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Compaction of a Clay Loam Soil in Pannonian Region of Croatia under Different Tillage Systems

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ABSTRACT

Many farmers periodically use deep tillage operations to alleviate compaction in the soil profile caused by natural factors or machinery traffic. In 2012 and 2013, a study was initiated in the Pannonian region of Croatia to study the effects of No-Tillage (NT), Conventional Tillage (CT), and Deep Tillage (DT) on soil compaction, measured by Bulk Density (BD), Soil Water Content (SWC), Penetration Resistance (PR) and Total Soil Porosity (TSP). The experiment was conducted on Pseudogley (Stagnosol). The results showed that DT was superior to CT and NT treatments. DT caused least soil physical degradation, with *BD* being in the following order: DT< NT< CT. Soil water depletion under NT treatment was confined more to the upper soil layers than under DT and CT. Under the CT treatment, the *PR* values indicate the occurrence of impermeable layers at depths greater than 25 cm in wet conditions (2012) and at depths greater than 10 cm in dry conditions (2013). NT did not differ significantly from tilled treatments in soil compaction measured by *BD*, providing an interesting alternative for soil management. Perennial ploughing should be avoided as the only long term soil management strategy, while additional strategies which include controlled traffic and soil loosening every 1-2 years should be implemented on Pseudogley in Pannonian Croatia.

Keywords: Bulk density, Penetration resistance, Pseudogley, Soil water content, Total soil porosity.

INTRODUCTION

The Pannonian region is the most important and largest agricultural region of Croatia, with highly developed intensive arable farming and high yields of all crops (Basic, 2013). Pseudogley is the most widespread soil in the western part of the region. Pseudogley is a soil that largely correlates with Stagnosol (IUSS Working Group WRB, 2006). It is generally characterized by unfavourable physical, chemical, and biological properties. With the presence of a natural (pedogenic) poorly permeable horizon in the profile of Pseudogley, water movement (stagnation during rainfall and capillary rise during dry period) is the main challenge of this soil. Regardless of the mentioned limitations Pseudogley is widely used in agricultural production. The total area under Pseudogley in Croatia amounts to 540,554 ha and it represents the second most frequent soil type in Croatia (Bogunović *et al*., 1998). Indeed, 55% of Croatian Pseudogleys comprise agricultural land or agro-ecosystems (Husnjak *et al*., 2011). High soil strength from machinery traffic, the existence of plough pans or pedogenetic compacted soil layers impedes plant growth (Javadi and Spoor, 2006; Loghavi and Khadem, 2006; Rashidi *et al*., 2007) and reduces yield of crops (Barzegar *et al*., 2005; Yousuf, 2006) like maize, winter wheat, soybean and oilseed rape, which are a part of usual crop rotation in Pannonian region of Croatia.

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Conventional tillage systems dominate in Croatia and are mostly based on mouldboard ploughing in autumn and disking before seeding in autumn (winter crops) or spring (spring crops) (Bogunovic *et al*., 2014), although some farmers perform subsoiling after winter cereal harvest. The high soil strength of Pseudogley can be reduced, and yield improved, through deep tillage (Butorac *et al*., 1981). The positive effects of deep tillage may be seen for years afterward (Varsa, 1997) or can diminish after one or two seasons (Díaz-Zorita *et al*., 2002; Chan *et al*., 2006).The duration of the effects mostly depends on tillage tool differences, soil type, machinery traffic, annual tillage operations and cumulative rainfall. Furthermore, current trends in central Europe include the adoption of conservation tillage wherever soil and agro-ecological conditions allow that kind of management. Conservation tillage includes any tillage or sowing system that maintains at least 1/3 of the soil covered with crop residue after planting (ASAE Standard 1993). This mostly includes non-inversion tillage systems like chisel ploughing and sowing directly into dead mulch. A continuous no-tillage system on Pseudogley is still an unexplored and underutilized method of soil management.

