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Research paper

Spatial variability of soil properties and cereal yield in a cultivated field on sandy soil

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ABSTRACT

Sandy soils are used in agriculture in different regions of the world. In Poland soils derived from sands occupy about 50% of agricultural area. Productivity of the soils depend on the soil properties that vary in the scale of field. This study aimed at determining and mapping the within-field variation of soil physical and chemical properties and grain yield of oats, rye, oats and triticale in 2001, 2002, 2003, 2015, respectively. The experiment was set up in a field (200 × 50 m) on sandy soil in Trzebieszów (region Podlasie, Poland). The soil measurements included sand, silt, clay, and organic carbon (SOC) contents, cation exchange capacity (CEC), pH in the topsoil (0–10 cm) and subsoil (30–40 cm) layers in 2001, and water content and bulk density in the topsoil layer in spring and summer 2002–2003. The yields of oats were assessed in 2001 and 2003 and those of rye and triticale in 2002 and 2015, respectively. The soil properties and cereal yields were determined at 33–55 points in a grid evenly covering the whole field area. The results were analyzed using classic statistics and geostatistics by constructing semivariograms and 2D mapping by Inverse Distance Weighting (IDW). The cereal grain yields were significantly positively correlated with the topsoil water content (SWC) ($r = 0.295–0.711$), clay content ($r = 0.081–0.174$), and SOC in the subsoil ($r = 0.208–0.271$) and CEC in both layers ($r = 0.123–0.298$) and negatively correlated with bulk density (BD) ($r = –0.065$ to -0.279). The spatial dependence determined by the "nugget-to-sill" ratio was moderate or weak for the silt and clay content, CEC, and pH (29–79%) and strong for SOC, BD, SWC, and crop yield (0.2–13.2%). The effective range of the spatial dependence for all studied quantities varied from 9.9 to 120 m. The cereal yields were positively and significantly correlated between all study years ($r = 0.141–0.734$), which indicates inter-annual similarity in their spatial distribution. The 2D maps based on the IDW allowed assessing how gradual or sharp the changes in the studied quantities from one place to another are. Similar spatial patterns of the SWC, SOC and CEC, and crop yields were observed. This is of importance in precise and sustainable field management aimed at increasing and aligning spatial crop productivity of the studied low-productivity sandy soils that will have to be used in crop production due to the current shortage of land resources and food supplies on a global scale.

1. Introduction

Sandy soils are used in agriculture in many regions of the world (Bronick and Lal, 2005; Schjønning et al., 2009; Jankowski et al., 2011). In Poland, approximately 50% of soils were derived from sands (Białousz et al., 2005; Rutkowska and Pikuła, 2013). Most of the soils show low content of soil organic matter ranging from 1 to 2% (Rutkowska and Pikuła, 2013) and exhibit low water holding capacity and high permeability. Consequently, in rain-fed environments with low and uneven precipitation, sandy soils induce water deficit during the growing season, which largely determines their relatively low productivity. Moreover, these soils have low cation exchange capacity associated with low both clay content and organic carbon content and hence low specific surface area (Usowicz et al., 2004). They are in general acidic ($pH < 5.5$) due to the post-glacial acidified parent material and leaching of exchangeable basic ions (Krasowicz et al., 2011; Behera and Shukla, 2015). On the other hand, they require relatively low energy inputs for tillage (Novák et al., 2014) and warm up quickly in the early spring to get the minimum soil temperature for plant growth. The largest area of sandy soils in Poland is used for cultivation of cereal crops.

Sandy soils are morphologically, chemically, and ecologically spatially variable at various scales (Jankowski et al., 2011; Pedrera-Parrilla et al., 2016). The main sources of the variability are related to soil-forming factors, topography (Jankowski et al., 2011; Silva and Alexandre, 2005), and management practices (Ozpinar and Cay, 2006;

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Ozpinar and Ozpinar, 2015; Gałka et al., 2016). Evaluating and understanding the spatial and temporal variability of the physical and chemical properties of soils and crop yields across a field are required for precise determining the best soil management practices and amendments to improve crop quantity and quality while being environmentally sustainable (Awe et al., 2015; Gajda et al., 2016; Aranyos et al., 2016). The within-field variability is an important source of uncertainty in crop production (Diacono et al., 2013). The use of geostatistical analysis facilitates identification of soil spatial variability in un-examined sites (Nielsen and Wendroth, 2003) and increases the accuracy of modeling soil behavior fluctuations (Serrano et al., 2010; Behera et al., 2011). Most studies dealing with spatial variability of soil properties in relation to crop yields were performed on more productive finely textured than coarsely textured soils although they are largely used in crop production.

The major objective of this study was therefore to determine the spatial variability of selected physical and chemical properties including the content of textural fractions, water, bulk density, organic carbon, cation exchange capacity, pH, and cereal grain yield in the field-scale on sandy soil in a four-year experiment. The specific objectives were to (i) identify soil properties that control cereal yields in different weather conditions during the growing season (ii) mapping soil properties and crop yields across the field using Inverse Distance Weighting.

