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The effects of various tillage treatments on soil physical properties, earthworm abundance and crop yield in Hungary

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ABSTRACT

Historically, tillage has been essential for seedbed preparation and weed control, but it has also accelerated soil degradation through erosion and loss of soil organic matter (SOM). Our objective was to quantify the changes in soil physical properties and earthworm abundance under six tillage treatments on an Endocalcic Chernozem (Loamic) soil (2016 and 2017). The long-term tillage experiment was set up in 2002 with the following tillage treatments: *disking* 12 to 14 cm deep (D); *shallow tine cultivation* (18 to 20 cm) (SC); *no-tillage* (NT); *deep tine cultivation* (22 to 25 cm) (DC); *loosening* to a depth of 40 to 45 cm (L); *moldboard ploughing* to a depth of 28 to 30 cm, followed by leveling (P). Soil samples were collected in the autumn of 2015 from four depth increments (0–10, 10–20, 20–30, 30–40 cm). Soil moisture content (SMC), soil penetration resistance (SPR), soil texture, pH (H_2O), soil organic carbon (SOC), and earthworm abundance were measured. SMC and SPR were taken at 30-day intervals unless the weather prevented sampling. Earthworms were sampled *in situ* seven times per year by hand-sorting 25 × 25 x 30 cm soil blocks. No-tillage had a positive effect on crop yield and earthworm abundance. Compared to conventional tillage (P), SMC and SPR were improved by conservation tillage (DC, SC, D or NT). When measured during the summer months, SPR reached 6 MPa for all tillage treatments due to low SMC. Overall, NT had the highest earthworm abundance while conventional tillage (P) had the lowest. Maize (*Zea mays* L.) yield was highest with SC (9.32 Mg ha^{-1}), lowest with D (7.92 Mg ha^{-1}). For winter oat (*Avena fatua* L.), L resulted in the highest yield (5.87 Mg ha^{-1}) but required more time and energy. As weather patterns become more erratic, tillage has the potential to make crop production even riskier. Therefore, to improve both physical and biological soil properties, efforts should be made to decrease tillage intensity each year.

1. Introduction

Tillage is an elemental component in agricultural production (Lal, 1991), which affects the environmental components of the soil (Busari et al., 2015; Gao et al., 2017), it may improve, preserve or deteriorate soil quality (Birkás et al., 2015; Madari et al., 2005), with the aim of providing good soil conditions for proper growing. The main rules of conservation tillage system (minimum soil disturbance; *in situ* crop residue on top soil; crop rotations) are to enhance soil health (FAO, 2008; Thierfelder et al., 2013). Its positive effects were studied by several authors, e.g. decreasing the ill effects of seasonal dry-spells, creating higher soil moisture accessibility for crops under mulch retention (Kassam et al., 2012; Li et al., 2011), improved water infiltration, increased SOM and more stable crop yields (Hobbs, 2007; Paul et al., 2013), reduced impact of climate change (Kuhn et al., 2016).

Earthworms are considered important ecosystem engineers and one of the most valuable soil biological indicators (Doran and Zeiss, 2000; Van Capelle et al., 2012). Tillage is referred to as mechanical manipulation of the physical conditions of soils, by which it can affect earthworms directly and indirectly. As for direct effect, it can mechanically hurt or kill the earthworms (Johnston et al., 2018), and indirectly, it can drastically change soil environment, e.g. it can destroy earthworm burrows and habitats, it influences the physical conditions of soil, it incorporates plant residues deeper into the soil by removing the insulating plant matter on the topsoil, and thus reduce food supply, etc. By changing the physical conditions of the soil, including water content, soil temperature, soil structure can be also changed (Edwards and Lofty, 1982; Chan, 2001; Briones and Bol, 2003; Birkas et al.,

Abbreviations: D, disking; SC, shallow tine cultivation; NT, no-till; DC, deep tine cultivation; L, loosening; P, moldboard ploughing; CT, conventional tillage; SMC, soil moisture content; SPR, soil penetration resistance; SOC, soil organic carbon; SOM, soil organic matter

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2004).

