Eurasian J Soil Sci 2016, 5 (3) 192 - 200

Eurasian Journal of Soil Science

Journal homepage : http://fesss.org/eurasian_journal_of_soil_science.asp

Spatial variability of soil physical properties in a cultivated field

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Article Info

Received : 10.10.2015
Accepted : 21.01.2016

Abstract

Spatial variability of soil physical properties in a cultivated field such as; bulk density (BD), penetration resistance (PNT), saturated hydraulic conductivity (Ks), field capacity (FC) and permanent wilting point (PWP), were determined by geostatistical method. While BD values varied between 1.12 and 1.41 g cm^{-3}, PNT resistance (0.66 to 1.88 MPa), clay content (31.48 to 43.97%), Ks (1.46 to 3.37 mm h^{-1}), FC (30.40 to 39.66%) and PWP (19.22 to 24.42%) values showed variations with soil cultivation. In kriging interpolation for the spatial variability of soil properties, the biggest r^2 and cross validation r^2 values were determined with spherical model for PNT, Ks, FC values, and exponential model for clay, BD and PWP. Spatial dependences of the properties, except BD, were found to be strong in the field. Ks values significantly increased with increasing BD (0.340*), and decreasing clay content (-0.905**) and PNT (-0.288*) values in the field. Spatial variations of soil physical properties in the field are generally controlled by the particle size distribution as a fundamental factor. Heterogeneity and variation of soil physical parameters in a field due to soil plowing should be taken into consideration for a successful agricultural management.

Keywords: Tillage, spatial variability, soil physical properties, kriging

Introduction

There are several spatially variable factors influencing crop yields. These are usually soil related, anthropogenic, topographic, biological, and meteorological factors (Tanji, 1990; Corwin, 2012). Knowledge of the spatial variation of soil properties is important for crop production in precision agricultural management systems. It has been known that most soil properties are spatially variable in a field (Burrough, 1993). Iqbal et al. (2005) reported that spatial variability of soil properties in any field position is inherent in nature due to geologic and pedologic soil forming factors, but some of the variability may be induced by tillage and other management practices. Benefits from soil tillage are known as i) improvement of soil-air-water relations in seedbeds, ii) control of undesired vegetation, and iii) reduction of the mechanical impedance to root growth (Gardner et al., 1999). Skuodiene et al. (2013) determined that the shallow ploughing and shallow ploughless tillage treatments contained more weed seed species in the soil compared with the deep ploughing treatment. Soil tillage practices causes changes to soil structure and hydraulic properties dynamically in space and time (Mueller et al., 2003; Strudley et al., 2008). The ordinary kriging is one of the most common methods in spatial interpolation of soil properties after estimating semivariogram parameters of soil properties using geostatistical tools (Goovaerts, 1998; Utset and Cid, 2001; Castrignanò et

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e-ISSN: 2147-4249 DOI: http://dx.doi.org/10.18393/ejss.2016.3.192-200

al., 2003; Zhao et al., 2009; Zhao et al., 2015). Tsegaye et al. (1998) studied the intensive tillage effects on spatial variability of soil physical properties such as; particle size, bulk density, soil strength, mean pore size and saturated hydraulic conductivity. They reported that all soil physical properties, except saturated hydraulic conductivity, were weakly spatially dependent for the 6 to 9 cm depth, and moderately spatially dependent for 27 to 30 cm soil depth. Although the major purposes of tillage are to reduce bulk density and soil strength and to control pests and diseases, soil cultivation may lead to the formation of a hard pan below the plough layer that restricts root penetration and downward movement of water, therefore zero or minimum till practices must be carried out in these areas. (Singh and Singh, 1996). Özsoy and Aksoy (2007) reported that soils, especially having vertic soil properties, must have a good and right soil management for a long term productivity. Inappropriate soil tilling and using unsuitable instruments, firstly cannot manage healthy plant growth and cause soil degradation in long time periods.

