Temporal Changes in Soil Water Content and Penetration Resistance under Three Tillage Systems

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Summary

This study aims to evaluate the impact of different tillage systems on water conservation and penetration resistance in Stagnosols on slopes. Three tillage systems were evaluated during a long-term experiment in Central Croatia in a period from 2011 to 2014, in order to identify sustainable land management practices: control treatment (CT), ploughing and other seedbed layer preparation up and down the slope; ploughing across the slope (PA) – to 30 cm, other operations depending on the crop, also across the slope; and ploughing across the slope (30 cm) with subsoiling (SUB) to 50 cm. Penetration resistance and soil water content were measured each investigated season during five terms to a depth of 60 cm. Tillage systems significantly influence soil water content and penetration resistance, but the results showed great temporal and vertical variation in each investigated season. The results also showed that in low quality Pseudogley deep loosening is required because of the inability of these soils to recover naturally. The hardness of these soils decreases after tillage, or when the moisture content increases, so the period with potentially limiting soil impedance is shorter in systems with subsoiling than in conventionally tilled soils. Fallow has been effective in reducing soil strength in non-traffic areas and increasing soil moisture content. When comparing cropping variants it was established that only a system including subsoiling ensures higher moisture content. Results indicate that since soil water content and penetration resistance were adversely affected, subsoiling should be applied continuously in Pseudogley sites in the hills. Generally, soil resistance increased with time from the date of primary tillage. Although penetration resistance values increase after tillage, the differences were attributed to temporal variation of soil water content. In this study soil moisture condition is presented as a more important factor for soil resistance than the time between primary tillage and measurements.

Key words

compaction, penetration resistance, soil water content, tillage systems

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Introduction

In Pannonian Croatia Stagnosol is the most widespread soil in the western part of the region. It is generally characterized by unfavorable physical, chemical and biological properties. With the presence of poorly permeable horizon in the profile of Stagnosol, water management is the main disadvantage of this soil. In addition, two of the most important climatic factors, precipitation and air temperature, are under great changes in the last decade in Central Croatia, characterized by decrease in average precipitation during summer months with extremes in distribution (Bogunovic and Kisic, 2013). Consequently, there are low, variable, and, in some years, no harvestable yields (Kisic et al., 2012). A deeper (50 cm) root zone may increase the chances of minimizing yield losses during a dry summer season. This root zone depth can be created by tillage or it can also be maintained by soil preserving farming methods (Birkás, 2011). Some farmers nurture a habit of deep ploughing or ripping in order to loosen the subsurface pans. Such deep tillage operations are expected to break up high density soil layers, improve water infiltration and movement in soil, enhance root growth and development, and increase crop production (Bennie and Botha, 1986; Hamza and Anderson, 2005), but unfortunately benefits of these operations often do not appear to persist beyond 1-2 years (Bishop and Grimes, 1978; Chan et al., 2006).

Because of its particle size distribution and poor structure, poor chemical properties, calcium carbonate deficiency and low organic matter content, in combination with very low aggregate stability (Basic et al., 2001, 2004; Kisic et al., 2002a; Rubinić et al., 2014) Stagnosol is susceptible to compaction. Soil compaction occurs in a wide range of soils and climates and it is a typical phenomenon of industrialized and poorly developed agricultures (Birkás et al., 2011). In Central and Eastern Europe soil compaction is often induced by tillage operations (Birkás et al,. 1996), but it is often less important than the traffic induced compaction by machinery that was the subject of research found in western scientific literature (Hakansson and Voorhees, 1997).

In addition, nowadays in Croatia conventional tillage that includes mouldboard plowing is dominant (Bogunovic et al., 2014), and farmers mostly perform the same tillage procedures. This way of management led to the occurrence of compacted tillage-induced pan while loosening the top layer between cultivated and the undisturbed layer (Birkás et al., 2008). Generally, each tillage system produces non-uniform changes in soil physical properties (Cassel, 1982) resulting in a large spatial and temporal variability. Hence, soil and water conservation is an issue of primary concern in this region. Different tillage systems could be a promising alternative to traditional tillage on hilly areas for plant production in Central Croatia. Testing and adoption of these systems would reduce production costs and help to protect soil and water resources as well as reduce climatic-induced damages.

The primary goals of this investigation were to determine how various tillage and cropping practices affect soil compaction and water conservation in this region and to use these results to identify sustainable land management practices. This study will present the results and discussion about the effects of different tillage practices on seasonal changes in soil water content (SWC) and penetration resistance (PR) and their evolution over three seasons (2011-2012, 2012-2013 and 2013-2014) in Stagnosol on hilly areas.

