisms, relief, parent material, and time (Jenny, 1941). Soil spatial variability is also critical in agro-ecosystems, causing spatial variability in crop yields (Bogunovic et al., 2014a; Bogunovic et al., 2017) with deep impacts on food and biomass production. Unsustainable soil management practices in agro-ecosystems during the last two centuries have

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led to various phenomena of severe soil degradation with profound consequences for soil productivity (Kisic et al., 2002; Loveland and Webb, 2003; Hamza and Anderson, 2005; Cerdà et al., 2009; Novara et al., 2011; Nawaz et al., 2013; Keesstra et al., 2016). Soil degradation processes are mainly associated with land use, climate change, fertilization, contamination with agrochemicals, misuse of groundwater resources (e.g., Ji et al., 2006), and loss of biodiversity. These negative processes also produce negative impacts on human health (Brevik and Sauer, 2015). Soils are thus under increasing environmental pressure, and this will have consequences for the capacity of the soil to continue to perform its various functions (Brevik et al., 2015). Therefore, spatial and temporal characterization of soil properties in agro-ecosystems is crucial for monitoring the evolution of soil functions and for understanding the main influential processes. Moreover, the objective mapping of soil properties in agro-ecosystems is urgently needed for regional planning purposes and the proper choice of land management practices.

Spatial characterization of soil properties requires the analysis of many related field data that can be collected by means of various direct and indirect methods, such as sampling and chemical analysis, proximal and remote sensing, geophysical methods, etc. Consequently, the collected field data often lead to the generation of complex spatial and spatiotemporal multivariable datasets that are frequently characterized by different levels of coverage and spatial density. To maximize the information retrieved from these data sets, the use of robust spatial statistical methods is necessary (e.g., Hengl et al., 2004, 2007; Rossel et al., 2006; Pereira et al., 2015; Fabbri and Trevisani, 2005a, 2005b; Trevisani and Fabbri, 2010). From this perspective, geostatistical methodologies have a long record of applications in soil sciences (e.g., Yost et al., 1982; McBratney and Webster, 1981, 1986; Burrough, 1983; Collins and Ovalles, 1988; Cambardella et al., 1994; Goovaerts, 1998), in addition to a well-known theoretical framework (Matheron, 1963; Campbell, 1978; Clark, 1979; Huijbregts, 1975; Journel and Huijbregts, 1978). Geostatistical methodology, by means of the family of best linear unbiased interpolators, known as "kriging", offers a rich mapping toolset, enabling maximization of the available information to produce maps of the studied spatial property as well as evaluation of the related uncertainty (e.g., Bogunovic et al., 2014a; Pereira et al., 2015).

Numerous geostatistical studies have been conducted to analyse the spatial distribution of soil physical (e.g., Weindorf and Zhu, 2010; Bevington et al., 2016), chemical (e.g., Bednářová et al., 2016; Wilson et al., 2016) and biological properties (e.g., Cao et al., 2011) across a variety of geographical and ecological settings and spatial scales. In this regard, soil organic matter (OM), soil reaction (pH), plant available phosphorus (AP) and potassium (AK) play important roles in agro-ecosystem productivity and preservation. The spatial analysis of these parameters is relevant given the strong links with soil productivity and anthropic influences (Cambardella et al., 1994; McGrath and Zhang, 2003; Mzuku et al., 2005; Liu et al., 2014).

In the context of Croatia, some studies have been conducted to analyse the spatial variability of soil properties. Hengl et al. (2007) used regression kriging to predict organic matter in the topsoil, while Pilaš et al. (2013) used existing soil database to predict soil carbon stocks at the national level. National-scale spatial variability of soil pH and OM was analysed by Hengl et al. (2004), while Romić et al. (2007) and Sollitto et al. (2010) investigated county-scale spatial variability of heavy metal concentrations. Field-scale spatial modelling of soil AP and AK to provide the most accurate fertility maps was analysed by Bogunovic et al. (2014a). However, studies that address the spatial variability of all four soil properties, i.e., OM, pH, AP and AK, at both the within-field and regional scales are not available. Furthermore, the spatial variability of soil nutrients, pH and OM and their temporal changes in agro-ecosystems of countries such as Croatia are poorly understood.