Strudley et al. (2008) reviewed tillage effects on soil hydraulic properties in space and time, and stated that zero tillage practices generally increase macropore connectivity and saturated hydraulic conductivity while generating inconsistent responses in total porosity and soil bulk density compared with conventional tillage practices. Specific management effects are often overshadowed by spatial and temporal variability, and differences in temporal variability depend on spatial locations between rows, within fields at different landscape positions, and between sites with different climates and dominant soil types. They reported that soil hydraulic properties are influenced by most tillage practices immediately, but these effects can diminish rapidly. Hangen et al. (2002) watched the infiltration of dye tracer (methylene blue) on small plots in sandy and silty loams under conventional tillage and minimum tillage. They found that dye stains were much deeper under minimum tillage than conventional tillage, indicating greater vertical connectivity of the macropore network.

The objective of this study was to determine changes in spatial variability of some physical properties of Vertic Haplustoll on a small-scale part of cultivated field by geostatistical method. Haplustolls are the great group of Ustoll suborders of Mollisols which are naturally fertile soils, because they are rich in humus that stores mineral nutrients, water and have a strong structured surface layer including high organic carbon content (Soil Survey Staff, 1999). Ustolls are common throughout the Middle and Eastern parts of Black Sea Region and Eastern Anatolia of Turkey. Soil fertility of Mollisols in Turkey are restricted by their shallow soil depth and erosion problem due to moist climate properties of the region and slope factor. Therefore, if these lands are used in agriculture, much more attention should be paid for the erosion, cultivation, fertilization and irrigation by the decision makers, planners and farmers in order to produce the new management plans economically regarding the soil type.

Material and Methods

This study was carried out on Vertic Haplustoll in the Experimental Field having a 4% slope north to south (41º21´ N, 36º10´ E) direction in Ondokuz Mayis University, Samsun-Turkey. Conventional tillage was used with a mouldboard plough at a depth of 15 cm in 4 ha size field in November 2010. Soil properties were measured in a randomly selected small-scale plot near the center of the field 20 days after soil plowing. The measurements in 49 different soil sampling points were made in a square grid at 5 m spacing in the 30 x 30 m^2 plot. A hand-pushing penetrometer (Eijkelkamp) was used for the measurements of penetration resistance with a cone diameter of 15.96 mm and the cone base area of 2 cm^2. The PNT measurements in each soil sampling point were made pushing vertically the penetrometer to the soil at an approximated speed of 3 cm/s up to 15 cm with five replicates (Bradford, 1986). After determining the bulk density (BD) by undisturbed soil core method (Demiralay, 1993), total porosity (F) was calculated using the equation; F=1-(BD/2.65). Saturated hydraulic conductivity (Ks) values of the soils were measured with the constant head method (Richards, 1954). Moisture contents at the field capacity (FC) and the permanent wilting point (PWP) were determined equilibrating soil moisture of the saturated samples on the ceramic pressured plates at 33 kPa for 24 hours and 1500 kPA for 96 hours, respectively (Tüzüner, 1990). Particle size distribution of the surface soil samples (0-15 cm depth) was determined by hydrometer method (Demiralay, 1993). Organic matter contents of the samples were analyzed by Walkley-Black method (Kacar, 1994).

The geostatistical analyses were performed with the GS+ version 9, and the correlations among the soil properties were calculated using SPSS program. The semivarince describing degree of spatial dependence of random variable Z(xi) over a certain distance was estimated from (Trangmar et al., 1985): ($\gamma(h)$)

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

Where γ(h) is the semivariance for the interval distance class h, N(h) is the number of pairs, Z(xi) and Z(xi + h) are the measured sample values at position i and (i + h), respectively. Models used in the study to estimate semivariograms are given in below:

Exponential model: $$\gamma(h)=\begin{cases} C_0 + C\left[1-\exp\left(-\frac{h}{a}\right)\right] & h \le a \\ C_0 + C & h > a \end{cases}$$

Spherical model: $$\gamma(h)=\begin{cases} C_0 + C\left[\frac{3}{2}\left(\frac{h}{a}\right)-\frac{1}{2}\left(\frac{h}{a}\right)^3\right] & h \le a \\ C_0 + C & h > a \end{cases}$$

Where, C_0: nugget variance, C: structural variance, (C_0+C): sill value of semivariogram, a: range of spatial correlation (Samra et al., 1988).