Materials and methods

The site is located in the Moslavina province (45°33' N, 17°02' W, 130 m.a.s.l), 130 km east of Zagreb. The soil is clay loam, mapped as Stagnosol (IUSS, 2014) with a slope of 9% present in the SE-NW direction. In the Croatian soil classification it is simply called Pseudogley on slope terrain (Škorić, 1986; Husnjak, 2014). Detailed physical and chemical characteristics of soil are presented in Table 1.

The site location has semihumid to humid climate with annual precipitation of 889 mm and average annual temperature of 10.7°C in the period 1960-1999 (Meteorological and Hydrological Institute of Croatia, Weather Station from Daruvar, approximately 10 km from site location).

Three tillage systems, and implements that were included in some systems, are as follows: 1) Control treatment (CT) – ploughing (to 30 cm) and other operations up and down the slope - black fallow; 2) Ploughing across the slope (PA) – to 30 cm, other operations depending on the crop, also across the slope; 3) Ploughing across the slope (30 cm) with subsoiling to 50 cm (SUB) – subsoiling repeats after termination of prolonged effect (every 3-4 years when crop rotation allows), other operations depending on the crop.

CT, PA and SUB treatments consisted of mouldboard ploughing to the depth of 30 cm in summer-autumn period followed by secondary tillage to the depth of 10-15 cm with a discs or harrow prior to sowing. In SUB treatment in summer, after harvest of wheat or barley, subsoiling to the depth of 50 cm (non-inverting action) followed. The last subsoiling operation before measuring the data presented in this study was performed on July 29th 2011 after oilseed rape harvest. CT treatment was not tilled after primary and secondary tillage and weeds were controlled by herbicides. The experimental design consisted of three plots each 50 m long and 25 m wide, and a plot area of 1250 m^2. Crops cultivated in the experiment were maize (*Zea mays* L.) in 2012, winter wheat (*Triticum aestivum* L.) in season 2012-2013 and spring barley (*Hordeum sativum* L.) with soybean (*Glycine hispida* L.) in season 2014. The most important dates and information on tillage, sowing and harvest are shown in Table 2.

During the investigation soil PR was measured using a penetrometer (Penetrologger, Eijkelkamp) with a cone angle of 60° and conical point of 1 cm^2. Each season PR was measured during five terms to a depth of 60 cm. Each term had 16 repetitions per plot. PR data were compiled and individual values were averaged for soil layers of 0-10 cm, 11-25 cm, 26-40 cm and 41-60 cm. Disturbed soil samples used to determine SWC were collected by hand sampling probe. Measurements for SWC were made at the same time as PR measurements and close to the sampling locations in each plot. Soil water samples were taken in 20 cm increments to a depth of 60 cm, in three replicates. These samples were dried at 105°C for 24 h in an oven. Water content was converted to a volume basis using previously determined bulk densities. All measurements and soil samples were collected from non-traffic zone.

Table 1. Physical and chemical characteristics of Stagnosol

Soil depth (cm)	Soil horizon	Coarse sand (2-0.2 mm)	Particle size distribution (g kg^{-1}) Fine sand (0.2-0.02 mm)	Silt (0.02-0.002 mm)	Clay (<0.002 mm)	Texture class
0-24	Ap+Eg	18 ± 4.7	586 ± 37	242 ± 35	154 ± 25	Clay loam
24-35	Eg+Btg	21 ± 5.5	571 ± 59	260 ± 54	148 ± 44	Clay loam
35-95	Btg	5 ± 2.3	545 ± 69	254 ± 32	196 ± 40	Clay loam
Soil depth (cm)	Soil horizon	pH -log(H$^+$)	Soil organic matter (g kg^{-1})	Available P_2O_5 g kg^{-1}	Available K_2O g kg^{-1}	Bulk density (g cm^{-3})
0-24	Ap+Eg	4.21 ± 0.15	16 ± 3.3	172 ± 18	308 ± 6	1.56 ± 0.04
24-35	Eg+Btg	4.20 ± 0.18	14 ± 4.2	65 ± 4	123 ± 8	1.61 ± 0.06
35-95	Btg	4.81 ± 0.23	6 ± 3.8	244 ± 24	502 ± 12	1.60 ± 0.04

Table 2. Summary of cultural practices during investigation period in the study area