2. Materials and method

2.1. Study area

The experimental field (200 × 50 m) is situated in Trzebieszów, region Podlasie, Poland (51°59'09.8“N 22°33'57.5“E) within a private farm. The region consists mostly of Podzol soils (WRB, 2015) derived from sandy and sandy loams of glacial origin, which are considered the least productive soils of Poland. More than 60% of the region area is used for crop production. A conventional tillage system after cereal harvest consists of stubble tillage (10 cm) using cultivator plus tooth harrows (1st half of August), moldboard ploughing (20–25 cm) and disking (10 cm) (2nd half of August) and tooth harrow (6 cm) to prepare seedbed for winter cereals (2nd half of September). As to spring crops moldboard ploughing (20–25 cm) is applied in late autumn and then in spring tillage operations similar as with winter cereals to prepare seedbed. Such tillage system is commonly used in the study area. Crop rotation includes mostly cereals and, intermittently, potatoes and legume species. The use of relatively light wheel tractors of about 2.5 to 3.5 Mg mass and combine harvesters of 7 to 10 Mg does not cause severe soil compaction. The stresses applied to the soil by the machinery range from about 30 to 80 kPa. The mineral fertilization was uniform on the whole field at an amount of 30–50 kg N ha^{-1}, 15–30 kg P ha^{-1}, and 20–30 K kg N ha^{-1}. The present management practices have been used for more than 30 years.

2.2. Weather

Fig. 1 illustrates the course of monthly mean air temperatures and rainfall sums for the years 2001, 2002, 2003, and 2015 in the study site. Average temperatures during the growing season (April-September) and annual temperatures in the successive years were 14.8, 15.8, 15.1, and 15.2 °C and 8.0, 8.7, 7.7, and 9.4 °C, respectively. The growing season temperatures in 2002, 2003, and 2015 proved to be among the highest during the past 50-year period for which the maximum was 16.3 °C. The respective sums of growing season and annual precipitations were 404, 285, 263, and 329 mm and 610, 550, 442, and 526 mm. The growing season precipitation rates in 2002, 2003, and 2015 were below the long-term average (567 mm).

2.3. Soil sampling and analysis

In 2001, we determined the textural composition with the sedimentation method of Bouyoucos's with modifications by Casagrande and Prószyński, (ISO, 1995), organic carbon content with the Tiurin titration method (Ostrowska et al., 1991), cation exchange capacity by neutralization of acidic groups with a barium chloride solution (ISO, 1995), and pH in 1 M KCl using a complex electrode Orion Research in the topsoil (0–10 cm) that was assumed to be representative for relatively uniform plough layer (0–25 cm) and subsoil layer (30–40 cm). Bulk density in cores of 100 cm^3 and a height of 5 cm was measured with the method developed by Blake and Hartge (1986) and the soil water content was assessed with a Time Domain Reflectometry meter (Malicki, 1990) in the topsoil layer in the spring and summer (just after harvest) in 2002 and 2003. The soil measurements were done at 50–55 points in a grid evenly covering the whole field area. Taking into consideration total area of the experimental field (1 ha) one measurement point corresponded to plot area of 182–200 m^2. The grain yields of physiologically similar cereals including oats (*Avena sativa*) (in 2001 and 2003), rye (*Secale cereale*) (in 2002), and triticale (*Triticosecale* Wittmack) (in 2015) were measured in 27–33 one-square-meter plots. In this case one measurement point corresponded to plot area of 303–370 m^2. Conducting of the experiment in the two stages (i.e. 2001–2003 and 2015) allowed assessing the effect of applying more frequent organic manure in the time span 2004–2015 on soil quality of the low productive soils. Completed in 2003 investigations were resumed in 2015 in the frame of the iSQAPER project (Horizon 2020) concerning assessment of soil quality in time and space. In this project our experimental field was accepted as a representative study site for sandy soils in continental climate. The cereals largely contribute in crop rotation of the region. Fig. 2 presents the spatial distribution of the measurement points of the soil properties and grain yields.

2.4. Geostatistical analysis

Basic statistical parameters i.e. the mean value, standard deviation, coefficient of variation (CV), and the maximum and minimum values for soil properties and crop yields were determined. The spatial dependence and variation of the quantities, $z(x_i)$ was studied with the help of semivariogram ($\gamma(h)$) that was calculated from the following equation:

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

where: $N(h)$ is the number of pairs of points distant from each other by h. The nugget values, sills, and ranges of spatial autocorrelation were determined, semivariogram models were fitted to the empirical values, and model fitting parameters were determined (Gamma Design Software, 2008):

$$\gamma(h) = C_0 + C[1 - \exp(h/A_0)]$$

where, $\gamma(h)$ semivariance for internal distance class h, h − lag interval, C_0–nugget variance ≥ 0, C − structural variance $\geq C_0$, A_0–range parameter. In the case of the exponential model, the effective range for the major axis is equal $3A_0$, which is the distance at which sill ($C_0 + C$) is within 5% of the asymptote. Proportion $C_0/(C_0 + C)$ is a measure of the proportion of sample variance ($C_0 + C$) that is explained by spatially structured variance C. This value will be 0 for a semivariogram with no nugget variance (where the curve passes through the origin); conversely, it will be 1.0 where there is no spatially dependent variation at the range specified. According to Chien et al. (1997), the spatial dependence ($C_0/(C_0 + C)$) < 25%, 25–75% and > 75% are strong, moderate, and weak, respectively.

To generate 2D maps of the studied quantities, the IDW (Gamma Design Software, 2008) was used: