GEOSTATISTICAL APPROACH TO DETERMINE THE EFFECTS OF DIFFERENT SOIL TILLAGE METHODS ON PENETRATION RESISTANCE IN A CLAYEY SOIL

KİLLİ TOPRAKTA FARKLI TOPRAK İŞLEME YÖNTEMLERİNİN PENETRASYON DİRENCİNE ETKİSİNİN BELİRLENMESİ İÇİN JEOİSTATİSTİKSEL BİR YAKLAŞIM

Assist.Prof.Dr. Selvi K.Ç.*[1], Assoc.Prof.Dr. Sağlam M[2], Prof.Dr. Dengiz O[2]
[1]Department of Agriculture Machinery and Technologies Engineering, Faculty of Agriculture, Ondokuz Mayıs University, Atakum, Samsun / Turkey;
[2] Department of Soil Science and Plant Nutrition, Faculty of Agriculture, OndokuzMayıs University, Samsun / Turkey
Tel: + 90362312199 / 1259; E-mail:kcselvi@omu.edu.tr

Keywords: *tillage methods, penetration resistance, geostatistical approach*

ABSTRACT

In this study carried out in 2011 and 2012, the effects of four different tillage practices [plow + disc harrow + rotary tiller + direct seeding machine (TP_1), chisel + disc harrow + rotary tiller + direct seeding machine (TP_2), plow + rotary tiller + direct seeding machine (TP_3), direct drilling (TP_4)] and control plot without planting (TP_5) on the soil bulk density (BD), moisture content and penetration resistance of a clayey textured soil were evaluated in the central Black Sea Region of Turkey with a geostatistical approach. The values of soil compaction indicators were significantly greater under the TP_4 treatment than in the case of TP_1 and TP_2 after harvest, especially at 20-40 cm depth in 2011 and 2012. Overall, our results suggest the avoidance of direct seeding practices in high clay content soils.

ÖZET

Bu çalışma ile 2011-2012 yıllarında, Türkiye'nin Orta Karadeniz Tarımsal Bölgesinde killi bünyeye sahip bir toprakta, dört farklı toprak işleme metodunun [(pulluk+diskaro+rotatiller+doğrudan ekim makinası;(Tİ$_1$), çizel+diskaro+rotatiller+doğrudan ekim makinası;(Tİ$_2$), (pulluk+rotatiller+doğrudan ekim makinası; (Tİ$_3$) ve doğrudan ekim; (DE)] ve ekim yapılmayan kontrol parselinin hacim ağırlığı, nem içeri ve penetrasyon direncine etkileri jeo-istatistiksel yaklaşım metodu ile değerlendirilmeye çalışılmıştır. Bu çalışmanın sonuçlarına göre ağır bünyeli topraklarda Doğrudan Ekim (DE) uygulamasından kaçınılması gerektiği söylenebilir.

INTRODUCTION

Soil is one of the necessary requirements for human existence and an essential contributor to human civilization. It is a fundamental prerequisite for agricultural production and is closely connected with food supply *(Badalikova B., 2010)*. Compacted soil can be a serious problem in agriculture as it can restrict access of the root system to water and nutrients, thus decreasing crop yields *(Clark et al. 2003).* Sustainable use of agricultural lands for optimal plant production is closely related to agricultural practices. Many soil properties are affected to some degree by soil management practices *(AksakalandÖztaş, 2010)*. Soil tillage, which requires high-energy inputs at considerable expense, creates favourable conditions for good stand establishment and development, and crop yields. Tillage practices play a crucial role in soil conservation *(El Titi., 2003)*. One of the main goals of soil tillage is to influence soil processes, predominantly modification of soil chemical, physical and biological properties *(Badalikova B., 2010; Botta et al., 2010).* However, from soil preparation to harvest, field operations can damage soil structure by compaction which is a major problem for agricultural lands *(Stafford and Hendrick, 1988)*.