Season	Crop	Tillage: Plowing	Tillage: Disking + seedbed preparation	Sowing date	Harvest date
2011/2012	Maize	November 18, 2011	April 29	April 30	October 1
2012/2013	Winter wheat	October 25, 2012	October 26	October 26	July 18
2013/2014	Spring barley + Soybean	October 28, 2013 (+ subsoiling)	March 17	March 18 (April 12)	July 19 (Spring barley)

Analysis of variance (ANOVA) was conducted using the GLM procedure (SAS Institute, version 9.3) to evaluate the effects of compaction management and soil depth. Soil depth will be referred to as depth zones (0-10, 11-25, 26-40 and 41-60 cm for PR). Differences in PR at depths throughout the profile were statistically compared to evaluate the effects of depth and compaction management. An estimate of the least significant difference (Tukey LSD) between treatments at the same depth or different depths was obtained. Statistical differences were declared significant at the 0.05 level.

Results and discussion

Precipitation

Precipitation data for all investigated seasons at study location with long-term means are shown in Figure 1. The data show long-term average rainfall for all analyzed years when compared with long-term annual averages. The rainfall in 2011 was particularly below the long-term mean with only 47% of normal long term precipitation. Each month, with the exception of July and December, showed rainfall shortage compared to a long-term mean. The whole 2011 was characterized by a long drought stress period. In 2012 and 2013 annual rainfall was less than 78% and 81% of the long-term mean, respectively. Great disturbance in distribution was also noticeable. This distribution disturbance is particularly prominent in 2012, when the recorded rainfall in summer months (June – September) was 162 mm lower and makes 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 average rainfall for that period was measured. Precipitation rates in 2014 during first three months do not differ from long term average, although amount of rainfall was highly increased during April and May. Generally, during the investigation period 2011-2014 rainfall shortage periods occurred several times that strongly affected soil water content.

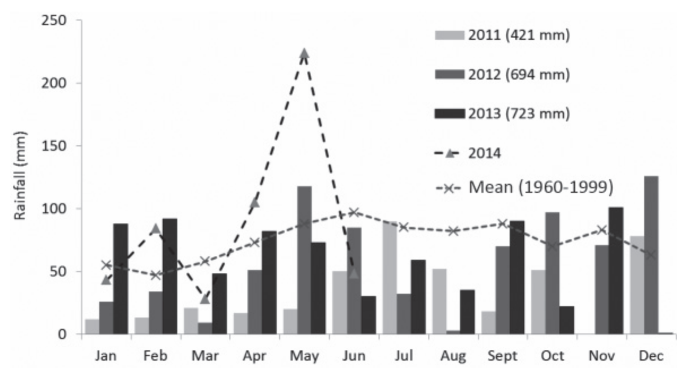

Figure 1. Mean monthly rainfall distribution for experimental site from 2011 until June 2014 compared to a multi-year average (1960-1999) precipitation

Seasonal changes of soil water storage

During the experimental period (2011-2014) there was an important variation in annual precipitation (Figure 1) and therefore it was necessary to evaluate both the effect of soil tillage and annual precipitation on SWC.

In season 2011-2012 temporal evolution of total soil water storage (0-60 cm) varied during the season depending on precipitation. The analysis of variance for SWC (Table 3) showed that tillage systems were significant for most of the measurements, therefore tillage systems have a great influence on SWC. SWC values for all comparisons in 2011-2012 varied for CT from 1228.9 to 2431.4 m^3 ha^{-1}, for PA from 1085.2 to 2365.3 m^3 ha^{-1} and for SUB from 1211.4 to 2309.6 m^3 ha^{-1}, depending on the measurement date. In season 2011-2012 SWC was always greater under CT (with the exception of June 13th) than under PA and

Table 3. Soil water content (m^3 ha^{-1}) in profile from 0 to 60 cm per each measurement

Sampling dates	CT	PA	SUB
		2011-2012	
Dec 10	1228.9a	1085.2b	1211.4a
March 2	2431.4a	2365.3b	2309.6c
June 13	2099.8b	2097.1b	2200.1a
July 26	1940.0a	1367.0c	1447.0b
Oct 5	1703.6a	1389.1c	1456.2b
		2012-2013	
Dec 5	2240.2a	2080.4c	2140.2b
March 5	2372.3a	2468.2a	2310.4a
April 19	1975.3b	2158.0a	2210.0a
June 14	2453.2a	1948.3c	2208.9b
Aug 30	1910.6a	1845.3a	1722.1a
		2013-2014	
Nov 29	2819.9a	2732.9ab	2650.8b
Jan 3	2301.8a	2462.6a	2647.5a
March 10	2673.0a	2591.3a	2948.0a
April 18	2174.8b	2383.3a	2523.2a
June 14	2216.4ab	2069.1b	2436.8a

*Different letters indicate significant differences ($P<0.05$) between tillage treatments

SUB, but differences increased towards the end of the crop cycle. Significantly the lowest SWC was recorded under PA in three measurements (Dec. 10th, July 26th and Oct. 5th). Comparing the variants with crops, SUB and PA, at all three measurements after sowing, SUB generally stored more water and offered favorable water conservation possibilities.