Conservation tillage practices can impact soil physical properties such as bulk density, total porosity, hydraulic conductivity, aggregate stability and penetration resistance, both positively and negatively. For example, Gomez *et al*. (2001) found that, after 5 years of conventional tillage, a clay loam soil had lower aggregate stability than no-tillage. Also, Manyiwa and Dikinya (2014) found that no-tillage had 7% lower bulk density than conventional tillage in sandy loam Chromic Luvisols.

Bulk density is considered to be a measure of soil quality due to its relationships with other properties. For instance, bulk density is inversely related to total porosity, which gives us an idea of the pore space available in the soil for air and water movement. Arshad *et al*. (1999), Ferreras *et al*. (2000), and Hajabbasi (2010) found that at surface layers no-tillage and conventional tillage had no significant bulk density differences, while in other resaerch, bulk density at soil surface was greater in no-tillage (Hill, 1990; Hubbard *et al*., 1994; Tebrügge and Düring, 1999). These inconsistencies can be found regardless of the climatic conditions and soil type. Furthermore, bulk density and soil water content are the most important factors affecting penetration resistance (Cassel, 1982; Campbell and O'Sullivan, 1991). In several studies, comparing tilled and direct drilled soils, greater penetration resistance was found under no-tillage (Hajabbasi, 2010; Kahlon *et al*., 2013), while Franzen *et al*. (1994) observed significantly smaller penetration resistance values under no tillage down to 10 cm soil depth due to retention of crop residues.

The majority of farmers still have prejudices against no-tillage mainly because loosening soil compaction, phosphorus mix and redistribution and incorporating lime are seen as good reasons to deep rip. On the other hand, periodic use of deep tillage and reliance on residual effects is still an unreliable method of soil tillage on Pseudogley. Adoption of soil management systems that are different from conventional tillage, and their influence on the soil physical state, are poorly understood on Pseudogley in agroecological conditions of Pannonian Croatia. Therefore, this study was conducted to investigate the effects of different types of tillage operations on soil Bulk Density (BD), Penetration Resistance (PR), Soil Water Content (SWC), and Total Soil Porosity (TSP) in a field that had been in continuous maize - winter wheat - soybean - barley - oilseed rape production for many years. The objective of this study was to: (1) Determine which tillage system would produce the most optimal soil physical properties and provide the best water conservation possibilities, and (2) To develop regression equations to relate penetration resistance to soil properties under these three tillage systems.

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MATERIALS AND METHODS

The experiment was conducted in the Pannonian Croatia region at 45° 56' N, 17° 02' E; altitude of 129 m above sea level; slope of 9%. The soil was a poorly drained clay loam Pseudogley on slopes (Škorić, 1986) or Stagnosol (IUSS Working Group WRB, 2006) with organic matter ranging from 16 g kg^{-1} at the 0-24 cm depth to 6 g kg^{-1} at 35-95 cm depth. Basic soil properties are given in Table 1. The climate is semi-humid with average annual precipitation of 878 mm and average annual temperature of 10.6°C (Meteorological and Hydrological Institute of Croatia). During the research period, in 2012 and 2013 annual rainfall was less than 78 and 81% of the long-term mean, respectively. Great variation in distribution was also noticeable. In 2012, rainfall in summer months (June–September) was 162 mm lower and made only 46% of long term average precipitation. In 2013, a shortage was also noticeable in the period from May to October when only 60% of the average rainfall for that period was measured (Bogunovic *et al.*, 2016).

The experimental plot area was established in the summer of 1994. The experimental design consisted of six plots, each 15 m wide and 30 m long. Each plot represented a different tillage system. For the purposes of this study, three tillage systems were used: (NT) No-tillage system – NT had no soil disturbance except for sowing using a John Deere 750A NT seeder. Sowing was performed up and down the slope. Weeds were controlled with total and pre-emergence herbicides; (CT) Ploughing across the slope – autumn mouldboard ploughing (30 cm depth) across the slope followed with one pass of a tandem disk harrow to a depth of 15 cm. Other operations, depending on the crop and seedbed preparation, were also performed across the slope; (DT) Ploughing across the slope with subsoiling – annual operations were similar to CT system. Every 3-4 years in the summer period, when crop rotation allowed for it, deep loosening to a depth of 50 cm was performed using a *V*-frame 7 shank subsoiler. The last subsoiling operation before measuring the data presented in this study was performed on July 29, 2011. Cultural practices for each growing season in the study area were as follows: ploughing (November 18, 2011; October 25 2012); seedbed preparation (April 29, 2012; October 26, 2012); sowing (April 30, 2012;October 26, 2012), harvest (October 1, 2012 – maize; July 18, 2013 – winter wheat).