Soil compaction is basically the reduction in volume of a given soil mass. It is commonly defined as an increase in soil bulk density (BD) that is manifested through closer packing of solid particles, and decreased porosity, especially the proportion of large pores *(Arslan S., 2006; Pınar et al, 2008; Çelik A., 2011)*. The relationship between soil compaction and penetration resistance (PR) has been described in many studies *(Utsetand Cid, 2001; Kılıç et al, 2004; Hamza and Anderson, 2005; Arslan S., 2006; Carrara et al, 2007; UsowiczandLipiec, 2009).* Soil compaction is an important physical limiting factor for root growth and plant emergence and is one of the major causes of reduced crop yield in worldwide *(Utsetand Cid, 2001; Hamza and Anderson, 2005; Pınar et al. 2008; Tekin et al, 2008)*. In soils compacted to more than 2 MPa resistance, root growth is extremely difficult *(Botta et al, 2006).* Sometimes, however, compaction is desirable, because it can lead to improved seed-soil contact, and hence better germination and growth of the seedling *(Çelik İ., 2011).*

As far as the determination of soil compaction and related soil properties, the determination of these properties and the spatial distribution of the soil compaction level in the vicinity are of great importance in terms of effective soil management practices. For precision agriculture applications, it is essential to determine the level of yield and productivity parameters change, including soil compressibility, and to prepare area indicator maps.

Geostatistical techniques, together with classical statistics, constitute an important tool in determining the spatial effects of soil management practices *(Usowicz andLipiec, 2009).* Traditional statistics assume that the spatial variability of soil is random and without spatial correlations, therefore they are not suitable for analysing spatially varying soil properties. However, geostatistical techniques accept that samples taken in close proximity are generally more similar than samples taken from a greater distance apart, and spatially analyse the relationships between soil properties *(Isaaksand Srivastava, 1989)*. Spatial continuity exists in most earth science data sets. Two data in close proximity are more likely to have similar values than two data that are far apart *(Isaaksand Srivastava, 1989)*. Geostatistical techniques can be divided into two groups, namely semivariogram for spatial modelling and kriging for spatial interpolation. To estimate the unsampled values, it is essential to know the semivariogram function associated with the soil properties evaluated. Kriging is a statistical procedure for interpolating values at unsampled locations between locations with measured values. It is one of many procedures available to estimate unknown values within a domain based on already known values *(Nielsen and Wendroth, 2003).* Geostatistical techniques have become widely used for the analysis of soil data *(Lopez-Granados et al, 2005; Sağlam M., 2015).*

Knowledge of the spatial distribution of PR can be helpful in identifying zones with soil compaction (strength) problems and developing management strategies that minimize the harmful impacts of infield traffic on crop production. The aim of this study was to examine the effects of different soil tillage methods on PR by using geostatistical techniques.

MATERIAL AND METHODS

The experiment was conducted on alluvial soil at the Karadeniz Agricultural Research Institute, Samsun, Turkey in 2011 and 2012. Average annual rainfall was 1045.2 mm. The soil of the study area had a clayey texture (67% clay, 18% silt and 15% sand) and according to its soil taxonomy, it was classified as Vertisol *(Soil Survey Staff, 1999).*

Four different tillage practices, namely plow+disc harrow+rotary tiller+direct seeding machine (TP_1), chisel+disc harrow+rotary tiller+ direct seeding machine (TP_2), plow+rotary tiller+direct seeding machine (TP_3) and direct drilling (TP_4), and an unplanted control plot (TP_5) were applied to experimental plots of 11 m x 50 m with three replicates. A Ford 6600 tractor (77 horsepower, 2.750 kg) was used for all soil tillage treatments. After the tillage treatments, maize (*Zea mays, L.*) was planted in all study plots in May and harvested in October.

Penetration resistance was measured with an Eijelkamp handheld penetrometer of 16.60 mm diameter and 30° cone angle. This instrument can measure a penetration force ranging from 0 to 1 kN (with a resolution of 0.02 kN) up to a maximum depth of 0.45 m. Penetration resistance was determined with the following equation *(Selvi K Ç., 2003):*

$$PR = \frac{F}{A} \text{x}\, 0.0981 \tag{1}$$

where:

PR is penetration resistance [MPa];
F is the reading; the value of force [daN];
A is the base area of cone [cm^2].