Season 2012-2013 was a better hydrological year than the previous season of 2011-2012. Average SWC for all measurements throughout the season 2012-2013 recorded a 22% higher SWC in 0-60 cm layer than in season 2011-2012. The analysis of variance for SWC (Table 3) showed that tillage had a significant influence on SWC. Profile SWC values in season 2012-2013 varied for CT from 1910.6 to 2453.2 m^3 ha^{-1}, for PA from 1845.3 to 2468.2 m^3 ha^{-1}, and for SUB from 1722.1 to 2310.4 m^3 ha^{-1} depending on the time of measurement (Table 3). During the investigated season of winter wheat, SWC was greater under CT than under SUB and PA, but these differences were much lower than in the previous season. Comparing the treatments with crops (PA and SUB), better results were again recorded under SUB with significantly higher SWC than under PA in two measurements (Dec 5th and June 14th), while in the other three measurements statistically justified difference was not observed.

In season 2013-2014 greater precipitation had improved soil water storage to a depth of 60 cm. The whole season of 2013-2014 recorded an improvement in SWC compared to the season of 2012-2013 and a big improvement compared to the season of 2011-2012, with 43% and 17% more stored water in 0-60 cm layer compared to seasons 2011-2012 and 2012-2013, respectively (Table 3). Rainfall in September and November 2013 (Figure 1) recharged soil profile on the first date of measurement (Nov. 29th) to values higher than 2600 m^3ha^{-1} in 0-60 cm profile. From this date until the end of this measurement season all tillage systems recorded values higher than 2000 m^3 ha^{-1} in soil profile.

In 2014 averaged SWC in all measurements was greater under SUB than under other two systems. Individual measurements do not show a clear trend. In the comparison of cropping variants (Table 3), SUB recorded significantly higher results than PA on June 14th. On other dates (Nov. 29th, Jan. 03rd, Mar. 10th and Apr. 18th) SWC was similar in both treatments, coinciding with a higher rainfall rate (Figure 1). The dynamics of soil water storage in season 2013-2014 was strongly conditioned by higher precipitation in November - May period. Higher SWC minimizes the differences between tillage systems, so statistical analysis (Table 3) did not mark justified differences between variants in two measurements on Jan. 3rd and Mar. 10th. Generally, CT retained in average 220 and 156 m^3 ha^{-1} more soil water than PA and SUB during the first season (2011-2012), and 90 and 72 m^3ha^{-1} during the second season (2012-2013). During the third season the highest average of all measurements was recorded under SUB with 204 and 193 m^3ha^{-1} more soil water than under CT and PA.

This study compares soil management on slopes where the tool, direction and depth of tillage make a difference in management practices. Comparing the systems that include crops, SUB retained higher annual water content than PA in all seasons. This can be explained by better soil hydraulic conductivity in SUB after deep tillage (subsoiling) and during the effect of subsoiling as a consequence of greater degree of aggregation. Subsoiling increased porosity and resulted in finer soil particles that increased the soil pore space and hence increased the water content retained by soil. This was particularly prominent during the last investigated season when precipitation rate was moderate to high. On silt loam soil Allmaras et al. (1977) reported an increase in hydraulic conductivity after chisel plowing. In tillage study Alvarez and Steinbach (2009) in comparison of reduced (included chisel plow to 40 cm) tillage and conventional (mouldboard plowing to 30 cm) tillage recorded significantly higher infiltration rate under reduced (loosened) variants, while moisture content depended on climate conditions. In humid climate the authors did not record significant differences between reduced and conventional tillage, but in semiarid climate differences existed with more favorable SWC under reduced tillage variants. On soils with root restricting layers, yield increases following subsoiling were attributable to greater utilization of subsoil moisture by crops (Kamprath et al., 1979). In a study conducted in the same agro-ecological conditions Butorac et al. (1981) noticed higher soil water conservation after subsoiling (to the depth of 40 cm) and concluded that subsoiling variant with deep ploughing variant (to the depth of 40 cm) represents a functional tillage systems in ecological conditions of Pannonia region. It should be noted that hydraulic conductivity increases by tillage and then decreases during the season due to the settling of soil structure created by tillage (Azevedo et al., 1998; Bormann and Klaassen, 2008). This is probably the main reason for greater differences marked in season 2011-2012 in SWC between SUB and PA than in season 2012-2013.