Results

Descriptive statistics for the soil physical properties in 15 cm soil depth of the cultivated field are given in Table 1. In 15 cm soil depth of the cultivated field, while bulk density values varied between 1.12 and 1.41 g cm^{-3}, PNT resistance varied between 0.66 and 1.88 MPa (Table 1). Also, clay (31.48 to 43.97%), silt (14.49 to 36.38%), sand (30.11 to 47.57%), organic matter (2.03 to 2.98%), Ks (1.46 to 3.37 mm h^{-1}), FC (30.40 to 39.66%), PWP (19.22 to 24.42%), AWC (8.67 to 15.65%) and gravimetric water content (15.19 to 32.56%) values showed variations among the sampling points in the field.

Table 1. Descriptive statistics for the soil properties.

	Minimum	Maximum	Mean	Std. Dev.	CV, %	Skewness	Kurtosis
Clay, %	31.48	43.97	38.31	2.92	7.62	0.030	-0.785
Silt, %	14.49	36.38	22.54	3.42	15.17	1.266	4.907
Sand, %	30.11	47.57	39.15	3.74	9.55	0.209	-0.463
OM, %	2.03	2.98	2.52	0.23	9.13	-0.254	-0.419
BD, g cm^{-3}	1.12	1.41	1.27	0.067	5.28	0.016	-0.109
PNT, MPa	0.66	1.88	1.12	0.275	24.55	0.739	0.849
Ks, mm/h	1.46	3.37	2.28	0.52	22.81	0.267	-0.988
FC, %	30.4	39.66	34.44	2.40	6.97	0.239	-0.682
PWP, %	19.22	24.42	21.76	1.53	7.03	0.332	-1.197
AWC, %	8.67	15.65	12.68	1.86	14.67	-0.201	-0.796
W, %	15.19	32.56	24.32	3.24	13.32	-0.069	0.681

OM: organic matter, BD: bulk density, PNT: penetration resistance, Ks: saturated hydraulic conductivity, FC: field capacity, PWP: permanent wilting point, AWC: available water content, W: gravimetric water content

To evaluate the spatial variability of the soil physical properties, the exponential model for clay content, BD, PWP, and the spherical model for PNT, Ks and FC were selected with their biggest r^2 values and the smallest reduced sums of squares (RSS) values using the GS+ 9 package program (Table 2). The semivariograms of the soil properties indicated that the range in spatial correlation varied among soil properties (Figure 2). The shortest range (10.24 m) was observed for FC and the longest range (80.19 m) was observed for clay content. According to the results, the ranges of spatial influence for the soil physical properties were generally ≤ 80 m for clay, ≤ 38 m for PWP, ≤ 20 m for BD and Ks, and ≤ 12 m for PNT and FC.

Block-kriged maps of the soil properties were created by GS+ 9 program (Gamma Design, 2010), using 0.32 x 0.32 m^2 grid system with 8836 points (Figure 3). Clay content in soil generally increased in the east to west direction of the plot. On the contrary, high BD is found in the eastern part of the plot. While clay content and PNT values decreased at the center of plot, Ks values increased in the same positions of the study area. Water content at FC and PWP values increased in the south east and the western part of plot where the clay content in soil was high. The correlation matrix among the soil properties are given in Table 3.