Before tillage, soil *BD* was determined with the cylinder method *(Blake and Hartge, 1986).* Soil gravimetric moisture content at 0-20 cm and 20-40 cm was determined for 100 cm^3 of undisturbed soil samples taken with rollers 24 h and dried in an oven at 105 °C.

The spatial variability of soil *PR* was examined with semivariogram models and the following equation was used to estimate the models.

$$\gamma(h) = \frac{1}{2N}\sum_{i=1}^{N}\left(Z_x - Z_{x+h}\right)^2 \tag{2}$$

where:

$z(x_i)$ and $z(x_i + h)$ are the variables of interest at locations xi and x_i + h, respectively,

N(h) is the number of pairs at locations separated by a distance ‘h’ *(Isaaksand Srivastava, 1989),* the theoretical spherical semivariogram model was used to establish the spatial variability of PR.

The isotropic spherical model:

$$\gamma(h) = \begin{cases} C_o + C\left[\dfrac{3h}{2a} - \dfrac{1}{2}\left(\dfrac{h}{a}\right)^3\right] & 0 \le h \le a \\ C_o + C & h > a \end{cases} \tag{3}$$

where:

C_0 is the nugget variance,

C is the structural variance,

C_0+*C* is the sill variance,

h is the lag distance,

a is the range of spatial correlation.

While selecting the best fit model, the model with the smallest residual sum of squares (RSS), the highest coefficient of determination (r^2) and the best cross-validation result was controlled. The semivariogram and spatial structure analyses for PR were performed with geostatistical software *(Robertson G P, 2008).*

RESULTS

The soil BD (g cm^{-3}) and volumetric water content (VWC) (%) before tillage and after harvesting in the experimental plots at 0-20 cm and 20-40 cm for both experimental years are shown in Table 1.

Table 1

Values of some soil properties before tillage and after harvesting for different soil tillage methods on the Black Sea coast of Turkey

Years	Tillage Practices	Depth, [cm]	Bulk Density, [gcm^{-3}]		Volumetric Water Content, [%]	
			BT	AH	BT	AH
2011	TP_1	0-20	1.28	1.07	37	43
	TP_2		1.28	1.08	36	45
	TP_3		1.24	1.12	33	46
	TP_4		1.27	1.12	31	48
	TP_5		1.28	1.12	25	48
	TP_1	20-40	1.30	1.12	36	52
	TP_2		1.30	1.14	38	54
	TP_3		1.32	1.21	40	52
	TP_4		1.36	1.22	40	55
	TP_5		1.30	1.21	38	54
2012	TP_1	0-20	1.23	1.21	35	38
	TP_2		1.23	1.20	41	44
	TP_3		1.22	1.17	42	44
	TP_4		1.22	1.20	41	42
	TP_5		1.21	1.20	42	44
	TP_1	20-40	1.28	1.24	34	56

Years	Tillage Practices	Depth, [cm]	Bulk Density, [gcm^{-3}]		Volumetric Water Content, [%]	
			BT	AH	BT	AH
	TP$_2$		1.26	1.23	42	54
	TP$_3$		1.26	1.28	42	56
	TP$_4$		1.28	1.28	44	56
	TP$_5$		1.26	1.27	44	54

TP$_1$: plow+disc harrow+rotary tiller+direct seeding machine. TP$_2$: chisel+disc harrow+rotary tiller+direct seeding machine. TP$_3$: plow+rotary tiller+direct seeding machine. TP$_4$: direct drilling. TP$_5$: control plot without planting. BT= before tillage; AH= after harvesting.