The comparison of CT and PA is based on cover culture, water management on sloping terrain and their ability to prevent surface runoff. Pseudogley is a type of soil characterized by poor soil infiltration and vertical water permeability and to the depth of 100 cm it usually ranges in class from low to very low (Rubinić, 2013). As a result large surface runoff under intensive rainfall with high erosion rates will occur, especially if the soil is unplanted or covered with wide-row crops (Basic et al., 2001, 2004; Kisic et al., 2002a, 2002b). Due to surface runoff, which is more prominent in CT treatment with fallow (Kisic et al., 2002a, 2002b), and reduced infiltration into the soil profile, there is reason to believe that the amount of water in profile will be smaller than in other plots. Nevertheless, 17 years of black fallow practice and the difference in comparison with other plots that had no crops certainly make a difference in soil water management. Fallow has been proved to affect water and nitrogen balances in soil, depending on soil type and season (French, 1978). Unger and Jones (1998) recorded higher SWC in plots with fallow rotation compared with wheat and sorghum rotation plots. A similar situation was recorded by Lopez et al. (1996) while comparing different tillage systems under crop rotations that included fallow and those with continuous cropping. Lampurlanés et al. (2002) noted that fallow period is valuable for water accumulation only in certain periods of year, and chemical fallow residues are a better solution than black fallow.

Normally, SWC varied during the investigated season according to rainfall distribution, but the differences between tillage systems can be attributed to crop management. Higher SWC in season 2011-2012 and 2012-2013 under CT than under PA and SUB indicate reduced water evaporation during the preceding period. Also, crop had a great influence as factor that was responsible for water absorption. Depending on the crop, plants require 250-400 g of water to build 1 g of dry matter, in north geographic latitude between 45 and 47 degrees (Jolankai and Birkás, 2007). This amount of water absorbed by crops can certainly be a significant factor influencing moisture in soil profile. Data obtained in this research indicate that SUB ensures higher SWC than other system with crop (PA). This can be attributed to the effect of subsoiling. Although the literature suggests that the effect of subsoiling diminishes after 1-2 season (Bishop and Grimes, 1978; Badalíková and Knakal, 1997; Diaz-Zorita et al., 2002; Chan et al., 2006), this should not be taken for granted and it should be adapted to climate conditions because the influence of tillage on physical characteristics of soil is stronger in humid areas and clayey soils than in lighter soils of arid areas (Buschiazzo et al., 1998). According to the data obtained in this study, the effect of subsoiling is also visible in the second season as indicated by the results for SWC and PR (which will be explained below) when comparing variants with continuous crop (SUB and PA). After repeated subsoiling in the third season, the differences were even more apparent and show the true advantage of water management due to deep tillage and accumulation of rainfall in winter period. It also depends on the annual rainfall. The beginning of a studied period marked an unfavorable hydrological year with only 47% of normal long-period rainfall (as shown in Figure 1), where the accumulation of moisture at the first measurement on Dec. 10th recorded a significantly higher SWC in SUB than in PA, and the same trend continued in most cases throughout the first season. In the second and the third season higher soil moisture content was recorded, and the differences between the variants decreased, but higher annual values of SWC were recorded in SUB than in PA. SWC in SUB after subsoiling exceeded the variant with fallow, while deep tillage is by far the best method when observing soil water management. These results suggest that occasional subsoiling provides benefits for soil water conservation and SUB system in our environment can be a good alternative or a better choice than PA on hilly areas in Pannonian Croatia.

Penetration resistance

Detailed results of PR measurements are presented in Figure 2. As expected, mouldboard ploughing followed by secondary tillage decreased relative compaction, although the actual decrease varied each year.

In all years and tillage systems PR increased with depth and the greatest PR was in majority of measurements in the deepest 41-60 cm layer. The statistically significant differences between tillage systems also exist, as presented in Table 4.