Intensive ploughing, different tillage treatments, using different pesticides, fertilizers, etc. can have negative effects on invertebrate communities (Bengtsson et al., 2005; Doran and Zeiss, 2000). Earthworms are important components of the soil macrofauna and represent a great portion of soil biomass, it can go up to 80% (Yasmin and D'Souza, 2010). Many authors have reported that earthworms are sensitive to soil tillage activities (Chan, 2001; Hubbard et al., 1999) and their population declines on cropped fields when compared to grassy habitats (Mele and Carter, 1999; Springett, 1992; Francis and Knight, 1993; Postma-Blaauw et al., 2010; Frazão et al., 2017). Several authors found that earthworm abundance decreased when conventional ploughing was carried out compared to NT (House and Parmelee, 1985; Springett, 1992; Francis and Knight, 1993). However, there are researchers who reported that earthworm abundance did not decrease due to tillage treatments (Hopp and Hopkins, 1946; Doube et al., 1994). Doube et al. (1994) did not find any effect of tillage intensity, *i.e.* 0, 1, and 4 passes before sowing, on earthworm abundance one year after cropping. Furthermore, some authors found an increase in earthworm abundance after tillage treatments (Edwards and Lofty, 1969; Lee, 1985). Edwards and Lofty (1969) found this initial increase in earthworm populations only in the first two seasons, which was followed by the decrease of earthworm populations when further tillage treatments were carried out. Boström (1995) observed that intensive rotary cultivation, after which ploughing was also carried out, in alfalfa lays eliminated 73–77% of earthworms. However, after one year, the earthworm biomass and the abundance had recovered to the former level measured in the alfalfa ley. Lee (1985) reported that after the initial increase of earthworm abundance due to tillage, there was a gradual decrease when further tillage treatments were carried out. This could be due to the negative changes that occurred in the soil chemical and physical conditions, along with soil disturbance e.g. decrease of SOM content, deterioration of soil structure, soil aggregation etc., which results in dangerous soil degradation processes. Thus, tillage with suitable, well-chosen machinery can also increase earthworm populations, as it increases the availability of plant matter (food source), loosens the soil and improves soil physical conditions (Chan, 2001). The overall effect of tillage on earthworm abundance depends on several human induced factors: use of tillage equipment; depth, intensity and time of tillage; and also, environmental factors, e.g. soil moisture content, weather conditions during tillage treatments, soil types, texture, etc. (Chan, 2001).

A few of the above-mentioned papers presented the complex role of various soil tillage treatments in the regional relations. Therefore, the objectives of this paper were to compare the effects of six different tillage treatments on (1) soil chemical (SOC, pH(H_2O)); (2) soil physical parameters (SMC, SPR); (3) earthworm abundance; and (4) crop yield.

We hypothesized that (Hyp. 1) tillage treatments with no tillage (NT) or shallow disturbances (D, SC, DC) would probably have a greater SOC content when compared to traditional treatments; (Hyp. 2) tillage treatments (NT, SC, DC, L) would probably resist more against the negative effects of summer drought, in terms of SMC and SPR when compared to P. (Hyp. 3) NT and D would have greater SPR compared to P, due to greater soil compaction. (Hyp. 4) we assumed that NT, SC and DC would have the largest earthworm abundances compared to the other treatments, due to less soil disturbance and more favorable soil microclimatic conditions.

2. Material and methods

2.1. Location of the field site and description of the experiment

The study site is located at the Józsefmajor Experimental and Training Farm (JETF) of Szent István University (47° 41′ 30.6″ latitude N, - 19° 36′ 46.1″ longitude E; 110 m above sea level). The long-term experiment was set up in 2002 (Fig. 1). According to the World Reference Base Classification system, the soil is Endocalcic Chernozems (Loamic) with a clay loam texture (IUSS Working Group WRB, 2015). The experiment was arranged in a randomized block design with four replicates, and the area of each plot is 2340 m^2 (13 m × 180 m). The crops in rotation of the last three years were: in autumn 2015 winter wheat (*Triticum aestivum* L.), in spring 2016 maize (*Zea mays* L.) (Limagrain 33.30 (FAO 340)), in autumn 2016 winter oat (*Avena fatua* L.) ("Mv Hópehely", a Hungarian variety from Marton Genetics). The seeding rate of maize was 64,000 seeds/ha.