The average *BD* for 0-20 cm for all experimental plots before soil tillage and after harvesting in 2011 were 1.27 g cm^{-3} and 1.10g cm^{-3}, respectively, and in 2012, 1.22 g cm^{-3} and 1.20g cm^{-3}, respectively. For 0-20 cm, the mean moisture content for treatments before tillage and after harvesting in 2011 were 32.4% and 46.0%, respectively, and in 2012, 40.2% and 42.4%, respectively. For 20-40 cm, the mean moisture content for treatments before tillage and after harvesting in 2011 were 34.4% and 53.4%, respectively, and in 2012, 40.2% and 42.4%, respectively. Differences in soil moisture among tillage methods were not statistically significant ($P>0.05$).

Values of soil *PR* ranged between 0.51 MPa and 1.97 MPa for 0-20 cm and 0.70 MPa and 1.37 MPa for 20-40 cm before tillage in 2011. Penetration resistance ranged between 0.76 MPa and 1.41 MPa for 0-20 cm and 0.91 MPa and 3.10 MPa for 20-40 cm after harvesting in 2011. Values of PR ranged between 0.61 MPa and 1.35 MPa for 0-20 cm and 0.61 MPa and 1.23 MPa for 20-40 cm before tillage in 2012. Penetration resistance ranged between 0.66 MPa and 1.33 MPa for 0-20 cm and 0.77 MPa and 2.07 MPa for 20-40 cm after harvesting in 2012.

The semivariogram model was fitted to empirical values with a determination coefficient >0.9 in all cases. In this study, only selected semivariograms are presented for 0-20 cm and 20-40 cm before tillage and after harvesting in 2011 and 2012. Semivariogram models of PRs evaluated in terms of both sampling times and sampling depths were fitted as spherical models, and all models fitted had a high coefficient of determination and small RSS which indicated that all the models were reliable (Table 2).

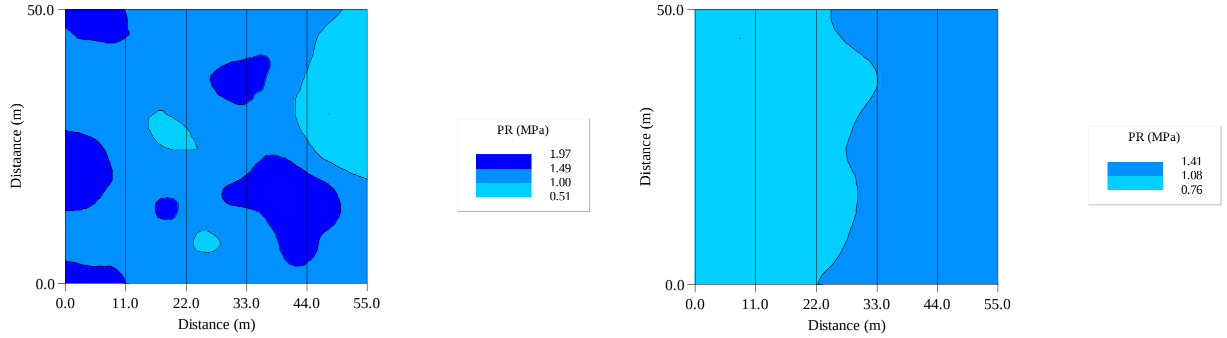
Table 2

Parameters of semivariogram models for different soil tillage methods on the Black Sea coast of Turkey

Year	Time	Depth	Model	Nugget	Sill	Range	R^2	RSS	r [for cross validation]
2011	**BT**	0-20	Sph	0.0001	0.108	20.28	0.98	2.203×10^{-4}	0.8
		20-40	Sph	0.0001	0.035	21.76	0.99	1.909×10^{-5}	0.76
	AH	0-20	Sph	0.00001	0.016	17.91	0.96	8.467×10^{-6}	0.92
		20-40	Sph	0.0001	0.223	22.44	0.94	1.281×10^{-3}	0.93
2012	**BT**	0-20	Sph	0.0001	0.041	15.16	0.97	2.486×10^{-6}	0.81
		20-40	Sph	0.00008	0.020	14.18	0.97	1.984×10^{-5}	0.8
	AH	0-20	Sph	0.00061	0.029	16.96	1.00	7.029×10^{-7}	0.77
		20-40	Sph	0.0039	0.067	4232	1.00	1.030×10^{-5}	0.81