In season 2011-2012 PR at the depth of 0-10 cm varied from 0.26 to 2.58 MPa, at 11-25 cm from 0.47 to 3.39 MPa, at 26-40 cm from 1.13 to 5.46 MPa and at 41-60 cm from 2.08 to 6.89 MPa depending on the time of measurement (Figure 2). The lowest PR in surface layer (0-10 cm) was recorded under CT in the first two measurements on Dec. 10th and Mar. 2nd, and under SUB on the last three dates: June 13th, July 26th and Oct. 5th. Surface layer has not shown any statistical differences between plots that led to a conclusion that the smallest recorded differences between variants were observed in surface layer. The lowest PR in 11-25 cm layer was measured under CT, except on Oct. 5th, while the differences between SUB and PA were not statistically justified. Deeper layers (26-40 and 41-60) follow a similar pattern. The lowest values were recorded under CT, while in most measurements better results were recorded under SUB than under PA. This indicates that the prolonged effect of deep tillage under SUB is still present 392 days after the last ripening in 2011. However, these differences were statistically justified on Dec. 10th and June 13th in 26-40 cm layer.

In this study, due to the range of PR values observed over the experimental period, 3.0 MPa was chosen as the most suitable reference for comparison purposes between variants and for root development. In season 2011-2012 PR values in plough layer (0-25 cm) were below threshold values in most measurements. The only exception was recorded under PA and SUB at the end of July 2012. Deeper horizons recorded values between 2.33 and 6.89 MPa depending on the time of measurement and tillage system. These soil resistance values can seriously inhibit root growth.

In season 2012-2013 the surface layer recorded PR values between 0.55 and 2.96 MPa, depending on the period and tillage system, while the highest PR values recorded under PA were on Dec. 10th, Mar. 5th, Apr. 19th and June 14th (Figure 2). Subsurface layer (11-25 cm) recorded higher PR, but it did not exceed critical values in most measurements. Exceptions were recorded under PA in June (5.10 MPa) and under SUB in Aug. (3.10 MPa). The highest PR value was recorded in the deepest layers with values above critical for normal root growth in Dec., June and Aug. PA recorded the highest values (from 2.51 to 5.12 MPa) below the edge of primary tillage (25-40 cm), while there was no difference in the deepest layer under PA and SUB. PR in 26-40 cm layer can inhibit root growth, but critical values were exceeded