The crops on the experimental plots were grown in a rotation typical for this part of Europe: 2008 and 2012 - maize (*Zea mays* L.); 2009 - soybean (*Glycine hispida* L.); 2012/2013 - winter wheat (*Triticum aestivum* L.); 2010/2011 - oil seed rape

Table 1. Soil profile characteristics of the Pseudogley.[a]

Horizons	Ap+Eg	Eg+Btg	Btg
Depth range (mm)	0 - 24	24 - 35	35 - 95
Organic matter (g kg^{-1})	16 ± 3.3	14 ± 4.2	6 ± 3.8
Available P_2O_5 (g kg^{-1})	172 ± 18	65 ± 4	244 ± 24
Available K_2O (g kg^{-1})	308 ± 6	123 ± 8	502 ± 12
Clay (< 0.002 mm) (g kg^{-1})	154 ± 25	148 ± 44	196 ± 40
Silt (0.02-0.002 mm) (g kg^{-1})	242 ± 35	260 ± 54	254 ± 32
Fine sand (0.2–0.02 mm) (g kg^{-1})	586 ± 37	571 ± 59	545 ± 69
Coarse sand (2–0.2 mm) (g kg^{-1})	18 ± 4.7	21 ± 5.5	5 ± 2.3
pH in KCl (w/w 1:2.5)	4.21 ± 0.15	4.20 ± 0.18	4.81 ± 0.23
Bulk density (g cm^{-3})	1.56 ± 0.04	1.62 ± 0.06	1.60 ± 0.04
Total soil porosity (%)	41.55 ± 1.47	40.96 ± 1.25	41.02 ± 1.34
Water holding capacity (%)	37.68 ± 1.08	39.09 ± 1.67	40.24 ± 1.57

[a] Values following ±indicate *SD*.

(*Brasicca napus* var. *oleifera* L.) and double crop: 2009/2010 and 2013/2014 - spring barley (*Hordeum vulgare* L.) with soybean. After harvest, crop residues remained on the surface (in NT treatment) or were incorporated in the soil (CT and DT treatments).

On April 2, 2012, and May 21, 2013, soil samples were taken for determination of *BD, TSP* and *SWC* on dry basis (w/w). From each plot, sampling was carried out using sampling cylinders of 100 cm^3 volume (cross section 53 mm, height 51 mm) at soil layers 0-10, 10-20, 20-40 and 40–60 cm, respectively. Each layer at each tillage system represents average of four replicates. Undisturbed samples were taken from surface visible non-trafficking zone. A total of 96 sampling cylinders were taken. *BD* and *SWC* were determined on an oven-dry mass basis after the samples had been dried at 105°C for 48 hours. *TSP* was calculated using Equation (1) based on bulk density and soil particle density (Jiao *et al*., 2011):

$$TSP = \frac{(1-BD)}{PD} x\ 100, \text{Eq.} \quad (1)$$

Where, Particle Density (PD) was determined using Pycnometer method (Blake and Hartge, 1986). *PR* was measured on April 2nd, 2012, and May 21st, 2013, by an electronic hand-pushed cone penetrometer (Eijkelkamp Penetrologger) using a cone with 2 cm^2 base area, 60° included angle and 80 cm driving shaft. Each measurement was repeated 16 times per treatment with penetration speed of 2 cm sec^{-1}. *PR* data were grouped in soil layers 0-10, 10–20, 20–30, 30-40 and 40-60 cm, respectively. Soil samples were taken for soil particle-size analysis, which was carried out using the combination of wet sieving and sedimentation, starting from air-dried soil. Sodium hexametaphosphate was used as a dispersing agent. The organic matter was removed with 30% solution of hydrogen peroxide during process of centrifugation in the bottle. The soil pH was measured using the electrometric method in 1:2.5 (w/v) ratio with the Beckman pH-meter Φ72, in KCl suspension. The content of organic matter was determined by the oxidation method with chromium sulfuric acid. Plant available phosphorus (P_2O_5) and potassium (K_2O) were extracted by AL solution (Ammonium Lactate-acetate) and detected by spectrophotometry and flame photometry, respectively.