Sph: spherical; BT=before tillage; AH= after harvesting; RSS: residual sum of squares

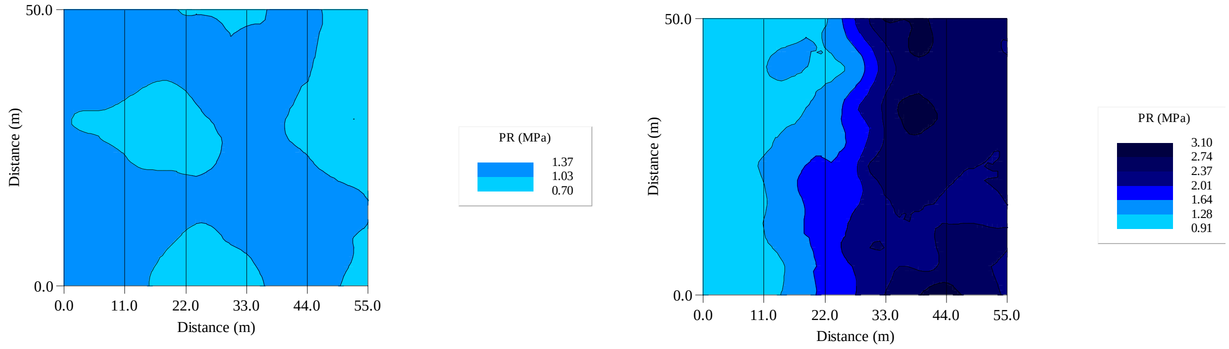
Semivariogram maps of *PR* for the two depths indicated the occurrence of spatial dependence with different values of semivariance, as affected by tillage methods. The effects of different tillage methods on distribution of *PR* in 2011 and 2012 are given in Figures 1 and 2, respectively.



a. before tillage (0-20 cm)

b. after harvesting (0-20 cm)

c.



d. before tillage (20-40 cm)

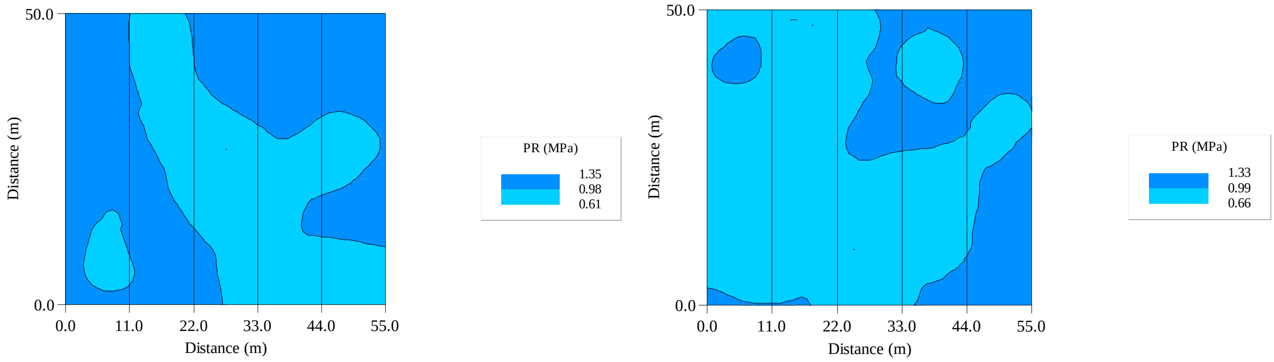
e. after harvesting (20-40 cm)

Fig 1 - The effects of different soil tillage methods on distribution of PR in 2011

TP_1: plow+disc harrow+rotary tiller+direct seeding machine. TP_2: chisel+disc harrow+rotary tiller+direct seeding machine. TP_3: plow+rotary tiller+direct seeding machine. TP_4: direct drilling. TP_5: control plot without planting; 0.0 m-11.0 m = TP_1; 11.0 m-22.0m = TP_2; 22.0 m-33.0 m= TP_3; 33.0 m-44.0 m= TP_4; 44.0 m-55.0 m= TP_5.