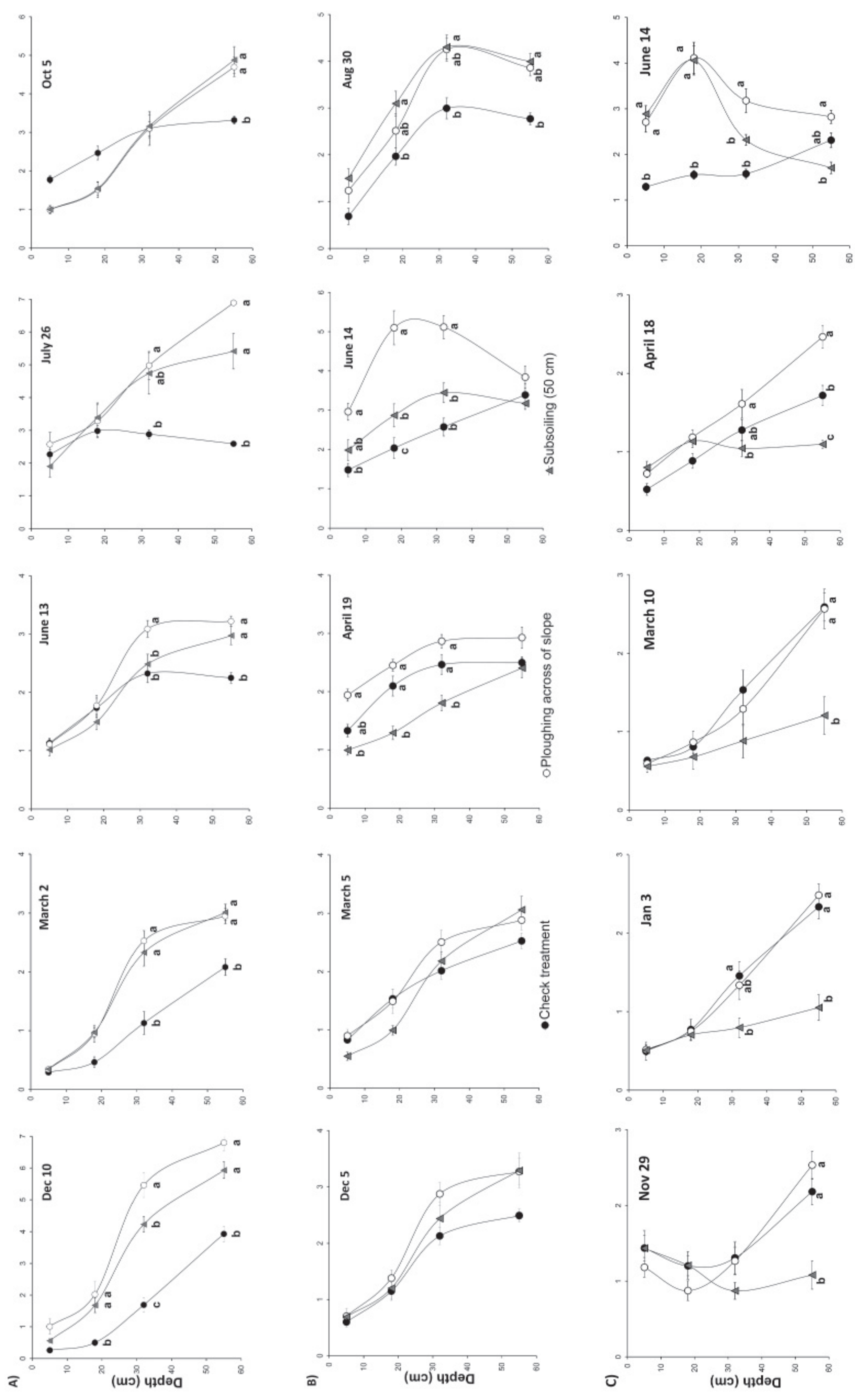

Figure 2. Results from ANOVA and interaction test. Different lowercase letters represent significant difference at $p<0.05$. Horizontal bars represent standard error

Table 4. Penetration resistance per measurement ANOVA

Source		Season 2011-2012				
	(n-1)	Dec 10	March 2	June 13	July 26	Oct 5
VARIANT (V)	2	<0.0001***	<0.0001***	<0.0001***	<0.0001***	0.8270 n.s.
DEPTH (D)	2	<0.0001***	<0.0001***	<0.0001***	<0.0001***	<0.0001***
V x D	4	<0.0001***	<0.0001***	<0.0001***	<0.0001***	<0.0001***
			Season 2012-2013			
Source	(n-1)	Dec 5	March 5	April 19	June 14	Aug 30
VARIANT (V)	2	0.0016**	0.0308*	<0.0001***	<0.0001***	<0.0001***
DEPTH (D)	2	<0.0001***	<0.0001***	<0.0001***	<0.0001***	<0.0001***
V x D	4	0.2181 n.s.	0.0079**	0.0065**	<0.0001***	0.0052**
			Season 2013-2014			
Source	(n-1)	Nov 29	Jan 3	March 10	April 18	June 14
VARIANT (V)	2	0.0022**	<0.0001***	<0.0001***	<0.0001***	<0.0001***
DEPTH (D)	2	0.0021**	<0.0001***	<0.0001***	<0.0001***	<0.0001***
V x D	4	<0.0001***	<0.0001***	0.0003***	<0.0001***	<0.0001***

*Least significant differences (P≥0.05 n.s., *P<0.05, **P<0.01 and ***P<0.001) according to Tukey LSD

in June and Aug. Resistance in the deepest layer (41-60 cm) is a limiting factor for root development under PA and SUB during the whole season, except for Apr. 19th.

PR value was smaller at all variants during the last experimental season (2013-2014) than it was in previous seasons. At a depth of 0-10 cm it varied from 0.50 to 2.88 MPa, at 11-25 cm from 0.70 to 4.11 MPa, at 26-40 cm from 0.80 to 3.18 MPa and at 41-60 cm from 1.05 to 2.82 MPa depending on the date of measurement. In season 2013-2014 PR values were significantly different for all variants in all measurements (Table 4). Measured values in 0-40 cm layers did not exceed 2 MPa and provided normal conditions for root growth (Hamza and Anderson, 2005), with the exception of a value measured on June 14th. Favorable results were recorded in the deepest layer (41-60 cm) for SUB and PA, and for CT plot was recorded statistically higher PR ranging between 1.72 and 2.82 MPa. This was probably associated with the persistence of soil loosening effect by tillage, enhanced by overall higher initial SWC. The differences recorded under SUB in 41-60 cm layer resulted in the average resistance decrease and make only 55% and 48% of PR values recorded in PA and CT if compared with the means of all three seasons.