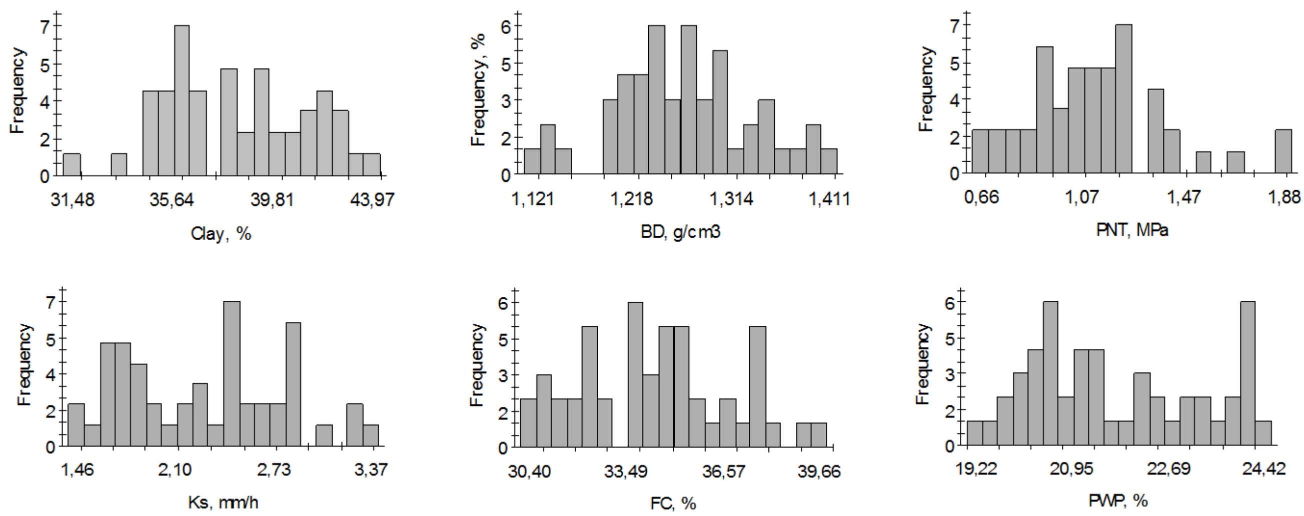

Figure 1. Frequency distribution of the soil physical properties.

Table 2. Semivariogram models and parameters for the soil properties.

	Model	Nugget, (C_0)	Sill, (C_0+C)	C_0/(C_0+C)	a	r^2	RSS	Cross Val. r^2
Clay	Exponential	3.750	28.490	13.16	80.19	0.723	16.20	0.541
BD	Exponential	0.00269	0.00599	44.91	19.67	0.786	7.68E-7	0.122
PNT	Spherical	0.0054	0.00807	6.70	12.17	0.533	3.73E-4	0.151
Ks	Spherical	0.050	0.313	15.97	18.40	0.635	9.39E-3	0.523
FC	Spherical	0.030	5.752	0.52	10.24	0.365	2.50	0.275
PWP	Exponential	0.950	4.910	19.35	37.41	0.814	0.787	0.443

Table 3. Correlation matrix among the soil properties

	Si	S	OM	BD	PNT	Ks	FC	PWP	AWC	W
C	-0.313*	-0.495**	0.365**	-0.365**	0.367**	-0.905**	0.497**	0.915**	-0.114	-0.347*
Si		-0.671**	0.157	0.149	0.032	0.596**	-0.165	-0.260	0.001	0.066
S			-0.429**	0.148	-0.316*	0.161	-0.236	-0.477**	0.089	0.211
OM				-0.286*	0.079	-0.105	0.303*	0.340*	0.111	-0.289*
BD					0.366**	0.340*	-0.761**	-0.577**	-0.505**	0.154
PNT						-0.288*	-0.139	0.209	-0.351*	-0.408**
Ks							-0.479**	-0.825**	0.063	0.259
FC								0.631**	0.768**	-0.156
PWP									-0.012	-0.414**
AWC										0.141