In this work, the geostatistical analysis of a rich dataset of soil properties in Vukovar-Srijem County (Croatia), highlighted the multiple benefits of the proposed spatial-statistical approach. In a first approach, the quantitative analysis of the spatial variability of soil properties and their mapping is extremely useful for highlighting possible connections with influential factors and for management purposes. Then, the quantification of spatial continuity can be used as the basis for optimizing the sampling density for mapping soil properties at the desired spatial resolution and accuracy (Burrough and McDonnell, 1998). Consequently, the objectives of the present study were to: (i) characterize within-field and regional spatial variability of OM, pH, AP and AK; (ii) analyse possible connections between the spatial patterns of soil properties and the influential factors, such as soil classes; (iii) propose the use of produced maps of soil properties for guiding site-specific land management strategies; and (iv) use the spatial continuity structure for defining sample spacing for mapping purposes.

2. Materials and methods

2.1. Study site

The study was conducted in eastern Croatia in Vukovar - Srijem County (18°30′–19°26′ E, 44°50′–45°29′ N), which covers an area of 2454 km^2. The land use is predominantly arable, while forests cover approximately 700 km^2 (Fig. 1). The studied area has a temperate continental climate; summers are hot and sunny, and winters are cold and snowy. The mean annual temperature is 10.8 $\pm$ 0.69 °C, with average annual precipitation of 654 $\pm$ 208 mm (1961–1990). The warmest month is July (21 °C) and the coldest is January ($-$1.3 °C). The lowest annual rainfall occurs in the easternmost part of the county with an average value of 650 mm, and it gradually increases to 800 mm in the western part of the county (Meteorological and Hydrological Institute of Croatia). Most precipitation falls in spring and the mid-summer period. The mean relative humidity is 79%. Based on relief, the land is predominantly flat with elevation up to 200 m a.s.l. The most dominant soil types are very fertile: Chernozem, typically, and Humogley. The other major soil groups include Regosols on loess (Leptosol, WRB, 2014), Cambisols (Eutric) and Luvisols. Colluvial, Cambisol Distric, Pseudogley (Stagnosols, WRB, 2014), Hypogley and Humogley (Gley soils, WRB, 2014) soils cover limited sections of the studied area. The dominant species used in crop rotation include winter wheat, maize and sugar beet.

2.2. Soil properties dataset

A total of 2411 homogenized soil samples were collected from arable land at a depth of 0–30 cm from 2008 to 2012. Punctual soil samples were collected using a manual soil auger and were georeferenced using a GPS device (Trimble GeoExplorer 6000). The samples were homogenized to obtain samples that represented an area of 1 ha, which represents the data spatial support for the subsequent geostatistical analysis. The samples were placed in plastic bags, air-dried, milled and sieved through a 2-mm mesh before analysis. Soil pH was measured at a ratio of 1:5 (w/v) in a KCl suspension, following the electrometric method, using pH meter (Beckman Φ72). Ammonium lactate solution was used for AP and AK extraction, followed by spectrophotometric and flame photometric analyses, respectively. The soil OM content was estimated using the Walkley and Black (1934) method. In relation to the different requests from financing farmers, under rare circumstances, the chemical analyses were not performed for all soil parameters, leading to slight differences in the number of data points for the different soil properties.

2.3. Statistical and geostatistical analyses

Spatial-statistical analysis of soil properties has been conducted by means of statistical summaries and spatial statistical tools such as classed post maps, variogram cloud (Ploner, 1999) directional variograms and variogram maps (Goovaerts, 1998; Hengl et al., 2004;