In all seasons and tillage systems, PR value increased with depth and the greatest increase in average from the surface to the depth of 60 cm was observed under PA, then under SUB and CT, with 189%, 174% and 154%, respectively. The increase of penetration resistance that comes with depth has been observed in numerous studies (Gooderham, 1976; Bishop and Grimes, 1978; Lopez et al., 1996; Unger and Jones, 1998; Celik, 2011) and it is mostly influenced by vertical differences in structure, texture and organic matter content (Cruse et al., 1980; Cassel, 1982). An increase of PR with depth is typical for Stagnosols as can be seen in other studies (Kisic et al., 2000; Bogunovic et al., 2014).

Statistically significant differences in PR between different soil depths and variants exist in each measurement as is shown in Table 4. However, only the values at the same depth in different variants were compared in this study. PR variability results from vertical and lateral changes in soil properties such as texture, structure, bulk density, particle surface roughness, SWC and organic matter content (Cassel, 1982; Campbell and O'Sullivan, 1991) and this is the main reason for choosing the comparison of the same depth layers.

The differences in PR in the plough layer (0-25 cm) among tillage treatments may be attributed to the differences in SWC at the time of sampling and the number of days that passed since primary tillage. Approximately 200 days after tillage, regardless of the study season, all tillage systems show a loose soil condition of plough layer with at least 95% of measured values in 0-25 cm layers ranging between 0 and 2 MPa. In contrast, in a dry summer period (June - Aug.) smaller percentages of measurements (less than 40%) in plough layer (0-25 cm) were found in this soil resistance range. Soil consolidation and drying processes under the influence of plant roots caused a gradual increase of soil resistance as seen in other studies (Lopez et al., 1996). This temporal variation is directly attributable to temporal changes in bulk density due to settling under drying process and soil water suction which is related to SWC.

At depths below 40 cm the soil showed soil resistance value up to 5 MPa, while certain measurements were up to almost 7 MPa. The results of these measurements in dry period indicate serious limitations of these soils for crop production. SUB recorded several results that were better than PA in the first season at each depth as a result of prolonged effect of loosening. A greater persistence of soil loosening indicated by lower PR after subsoiling compared to mouldboard ploughing was also observed by other researchers (Cassel et al., 1978; Bishop and Grimes, 1978; Sommer and Zach, 1992; Diaz-Zorita, 2000). In season 2011-2012 after June, PR increased above critical levels during drying and in spite of the prolonged effect of deeper tillage favorable conditions for root growth were not recorded under SUB, except in the third season (2013-2014) in a period soon after the repeated subsoiling. After subsoiling, the loosening effect of tillage reduced PR drastically with values below 2 MPa in the deepest layers.

When comparing CT with other two variants the influence of fallow on physical soil characteristics must be considered. Greater SWC in soil profile under fallow may modify the restructuring process of soil and its biological activity (Lampurlanés and Cantero-Martínez, 2003). Tillage performed on fallow variant and the lack of crops, combined with non-traffic, the absence of soil profile disturbance and natural factors induced by fallow, proved to be effective in reducing soil strength. It is not an unseen situation as proved by Lampurlanés and Cantero-Martínez (2003) when they investigated the effect of long term fallow on soil properties. In soil compaction measurements an indirect correlation between soil PR and SWC has almost always been confirmed (Badalíková, 2010). At all soil horizons PR increases with a decrease in soil moisture (Lipiec et al., 2002). This seems to indicate that season average SWC with a maximal value recorded under CT in the first two seasons is the greatest reason for a decreased PR value in fallow variant.

Conclusion

Deep loosening on low quality Stagnosol is necessary because the soil is not capable for recovering naturally. The PR values were lower in surface layers and increased with depth under all variants.

Ploughing was a sufficient measure in this area to keep PR under critical values in wet soil phase while in other part of years deep loosening would suffice. The state of soil compaction diminishes after tillage or with the increase of SWC, so the period with potentially limiting soil impedance is shorter in system with subsoiling than in conventionally tilled soils.

Fallow has been effective in reducing soil strength under non-trafficking and increasing SWC. Between cropping variants, SUB ensures higher SWC content than PA. The results of this study suggest that since SWC and PR were adversely affected, SUB system should be applied continuously on Pseudogley soil on hills, in semihumid to humid climate.

Generally, PR increased with time after primary tillage. Although PR increases from tillage date, the differences were attributed to temporal variation of SWC that depends on weather conditions interacting with soil properties. In this study soil moisture condition is represented as a more important factor for PR than the moment in time after primary tillage. In the Pannonian Region of Croatia the production of crops on Stagnosols under inclination is dependent on tillage systems and their ability for water conservation.

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