**correlation is significant at 0.01 level, *correlation is significant at 0.05 level. (C: clay, Si: silt, S: sand, OM: organic matter, BD: bulk density, PNT: penetration resistance, Ks: saturated hydraulic conductivity, FC: field capacity, PWP: permanent wilting point, AWC: available water content, W: gravimetric water content)

Discussion

Soil properties having a coefficient of variation (CV) between 0 and 15 % are considered least variable, 15 and 35 %, moderately variable, and bigger than 35 % highly variable (Ogunkunle, 1993). The CV values of the soil properties indicated that PNT (24.55%) and Ks (22.81%) were more variable in the field than BD (5.28%), FC (6.97%), PWP (7.03%) and clay (7.62%). Skewness and kurtosis values and frequency distributions for clay, BD, PNTR, Ks, FC and PWP indicated that the soil properties usually showed normal distribution (Table 1, Figure 1). Therefore, the original values of soil properties were not transformed. Warrick and Nielsen (1980) reported that the spatial variability of the static soil physical properties is commonly fitted to normal probability distributions; whereas the dynamic properties, related to water or solute movement, are usually lognormally distributed. Veronese-Junior et al. (2006) reported that coefficient of variation for PNT values for Brazilian Ferralsol decreased from the surface layers (52.31%) to the deepest layers (15.18%), and PNTR and moisture content values showed normal distribution. Utset and Cid (2001) found that PNT and BD in 30 x 30 m² plot of Rhodic Ferralsol are normally disturbed.