The maize harvest was carried out in 24th October 2016. The seeding rate of winter oat was 170 kg ha^{-1}. The winter oat harvest was carried out in 12th July 2017. In both cases, Claas Lexion 650 combine was used for harvesting. The crop yield was measured at the JETF of Szent István University. The accuracy of the scale was ± 10 kg. The seed emergence rate was observed during both vegetation years by visual method every month.

The fertilizer was applied before the tillage treatments and the seeding of winter oat was NPK 6-12-24 at a rate of 160 kg ha^{-1}. The fertilizer was applied before the tillage treatments and the seeding of maize was NPK 8-24-24 at a rate of 300 kg ha^{-1}. Calcium ammonium nitrate (N 27%) was added in one pass with maize seeding (Table 1).

In this study, six different soil tillage treatments were applied in 24 plots in four replicates from 2002 (Tóth et al., 2018). The following tillage treatments were applied: *disking* (D) [12–14 cm] (Väderstad Carrier 500); *shallow tine cultivation* (SC) [18–20 cm] (Kverneland CLC Pro); *no-till* (NT); *deep tine cultivation* (DC) [22–25 cm] (Kverneland CLC Pro); *loosening* (L) [40–45 cm] (Vogel & Noot TerraDig XS; with five tines, equipped with double spiked roller, total working width 2,5 m); conventional tillage - *moldboard ploughing + leveling* (P) [28–30 cm] (Kverneland LM100). Regarding the depth of loosening, 40–45 cm was chosen in order to break the plough pan in the soil in order to help water infiltration, air penetration and root growth. Details of tillage treatments (depth, plots size and the used equipment) are shown in Table 2.

In case of NT, sowing was carried out in the previous crop residue using Väderstad Rapid 300 C (working width: 3 m; row spacing seed: 125 cm; seed coulter pressure: min/max: 85/245 kg). Väderstad Rapid 300 C had mechanical metering, equipped with CrossBoard heavy system disc aggressive, two coulters by a unique mechanical linkage and packer wheel for consolidation. As a finishing operation, a mechanical following harrow creates a loose evaporation barrier to prevent surface crusting after heavy rain. Kuhn Maxima 6 (seed coulter pressure: until 150 kg/row; space between rows: 76 cm) was used for maize seeding. The field was leveled, and seeds were sown with a one-pass system.

2.2. Meteorological data

The climate is continental with average annual temperature of 10.3 and 15 °C, during the vegetation period (New et al., 2002). The average temperature above 10 °C is usually 183 days annually, and it is usually between 13th April and 13th November. The annual average precipitation (for the 1961-90 period, based on a climate dataset of the Climatic Research Unit) is 560 mm, of which 395 mm falls in the vegetation period (Fig. 2). The area of the Experimental Farm is below the average multi-annual rainfall in Hungary. There was no irrigation carried out on the experimental area.

2.3. Soil sampling and chemical analyses

The soil sampling was carried out in autumn 2015. The samples were taken from 0–10, 10–20, 20–30, and 30–40 cm depth in three repetitions. The soil parameters were determined according to the Official Hungarian Standards (MSZ) in the Soil and Plant Laboratory of János Neumann University in Kecskemét (the former College of Kecskemét). The pH(H_2O) was determined potentiometrically by 1:2,5

1st Replicate						2nd Replicate						3rd Replicate						4th Replicate					
D	SC	NT	DC	P	L	P	SC	L	DC	NT	D	DC	L	NT	D	P	SC	L	D	DC	SC	NT	P

Fig. 1. Layout of the long-term experiment at Józsefmajor Experimental and Training Farm (D – disking, SC – shallow tine cultivation, NT – no-till, DC – deep tine cultivation, P – ploughing, L – loosening).

soil to distilled water ratio with digital pH meter (HACH-LANGE, HQ411D) (MSz-08-0206/2–1978). According to the Hungarian Standards (MSZ-08-, 0452:, 1980), the soil organic carbon (SOC) was determined by the oxidization with the mixture of 5% $K_2Cr_2O_7$ + cc. H_2SO_4 with 1:2 ratio. The color of the mixture was measured by UNICAM Photometer (UV2 043,506).