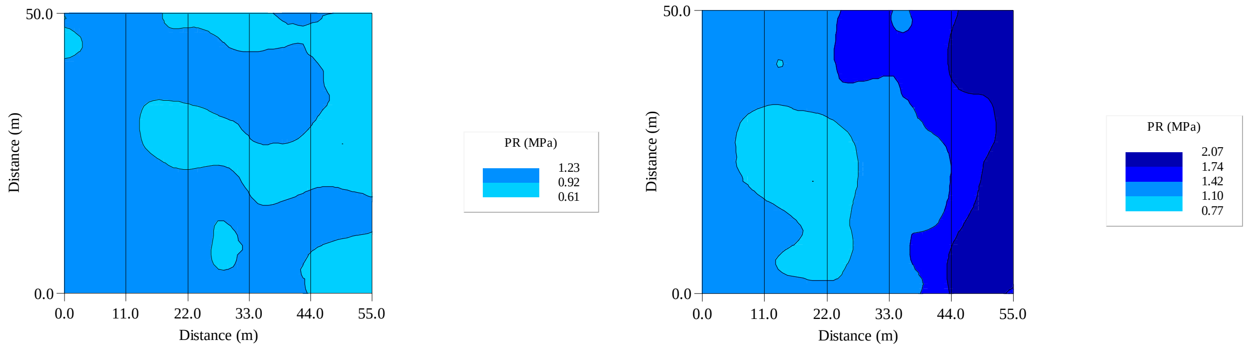
In 2011, for 0-20 cm, the *PR* values were heterogeneous in all experimental plots before tillage. Penetration resistance values obtained after harvesting (AH) showed that they were most reduced by the TP_1 method. For 20-40 cm before tillage, *PR* values were more homogeneous and the average values of PR were lower than for 0-20 cm.

However, after harvesting, *PR* values were high enough to limit the crop yield *(Botta et al, 2006)* in the TP_3 and TP_4 plots at 20-40 cm. Penetration resistances for TP_1 decreased at both depths. This result may be explained by inversion of the soil by the plow, which increases pore size. These results support the results of Çetin et al. (2009) and Doğan and Çarman (1997).



a. before tillage (0-20 cm)

b. after harvesting (0-20 cm)



c. before tillage (20-40 cm) d. after harvesting (20-40 cm)

Fig. 2 -The effects of different soil tillage methods on distribution of PR in 2012

TP_1: plow+disc harrow+rotary tiller+direct seeding machine. TP_2: chisel+disc harrow+rotary tiller+direct seeding machine. TP_3: plow+rotary tiller+direct seeding machine. TP_4: direct drilling. TP_5: control plot without planting; 0.0 m-11.0 m = TP_1; 11.0 m-22.0m = TP_2; 22.0 m-33.0 m= TP_3; 33.0 m-44.0 m= TP_4; 44.0 m-55.0 m= TP_5.

The average *PR* values before soil tillage in 2012 were lower than in 2011. In 2012, the *PR* values at 0-20 cm were more homogenous than in 2011 in all experimental plots. In 2012, the PR values obtained at 0-20 cm after harvesting for the TP_1 and TP_2 methods were lower than for 2011. In addition, after harvesting, *PR* values were higher for the TP_3 and TP_4 methods for 20-40 cm in 2011 than in 2012. The TP_1 method decreased the *PR* at 0-20 cm. That result can be attributed to the short term loosening effect of tillage. However, the TP_3 and TP_4 methods increased the *PR* at 20-40 cm. These results were in good agreement with those of Scwartz et al. (2003) and Çelik (2011).