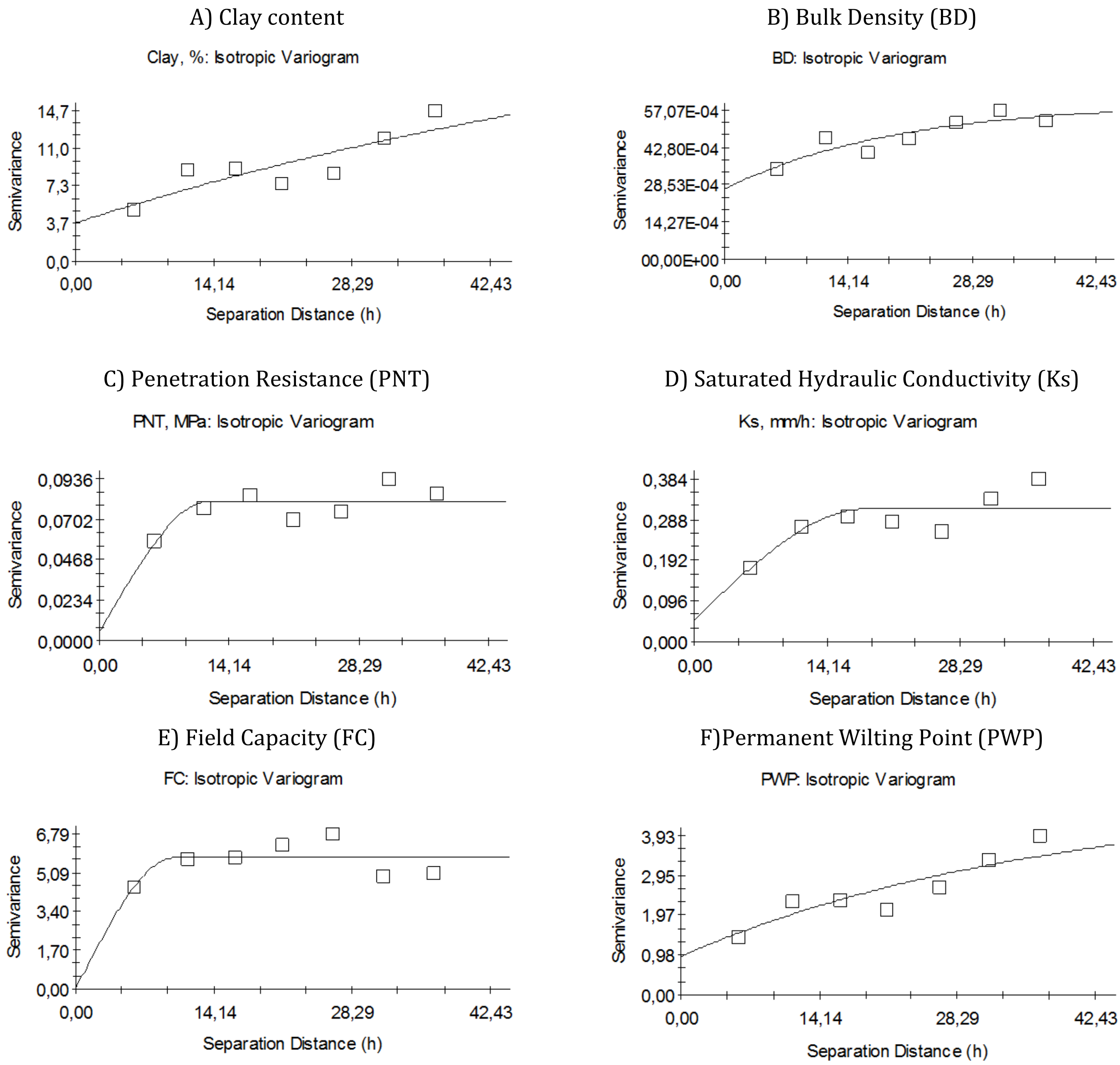

Figure 2. Isotropic variograms and models for the soil properties.

The range indicates the distance in a field where measured properties are no longer spatially correlated. Measured properties of the samples at a distance less than the range become more alike with decreasing distances between them (Tabi and Ogunkunle, 2007). The similar range for BD and Ks may be related to the interaction between soil structure and water flow. The nugget effect, which represents random variation caused mainly by the undetectable experimental error and field variation within the minimum sampling space (Cerri et al., 2004; Aşkın and Kızılkaya, 2006), was higher in clay content than in the other soil properties. Generally, the nugget values close to zero for the physical properties revealed that all variances of the soil properties were reasonably well explained at the sampling distance used in this study by the lag. A variable has strong spatial dependency if the ratio of nugget/sill is equal or less than 25%, moderate spatial dependency if the ratio is between 25 and 75%, and weak spatial dependency if the ratio is greater than 75% (Cambardella et al., 1994; Bo et al., 2003). Generally, strong spatial dependency of soil properties is related to structural intrinsic factors such as texture, parent material and mineralogy, and weak spatial dependency is related to random extrinsic factors such as plowing, fertilization and other soil management practices (Zheng et al., 2009). The ratios of nugget/sill in the soil physical properties, except BD, were less than 25% in

Table 2. Therefore, spatial dependence for these soil properties was strong. Spatial dependence of BD was moderate due to having 44.91% nugget/sill ratio. This indicates that soil plowing as an extrinsic factor weakened spatial dependency of BD in the field.