Univariate Analysis Of Variance (ANOVA) was applied to assess the effects of tillage treatments on *BD, TSP, PR* and *SWC* and for variances among soil tillage and depth. Following the ANOVA test, the Fisher test was performed to compare the differences in means of the parameters at significance level of $P< 0.05$. The statistical analyses were performed using SAS software (version 9.3).

RESULTS AND DISCUSSION

Bulk Density and Total Soil Porosity.

The analysis of variance values for each year, Treatment (T), Depth (D) and T×D interaction are given in Table 2. *BD* was significantly affected by Treatment (T), Depth (D), and T×D interaction in 2012, and D and T×D interaction in 2013. The average *BD* values taken in 2012 were 1.48, 1.55, 1.60, 1.57 g cm^{-3} at the 0-10, 10-20, 20-40 and 40-60 cm depths, respectively. In 2013, most of the soil layers recorded slightly higher *BD* values compared to 2012 (Table 3). Both years recorded significantly lower *BD* in the 0–10 cm layer compared to other depths. *Post-hoc* test for treatment variables did not record any significant difference between NT and other treatments in either season. In 2012, significant differences were found between CT and DT. *Post-hoc* analysis of T×D interaction detected a significant difference in 2012 and 2013 between tillage systems in the 20–40 cm zone. In 2012, the *BD* under CT (1.70 g cm^{-3}) was significantly higher than under NT (1.58 g cm^{-3}) and DT (1.53 g cm^{-3}). Similar relations were observed in 2013.

TSP followed a reverse trend to *BD*. Differences were detected regarding the

Table 2. Analysis of variance for the investigated parameters in spring 2012 and 2013.

	BD 2012	*BD* 2013	*TSP* 2012	*TSP* 2013	*SWC* 2012	*SWC* 2013	*CI* 2012	*CI* 2013
Treatment (T)	*	ns	*	ns	***	ns	***	***
Depth (D)	***	***	***	***	***	***	***	***
T×D	**	*	**	*	***	**	***	**

* $P< 0.05$; ** $P<0.01$, *** $P< 0.001$; ns: Not significant at a $P< 0.05$).

Table 3. Investigated parameters under No Tillage (NT), moldboard plow (CT) and Deep Tillage (DT) systems.[a]

		2012				2013			
Soil property	Depth (cm)	NT	CT	DP	$\bar{x}$	NT	CT	DP	$\bar{x}$
BD (g cm^{-3})	0-10	1.47	1.47	1.50	1.48C	1.53	1.50	1.50	1.51B
	10-20	1.57	1.53	1.54	1.55B	1.59	1.62	1.61	1.61A
	20-40	1.58b	1.70a	1.53b	1.60A	1.61b	1.71a	1.58b	1.63A
	40-60	1.57	1.61	1.54	1.57AB	1.60	1.62	1.57	1.57A
	$\bar{x}$	1.55ab	1.58a	1.53b		1.58	1.61	1.57	
TSP (%)	0-10	44.0	43.9	42.8	43.6A	41.8	42.9	43.0	42.5A
	10-20	40.0	41.6	40.9	40.8BC	39.1	37.8	38.2	38.4C
	20-40	40.5a	35.5b	42.1a	39.3C	39.1a	35.4b	40.3a	38.3C
	40-60	42.2	40.6	43.1	42.0B	41.0	40.3	42.0	41.1AB
	$\bar{x}$	41.7ab	40.4b	42.2a		40.2	39.1	40.8	
SWC (%)	0-10	25.8c	28.2b	30.0a	28.0D	14.4b	14.8b	19.6a	16.3D
	10-20	29.0b	30.4b	32.5a	30.6C	19.7	18.5	19.4	19.2C
	20-40	31.7b	33.0ab	33.5a	32.7B	23.1	21.8	22.0	22.3B
	40-60	35.9a	34.0b	34.8ab	34.9A	24.1	24.3	22.6	23.7A
	$\bar{x}$	30.6c	31.4b	32.7a		20.3	19.8	20.9	
PR (MPa)	0-10	2.01a	0.86b	0.84b	1.23D	2.54ab	2.00b	2.95a	2.50C
	10-20	3.17a	1.25b	1.59b	2.00C	3.51	4.21	3.80	3.84A
	20-30	3.12a	2.72a	2.13b	2.66B	3.42b	4.81a	3.96b	4.06A
	30-40	3.01	3.52	3.01	3.18A	3.32b	4.57a	3.53b	3.81AB
	40-60	3.07	3.23	3.13	3.15A	3.15	3.58	3.45	3.39B
	$\bar{x}$	2.87a	2.32b	2.14b		3.19b	3.84a	3.54a	