2.4. Texture, soil moisture content and soil penetration resistance determination

The soil texture was determined by saturation percentage method (Buzás, 1993) in four depths (0–10; 10–20; 20–30; and 30–40 cm) in 2015. By this method, the amount of distilled water (cm^3) that 100 g of air-dried soil can adsorb to the upper limit of plasticity can be determined. The soil is homogeneously mixed with the gradually added distilled water until the so-called "thread probe" is reached. The consumed water can be read in the burette, and based on the reading the soil texture can be gained from tables.

All measurements for soil moisture content (SMC) and soil penetration resistance (SPR) were carried out at the same time. All plots were measured in three replicates at random, 5–10 m away from each other. Measurements were taken in 30-day intervals, except when the weather did not allow. The SMC was measured by PT-I type gauge (Kapacitiv Kft., Budapest, Hungary), LCD display showed the SMC in unit %, g g^{-1}. The SPR was measured with a handheld Szarvas-type penetrometer (Mobitech, Hungary). The conical point was 1 cm^2 in area with 60° angle. The measurement range was 0 to 150 lbf, at 2 lbf intervals (0 to 6.67 MPa). Multiplying the readings by 0.04448 yields the SPR values were converted in MPa. Data were grouped in soil layers 0–10 cm and 10–20 cm, respectively.

2.5. Earthworm sampling

The earthworms were sampled by hand-sorting *in situ* (25 x 25 cm, 30 cm deep) in all plots in four replicates according to the ISO Standards (ISO, 2006). The duration of hand sorting lasted about 30–40 minutes, depending on the physical status of the soil. The locations among replicates were chosen randomly and the distance between soil blocks was about 5–10 m. The earthworms were sampled seven times, in four replicates, in all tillage treatments in 2016 (20th April, 18th May, 20th June, 21st July, 19th August, 15th September, 29th October) and in 2017 (17th March, 25th April, 19th May, 20th June, 17th July, 15th August, 11th September). The earthworm abundance was expressed (ind m^{-2}).

2.6. Statistical analyses

The effects of tillage treatments on SMC and SPR were investigated using one-way ANOVA with Tukey HSD (Honestly Significant Difference) multiple comparison post-hoc tests. ANOVA uses F-tests to statistically assess the equality of means. The ANOVA F-test is always robust to variance heterogeneity when sample sizes are equal (Rogan and Keselman, 1977). The sample sizes in our statistical analyses were equal: $n_D = n_{SC} = n_{NT} = n_{DC} = n_L = n_p = 4$ plots x 3 replicates = 12 observations for each sampling date (7 in 2016 and 7 in 2017), for two depths (0–10, 10–20 cm). A Balanced design where sample sizes are

Table 1
List of tillage treatments, applied equipment, working depths, widths, and plot dimensions in the experiment.

Tillage treatments	Equipment	Working depth (cm)	Working width (cm)	Plot dimension (m)
Loosening (L)	Vogel & Noot TerraDig XS	40-45	250	4 × (13 × 180)
Moldboard ploughing + leveling (P)	Kverneland LM100 + packomat	28-30	160	
Deep tine cultivation (DC)	Kverneland CLC Pro	22-25	300	
Shallow tine cultivation (SC)	Kverneland CLC Pro	18-20	300	
Disking (D)	Väderstad Carrier 500	12-14	500	
No-till (NT)	Väderstad Rapid 300 C or Kuhn Maxima 6	3-5 (rows)	300 76 × 6	
Seeding (Maize)	Kuhn Maxima 6	5-6		
Seeding (Winter oat)	Väderstad Rapid 300 C	4-6		

Table 2
The timetable of agricultural management.