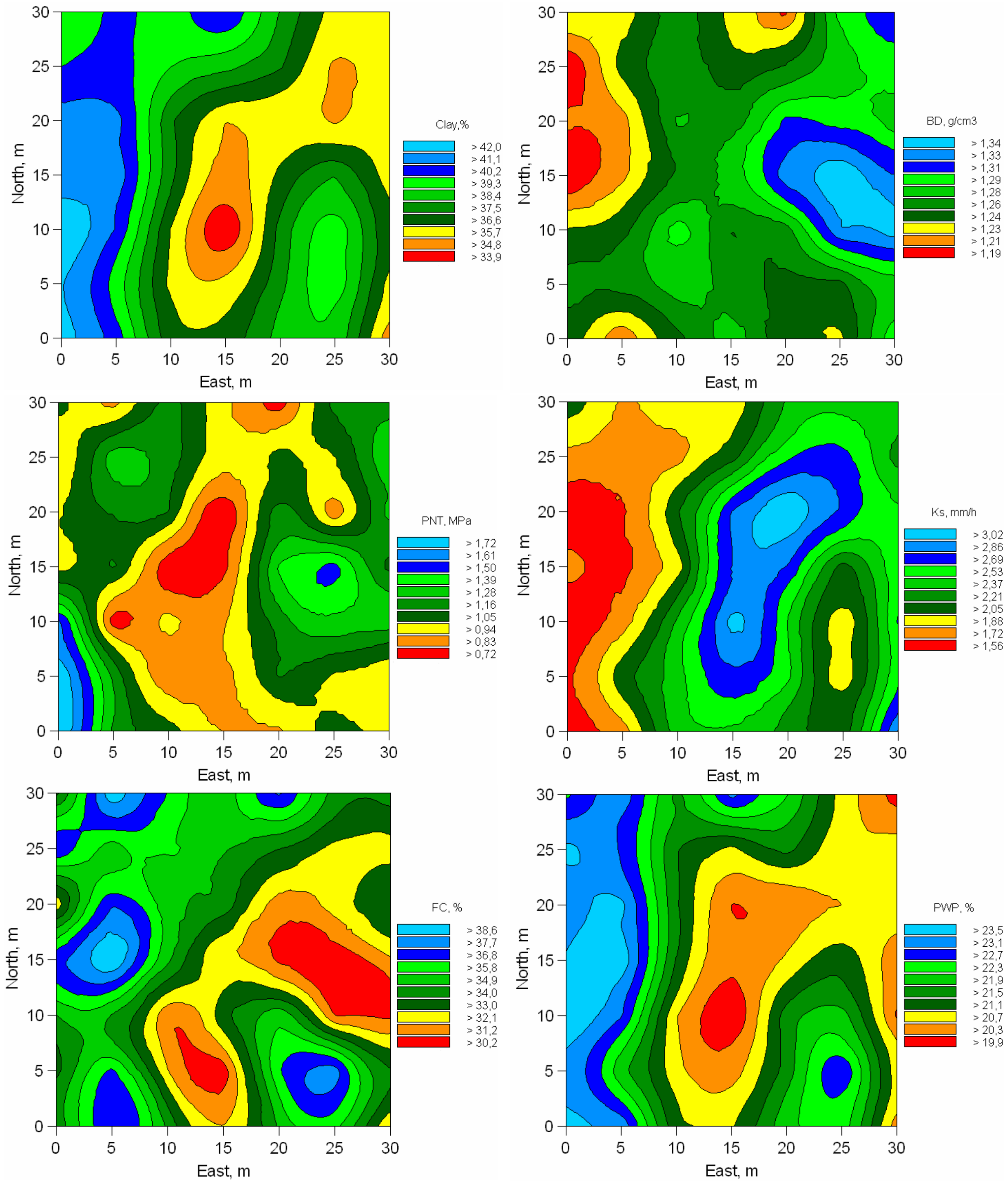

Figure 3. Block kriged maps for clay content, bulk density (BD), penetration resistance (PNT), saturated hydraulic conductivity (Ks), field capacity (FC) and permanent wilting point (PWP).