[a] Different letters (lowercase in rows and uppercase in columns) indicate significant difference at $P< 0.05$.

influence of Treatment (T), Depth (D) and T×D interaction in 2012, and D and T×D interaction in 2013 (Table 2). Average *TSP* was the highest in DT (42.2 and 40.8%) and the lowest in CT (40.4 and 39.1%) in both years. TSP in the NT treatment was not statistically different from other treatments in either 2012 or 2013. In the 20-40 cm layer, T×D interaction recorded significant differences between the CT and DT treatments in both years (Table 3). In both years at depths 20-40 cm, CT recorded a *TSP* of approximately 35%. According to Fulajtár (2000), total porosity below 45% on medium heavy soils had negative effects on plant growth. *BD* under NT was not significantly greater than under tilled treatments in the top 10 cm of soil, as has also been reported by other authors (Arshad *et al*., 1999; Ferreras *et al*., 2000; Husnjak *et al*., 2002). There could be two reasons for these results. Firstly, *BD* was measured eighteen years after the change from CT to NT. According to Kinsella (1995), the soil

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had been in transition for long enough to build humus, regain its structural stability and restore pore space. During this transition period, it is normal for there to be an initial increase in *BD* until it reaches a maximum, and then a decrease due to the restructuring process, until an equilibrium level is reached when the structure is fully restored. The second reason was the sampling which was done each year, 6 to 8 months after primary tillage in fall. After heavy rains in winter periods, the absence of vegetative cover and the exposure of the soil surface to direct impact of rainfall may be responsible for the increase in *BD* with time under CT and DT treatments. Similar findings have been reported by Cassel (1982), Logsdon and Cambardella (2000), and Osunbitan *et al.* (2005). Although samples were taken away from obvious trafficking zones, additional traffic on CT and DT due to disking and other seedbed preparation treatments, probably also significantly contributed to soil compaction, as measured by higher *BD*. Parallel to traffic, *BD* increased at a depth of 20-40 cm under CT as a consequence of wheel pressure on open furrow and repeated similar tillage operations. Birkas *et al.* (2002) also found a tillage pan on disc tilled soil compared to subsoiled treatments. According to Birkás *et al.* (2004), several years of ploughing with a mouldboard or disc plough creates dense layers on the border of the tilled layer after three years, and after five years, compacted layers tend to increase in depth. Furthermore, we speculated that higher *BD* at CT also occurs as consequence of vehicle traffic on the furrow during ploughing operations.

Soil Water Content and Penetration Resistance

The profile water content of the three tillage treatments is presented in Table 3. During 2012, *SWC* under the NT treatment was on average 2.7 and 7% lower than CT and DT, respectively (P< 0.001), while in 2013, the differences between treatments were not significant (Table 2). *SWC* generally increased with depth under all treatments (Table 3). The interaction of T×D showed a difference at all soil layers in 2012 and only at the 0–10 cm depths in 2013. *SWC* was much higher in the upper 10 cm layer under DT compared to NT treatment.