Penetration resistances for the two soil depths were the highest under the TP_4 method and the lowest under the TP_1 method in both experimental years, relative to TP_5 (Control). This result supported those of Alvarez et al. (2009) and Çelik (2011) and the lowest values of PR were obtained for the TP_1 method. In our study, the *PR* increased with soil depth for all methods, which supported the results of Boydaş and Turgut (2007) and Amin et al. (2014).

CONCLUSIONS

The results of the current study showed that the use of the TP_1 and TP_2 methods for two years in maize growing resulted in lower bulk densities than for other tillage operations on a heavy clayey soil (Vertisol). The *BD* and *PR* were significantly greater under TP_3 and TP_4, especially TP_4, than those under TP_1 and TP_2 at 0-20 and 20-40 cm. The values of *BD* and *PR* were lower in the surface layers. The TP_4 method had detrimental effects that varied according to the sampling period and soil depth.

Overall, soil properties influencing *PR* in all plots were water content, *BD* and clay content. Our results suggest that since the *PR* was adversely affected, direct seeding (TP_4) should be avoided on high clay content soils under the Black Sea Region climatic regime.

ACKNOWLEDGEMENT

The authors are grateful to The Scientific Research Council of OndokuzMayıs University for financial support (project number PYO.ZRT.1901.011.013) and Gregory T. Sullivan of GPEM, University of Queensland in Brisbane, Australia for editing the English in an earlier version of this manuscript.

REFERENCES

[1] Aksakal E.L., Öztaş T., (2010), Changes in distribution patterns of soil penetration resistance within a silage-corn field following the use of heavy harvesting equipment, *Turkish Journal of Agriculture and Forestry.* doi:10.3906/tar-0906-189;

[2] Alvarez C.R., Taboada M.A, Gutierrez B.F.H, Bono A., Fernandez P.L., Prystupa P, (2009), Topsoil properties as affected by tillage systems in the Rolling Pampa Region of Argentina, *Soil Science Society of America Journal,* vol.73, pp.1242-1250;

[3] Amin M., Khan M.J., Jan M.T., Rehman M., Tariq J.A., Hanif M, Shah Z., (2014), Effect of different tillage practices on soil physical properties under wheat in semi-arid environment, *Soil Environ*, vol.33, pp.33–37;

[4] Arslan S, (2006), An alternative method for preventing soil compaction: controlled traffic, *K.S.U. Journal of Science and Engineering,* vol.9, pp.135-141;

[5] Badalikova B, (2010), Influence of soil tillage on soil compaction. Berlin: Heidelberg. Chapter 2, *Soil Engineering: Soil Biology,* pp. 19-30, doi: 10.1007/978-3-642-03681-1_2;

[6] Blake G.R., Hartge K.H., (1986), Methods of soil analysis: physical and mineralogical analysis. *Madison (WI): American Society of Agronomy. Chapter 14*, Bulk density and particle density, pp.363-381;

[7] Botta G.F., Jorajuria J., Balbuena R., Ressia M., Ferreo J., Rosatto H., Tourn M, (2006), Deep tillage and traffic effects on subsoil compaction and sunflower (Helianthus annus L.) yields. *Soil & Tillage Research,* doi:10.1016/j.still.2005.12.011;

[8] Botta G.F., Tolon-Becerra A., Lastra-Bravo X., Tourn M,(2010), Tillage and traffic effects (planters and tractors) on soil compaction and soybean (Glycine max L.) yields in Argentinean pampas. *Soil & Tillage Research.* doi:10.1016/j.still.2010.07.001;

[9] Boydas M.G., Turgut N, (2007), Effect of tillage implements and operating speeds on soil physical properties and wheat emergence. *Turkish Journal of Agriculture and Forestry*, vol.31, pp.399–412;

[10] Carrara M., Castrignanò A, Comparetti A., Febo P., Orlando S, (2007), Mapping of penetrometer resistance in relation to tractor traffic using multivariate geostatistics, *Geoderma.* doi:10.1016/j.geoderma.2007.08.020;