Cambardella et al. (1994) studied field-scale variability of physical and chemical soil characteristics at two sites undergoing different tillage practices in central Iowa. Soil bulk density on the conventional tillage site was moderately spatially dependent (nugget effect = 37%, range = 129 m), while bulk density at the no till site was also moderately spatially dependent for both the 0–7.5 cm and 7.5–15 cm sampled depths (nugget effects= 30% and 25%, ranges = 223 m and 115 m, respectively). In another study, Utset and Cid (2001) measured penetrometer resistance (PNT) in a deep clay soil immediately after tillage and before sugar cane seeding. They found that PNT semivariance was higher for dry soils and shows almost a pure nugget effect with an 80 m range, while irrigation yields a spatial structure with a range of about 8–10 m. PNT was spatially correlated with bulk density after irrigation. Cressie and Horton (1987) found that there was a strong spatial dependence (12 m lag distance) in infiltration rates for a silty clay loam undergoing moldboard plowing and chisel plow and no till had no spatial dependence over the same lag distance. van Es (1993) reported that the tillage effects on infiltration varied temporally within a season, and spatially within fields and between rows, under plowed and ridge-tilled corn. In another study, van Es et al. (1999) found that tillage effects were greatest for medium and fine textured soils, and spatial variability in water retention parameters was significant.

Bulk density had significant negative correlations with clay (-0.365**) and organic matter content (-0.286*) (Table 3). It is known that the variation in bulk densities is the result of differences in soil texture, organic matter contents and management practices (Wolf and Snyder, 2003). Penetration resistance is an empirical, easy and cheap measurement technique of soil strength, and widely used to assess soil compaction and the effects of soil management (O'Sullivan et al., 1987; Castrignanò et al., 2002). Critical PNT for successful root development in soil is about 1.7 MPa or 2.0 MPa (Canarache, 1990; Arshad et al., 1996). PNT values in this study reached to these critical levels in the south western and the eastern part of the plot. PNT had the significant positive correlations with clay content (0.367**) and BD (0.366**), and significant negative correlations with AWC (-0.351*) and gravimetric water content (-0.408**) (Table 3). Veronese-Junior et al. (2006) similarly reported that PNT values increased with decreasing soil moisture content. Utset and Cid (2001) determined that the PNT on a Rhodic Ferralsol over a 30 m x 30 m area after irrigation practices was considerably affected by the soil moisture condition, bulk density and micro topography.

Ks had significant negative correlations with clay content (-0.905**), PNT (-0.288*), FC (-0.479**) and PWP (-0.825**), and significant positive correlations with Si content (0.596**) and BD (0.340*) (Table 3). Candemir and Gülser (2012) determined that saturated hydraulic conductivity significantly increased with increasing sand and silt content and decreasing clay content. Iqbal et al. (2005) found that increased Ks values in surface horizons could be due to lower bulk density owing to the presence of root channels and macroporosities.

Both FC and PWP gave significant positive correlations with clay and organic matter content, and significant negative correlations with BD and Ks (Table 3). Iqbal et al. (2005) determined that the area in kriged maps with higher sand content had higher Ks values and lower clay content and lower water content at FC and PWP. In this study, spatial variations of soil hydraulic properties are generally controlled by the particle size distribution, especially clay content, as a fundamental factor.

Conclusion

According to the CV values, PNTR and Ks showed more variation in the field when comparing with the other soil physical properties. Generally, the range or the distance of spatial dependence for the soil physical parameters, except clay and PWP, varied between 10 m and 20 m. These are the distance between two sample-collecting points for soil hydraulic properties in the field. While the BD had moderate spatial dependence, the other soil physical properties had strong spatial dependence. Strong spatial dependency of the soil hydraulic properties (Ks, FC, PWP) may be attributed to clay content, and moderate spatial dependency of BD can be attributed to effect of soil tillage. There were strong relationships between the soil physical and hydraulic properties. Kriged maps illustrated positional similarity between the soil physical properties along the small scale plot of cultivated field.

As a result, soil hydraulic properties showed high spatial variability even if in 0.1 ha of small-scale plot in the field cultivated for preparing suitable seed bed and plant growth soil conditions. Therefore, expected yield from a field not only depends on soil fertility parameters, but also depends on variation of soil physical and hydraulic properties. In precision agricultural practices, heterogeneity and variation of soil physical parameters in a field due to soil plowing should be taken into consideration with other affecting factors for a successful site specific management.

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