Although NT generally contains higher *SWC* compared to CT or reduced tillage treatments in either humid or semiarid areas (Alvarez and Steinbach, 2009), our research recorded differences such as those found by Kováč *et al.* (2005). These differences were attributed to the improved drainage and higher hydraulic conductivity due to loosened layers (Allmaras *et al.*, 1977) under the DT treatment. Most of the annual rainfall occurs in winter in Pannonian Croatia (Meteorological and Hydrological Institute of Croatia), and treatments that were tilled had better water infiltration possibilities. Generally, NT treatment on Pseudogley under the agroecological conditions of Pannonian Croatia shows lower capacity for water conservation in the winter-spring period, and better water conservation compared to tilled treatments in the dry, hot summer period (Bogunović, 2015).

One-way ANOVA analysis indicated a strong significant influence (p<0.001) of treatment and depth on *PR* in both 2012 and 2013 (Table 2). NT recorded significantly higher PR in 2012, and significantly lower *PR* in 2013, compared to other treatments (Table 3). This is mostly due to the influence of differences of *SWC* and *BD*. In 2012, all treatments recorded *PR* below 3.0 MPa, used as the threshold for normal crop growth (Håkansson and Lipiec, 2000; Hamza and Anderson, 2005). During 2013, the soils were drier and *PR* exceeded 3.0 MPa under all treatments. The PR profile (Figure 1) indicates high *PR* from 25 cm under CT and from 35 cm under DT in 2012, and from 10 to 60 cm in 2013. The T×D interaction recorded significant differences in both years (Table 2). In 2012, CT and DT recorded significantly lower PR at the depth of 0–20 cm compared to NT, whereas DT

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had lower *PR* than NT and CT from 20-30 cm as an influence of tillage and higher *SWC*. The influence of tillage on PR in dry soil conditions (2013) was not noticeable as indicated in a higher *PR* under the tilled treatments (CT and DT) at the depth of 10–60 cm (Figure 1, Table 3). Significantly higher *PR* at CT compared to NT and DT in the range of 20–40 cm confirms the existence of a plough or/and traffic pan at the edge of tillage depth, which is already noted from *BD* data. Differences in *PR* among treatments are the result of the difference in *SWC*, *BD* and the time that has passed since the primary tillage. *PR* measurement in 2012 were made in an open furrow left through the winter and before seedbed preparation, while in 2013 measurements were performed seven months after primary and secondary tillage under winter wheat. During 2012, open furrow in winter period at CT and DT resulted in better water conservation compared to NT. Conversely, in the second season, the winter wheat planted in autumn of 2012 resulted in less surface roughness in winter period which affected soil hydraulic properties during winter period at CT and DT treatments in 2013 which probably affected the *SWC*. Soil moisture is an important factor affecting soil *PR* (Yasin *et al*., 1993; Franzen *et al*., 1994). This was confirmed in 2012, in wet soil conditions. Tilled treatments recorded lower *PR*. On the contrary, in 2013, lower *PR* under NT compared to CT and DT could be explained as a result of the cumulative natural soil consolidation over time under CT and DT, as well as additional traffic during seedbed preparation and seeding. As with *BD*, the differences between NT and treatments with intensive tillage are greater after tillage, but fall rapidly during the growing season (Pelegrin *et al*., 1990; Franzen *et al*., 1994). This implies that 6-8 months after tillage soil moisture effects on PR are greater than the effects of the intensity of tillage.

Penetration Resistance-Soil Water Content-Bulk Density Relationship

PR is related to soil physical properties such as soil textural parameters, *SWC*, *BD* and cropping system, along with tillage practices (Yousuf, 2006; Birkás *et al*., 2008). Linear trend lines were generated for describing the relationships. The coefficient of determination (R^2) of the trend lines were generally low, which was expected due to differences in soil properties between the tillage systems. In case of combined data for all tillage treatments, *BD* accounted for 0.231 (based on R^2 value) and *SWC* for 0.275 of the variation in *PR* (Table 4). All correlation relationships were significant. The linear trend was much steeper for CT than NT, both for *BD* and *SWC*, meaning that *PR* of CT increased more rapidly with a reduction in *SWC* and increase in *BD* than that of NT soil.