[11] Clark L.J., Whalley W.R., Barraclough P.B, (2003), How roots penetrate strong soil?, *Plant and Soil,* vol.25, pp.93-104;

[12] Çetin M., Akbaş T., Şimşek E., (2009), Determination of the effects of different soil tillage equipment on soil penetration resistance. *25thNational Agricultural Mechanization Congress*; 2009 October 1-3; Isparta Turkey;

[13] Çelik İ., (2011), Effects of tillage methods on penetration resistance, bulk density and saturated hydraulic conductivity in a clayey soil conditions. *Journal of Agricultural Sciences,* vol.17, pp.143–156;

[14] Doğan H., Çarman K., (1997), Effects of seedbed preparation application on some soil physical properties and fuel consumption at grain farming in Konya region. *Agricultural Mechanization 17nd National Congress*; 1997 September 17-19, Tokat /Turkey;

[15] El Titi A, (2003), Soil tillage in agro-ecosystem. *Secaucus (NJ): Taylor and Francis*;

[16] Hamza M.A., Anderson, W.K, (2005), Soil compaction in cropping systems: A review of the nature, causes and possible solutions. *Soil and Tillage Research,* vol. 82, pp.121-145;

[17] Isaaks E.H, Srivastava R.M, (1989), An introduction to applied geostatistics. New York (NY): Oxford University Press;

[18] Kılıç K., Özgöz E., Akbaş F, (2004), Assessment of spatial variability in penetration resistance as related to some soil physical properties of two fluvents in Turkey. *Soil & Tillage Research.* doi:10.1016/j.still.2003.08.009;

[19] Lopez G.F., Jurado E.M., Pena B.J.M., Garcia T.L, (2005), Using geostatistical and remote sensing approaches for mapping soil properties. *Europ J Agronomy*, vol.23, pp.279–289;

[20] Nielsen D.R., Wendroth O, (2003), Spatial and temporal statistics. Sampling field soils and their vegetation*. Reiskirchen: GeoScience Publisher*;

[21] Pınar Y., Selvi K.Ç., Yılmaz S, (2008), Effect of soil compaction (plough pan) on soybean yield at Samsun conditions*. Journal of Agricultural Machinery Science*, vol.4, pp.165-170;

[22] Robertson G.P, (2008), GS$^+$: geostatistics for the environmental sciences. *Plainwell (MI): Gamma Design Software;*

[23] Sağlam M, (2015), Evaluation of the physico chemical properties of alluvial and colluvial soils formed under ustic moisture regime using multivariate geostatistical techniques. *Archives of Agronomy and Soil Science*, vol.61, pp. 943-957;

[24] Schwartz R.C., Evett S.R., Unger P.W, (2003), Soil hydraulic properties of cropland compared with re-established and native grassland. *Geoderma,* vol.116, pp.47-60;

[25] Selvi K.Ç., Kirişci V., Korucu T., (2003), The effects of plow pan on cotton production in terms of soil dynamics. *21thNational Agricultural Mechanization Congress,* 2003 September 3-5, Konya/Turkey;

[26] Stafford J.V., Hendrick J.G, (1988), Dynamic sensing of soil pans. *Transactions of the ASAE*, vol.31. pp.9-13;

[27] Soil Survey Staff, (1999), Soil taxonomy: a basic of soil classification for making and interpreting soil survey. 2nd ed. Washington (DC): *NRCS, USDA, Agriculture Handbook* No.436;

[28] Tekin Y., Kul B., Okursoy R, (2008), Sensing and 3D mapping of soil compaction. *Sensors*. 8:3447-3459. doi: 10.3390-s8053447;

[29] Usowicz B., Lipiec J, (2009), Spatial distribution of soil penetration resistance as affected by soil compaction: The fractal approach. *Ecological Complexity*. doi:10.1016/j.ecocom. 2009.05.005;

[30] Utset A., Cid G, (2001), Soil penetrometer resistance spatial variability in a Ferralsol at several soil moisture conditions, *Soil & Tillage Research*, vol.61. pp.193–202.