Multiple linear regression analysis was

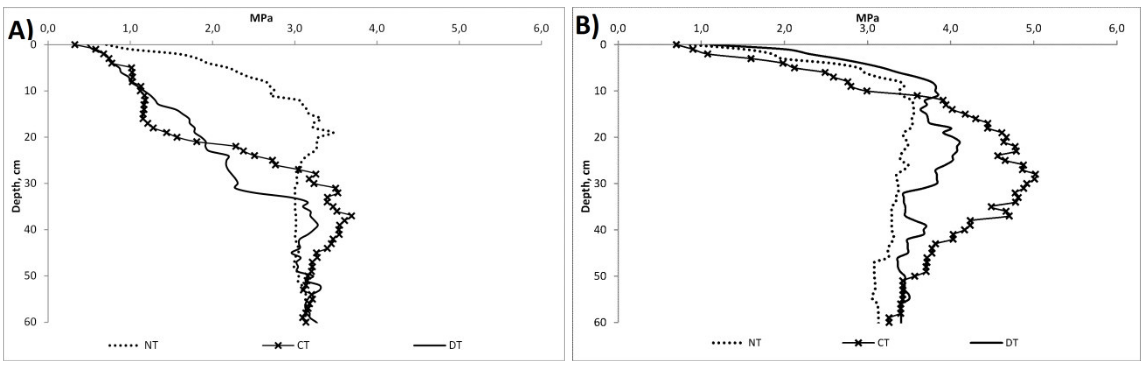

Figure 1. Treatment effect on penetration resistance (MPa) in: (A) April 02, 2012 and (B) May 21, 2013.

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Table 4. Correlation relationship among Penetration Resistance (PR), Soil Water Content (SWC) and Bulk Density (BD) as affected by tillage treatments.

Treatment	Equation	*r*	R^2	*t*	*P*
All	PR= 0.035BD+1.486	0.480	0.231	4.583	< 0.0001
DT	PR= 0.024BD+1.530	0.363	0.132	2.637	0.0114
CT	PR= 0.037BD+1.493	0.433	0.187	4.539	< 0.0001
NT	PR= 0.022BD+1.518	0.326	0.131	2.643	0.0112
All	PR= -0.103SWC+4.869	-0.524	0.275	18.071	< 0.0001
DT	PR= -0.104SWC+4.654	-0.576	0.332	11.913	< 0.0001
CT	PR= -0.120SWC+5.345	-0.560	0.314	11.431	< 0.0001
NT	PR= -0.082SWC+4.531	-0.433	0.188	8.129	< 0.0001

performed to obtain the regression equations showing the relationships between *PR, BD* and *SWC* (Table 5). The results based on the datasets of all tillage treatments showed that *PR* was significantly related to *BD* and *SWC*. Similar trends were also noticeable for individual tillage treatments. From the results presented, it is apparent that *PR* decreased with increasing *SWC*. Other researchers recorded similar findings (Mapfumo and Chanasyk, 1998; Badalíková, 2010; Lipiec *et al*., 2002; Tekeste *et al*., 2008). Values of *PR* tended to increase with increasing *BD*. This is in agreement with previous investigations (Stitt *et al*., 1982; Birkás *et al*., 2008; Kumar *et al*., 2012) who reported that PR varied directly with *BD*. The *PR* trend of CT had a steeper slope (R^2= 0.52) compared to other treatments, which suggests a greater sensitivity of *PR* to *SWC* and *BD* in CT soil. It can be concluded that the use of DT and NT does not have the same level of impact on soil physical conditions as is expressed in the CT treatment. CT treatment with a poorly permeable horizon in 20-40 cm in wet conditions stored higher amount of *SWC* at approximately upper 30 cm depth compared to DT and NT. This affected higher sensitivity of *PR* under *SWC* changes in CT compared to NT and DT, as noted from steeper coefficient of determination on CT (Table 5). On the other hand, the same poorly permeable layer under CT inhibits water movement to the soil surface in dry conditions resulting in a faster increase of *PR* due to soil drying under CT compared to NT and DT.

CONCLUSIONS

The results demonstrate that tillage practices had different effects on *BD, TSP, SWC* and *PR*. Compared with NT and CT, DT resulted in lower *BD* and *PR*, and a higher *SWC*. This result was observed in both seasons, but it was statistically significant only in 2012. *PR* was mostly dependent on *SWC* (followed by BD), and showed favourable results in 2013 under NT, while in 2012, DT and CT recorded the

Table 5. Effect of soil Bulk Density (BD) and Soil Water Content (SWC) on Penetration Resistance (PR).

Treatment	R^2	*SE*	*F*	*P*	Regression equation
All	0.28	0.81	13.44	< 0.0001	PR= -8.07-0.05SWC+7.61BD
NT	0.38	0.57	6.32	0.0071	PR= -12.66-0.11SWC+12.04BD
CT	0.52	0.74	11.17	0.0005	PR= -10.84-0.04SWC+9.11BD
DT	0.35	0.99	12.33	< 0.0001	PR= -1.75-0.10SWC+4.62BD

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lowest results for *PR*. The general trends were that higher PR occurred at the greater *BD* and lower *SWC*. *PR* under CT was more sensitive to those properties than under NT and DT. The regression equations showed that PR of all tillage treatments was significantly related to *BD* and *SWC*. NT did not differ significantly from tilled treatments in soil compaction and provided a possible alternative for soil management. A tillage pan below ploughing depth was recorded under the CT treatment. Additional strategies may be needed to avoid or manage this phenomenon on Pseudogley in Pannonian Croatia.

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تراکم یک خاک لوم رسی در سامانه های مختلف خاک ورزی در منطقه Pannonian در کرواسی

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چکیده

برای کاهش تراکم خاکرخ ناشی از فرایندهای طبیعی یا عبور ماشین آلات، کشاورزان زیادی به طور متناوب از عملیات شخم عمیق استفاده می کنند. در سال های ۲۰۱۲ و ۲۰۱۳، آزمایشی در منطقه Pannonianدر کرواسی آغاز شد تا اثر بی شخم ورزی(NT) ، خاک ورزی مرسوم(CT)، و شخم عمیق (DT) روی تراکم خاک و با اندازه گیری جرم مخصوص ظاهری (BD)، آب موجود در خاک (SWC)،مقاومت به فرو روی (PR)، و تخلخل کل خاک بررسی شود. این آزمایش روی خاک Pseudogley(استگنوسول) انجام شد. نتایج نشان داد که تیمار DTازCTو NTبرتر بود.. تیمار

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DTکمترین صدمات فیزیکی را موجب شد و ترتیب مقدار جرم مخصوص ظاهری در این تیمارهابه این صورت به دست آمد DT<NT<CT. تخلیه آب خاک در تیمارNTدر مقایسه با DT و CT بیشتر به لایه های بالایی خاک محدود می شد. در تیمار CT، بر پایه مقادیر PR،لایه های غیر قابل نفوذدر شرایط مرطوب (در سال ۲۰۱۲) در عمق های بیشتر از ۲۵ سانتی متر و در شرایط خشک (در ۲۰۱۳) در عمق های بیشتر از ۱۰ سانتی متر قرار داشت.همچنین، بر پایه مقادیر جرم مخصوص ظاهری در تیمارهای NTوتیمارهای شخم خورده، این تیمارها از نظر تراکم خاک تفاوت معناداری نداشتند و این یافته گزینه جالبی برای مدیریت خاک رافراهم می کرد. به این ترتیب، در این خاک Pseudogley در منطقه Pannonian لازم است که از شخم چندساله به عنوان تنها برنامه دراز مدت مدیریت خاکخودداری کرد و راهبرد های دیگری شامل عبور ومرور کنترل شده ماشین آلات و نرم کردن خاک (Soil loosening) به طور سالانه یا دوسال یکباررا در آنجا به کار برد.

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