Year	Culture	Management history	Seeding rate	Doses	Date
2015	Winter wheat stubble mulch	Fertilizing (NPK 8-24-24)		300 kg ha^{-1}	27th October
		Primary soil tillage			28th October
2016	Maize	Seedbed preparation			7th April
		Sowing	64 000 ha^{-1}		8th April
		Fertilizing (N 24)		300 kg ha^{-1}	8th April
		Plant protection*		3 l ha^{-1} Successor T	23rd April
				400 g ha^{-1} Principal Plus + 0.1 % ha^{-1} Trend 90	20th May
		Harvest			24th October
		Fertilizing (NPK 6-12-24)		160 kg ha^{-1}	28th October
		Soil tillage			29th October
		Sowing of winter oat	170 kg ha^{-1}		1st November
		Plant protection**		30 g ha^{-1} Granstar 50 SX	27th April
				0.5 l ha^{-1} Starane Forte 333 EC	12th May
				0.6 l ha^{-1} Sólyom 460 EC	18th May
2017	Winter oat	Harvest			12th July

* Active ingredients in Successor T (300 g/l pethoxamid + 187,5 g/l terbuthylazine); Principal Plus (92 g/kg nicosulfuron +23 g/kg rimsulfuron +550 g/kg dicamba); Trend 90 (90% ethoxy-isodecyl alcohol).

** Active ingredients in Granstar 50 SX (500 g/kg tribenuron-methyl); Starane Forte 333 EC (fluroxypyr 333 g/l); Sólyom 460 EC (167 g/l tebuconazole +43 g/l triadimenol +250 g/l spiroxamine).

equal across groups assumes homogeneity of variance. Tukey's HSD procedure allows the comparison of all pairs of means. When used with equal sample sizes, the family-wise error rate is exactly equal to the probability of a Type 1 error (Kao and Green, 2008). The type I error rate (α) was set at 0.05 for all statistical tests. *Box plots* were used to assess the dispersion and range of the data trend in the examined parameters.

3. Results

3.1. Soil chemical parameters

The *soil organic carbon* (SOC) content was determined in 2015 in four depths (Fig. 3). The SOC values showed gradual decrease with increasing depth. The greatest SOC values were obtained in NT (2.3%), while the lowest in P treatment (1.8%) at 0–10 cm depth. Significant differences in SOC content among tillage treatments was not found ($p = 0.55568$), however, according to the measurement depths, there have been many significant differences found at the surface layer (0–10 cm) ($p = 0.005$), while not in other depths. Significant differences were present among P < DC; P, L < D; P, L, SC < NT treatments.

The *soil pH(H_2O)* values were measured in four depths in 2015 potentiometrically, they were between 5.5 and 6.4 (slightly acidic) when all treatments and all depths were considered. They increased slightly with increasing depth in all cases. Significant differences were found among tillage treatments ($p = 0.003162$). Significant difference was found between DC and SC treatments (DC < SC), and DC, D, L, NT treatments were lower in comparison to P. Considering the measurement depths, significant differences were found in the surface layer (0–10 cm) ($p = 0.013598$). The highest value was obtained in P (6.1), while the lowest in NT (5.5) treatment. Furthermore, at the same depth, significant differences were found among NT < L; NT, D < SC; NT, D, DC < P treatments. At the other three depths there was no significant difference.

3.2. Soil physical parameters

The *soil texture* was determined in four depths by the saturation percentage method (Buzás, 1993) in 2015. The soil texture was *clay loam* at all examined depths and in all the treatments.

The *soil moisture content* (SMC) was measured in 2016 (Figs. 4 and 5) and 2017 (Fig. 6) fourteen times. The measurements for SMC were carried out on the same day as SPR at two depths (10 and 20 cm). In *2016*, there was not any significant difference found among treatments in the first five measurements (from April through August). The first significant difference was observed in September 2016 at both depths (10 and 20 cm). At 10 cm depth, the greatest SMC was found in DC (26.06%) as compared to P treatment (21.24%), which showed the lowest value (Fig. 4). At 20 cm, significant difference was measured at NT (27.11%) in comparison to P treatment (24.13%) (Fig. 5). In October, the highest SMC at both depths was measured in D (27.52% at 10 cm and 28.73% at 20 cm, respectively), which was significantly different compared to L (25.14% at 10 cm, and 26.86% at 20 cm, respectively) and P treatments (24.24% at 10 cm, and 25.01% at 20 cm, respectively).

In *2017*, the SMC measurements were taken between March and September (Fig. 6). There was not any significant difference among the

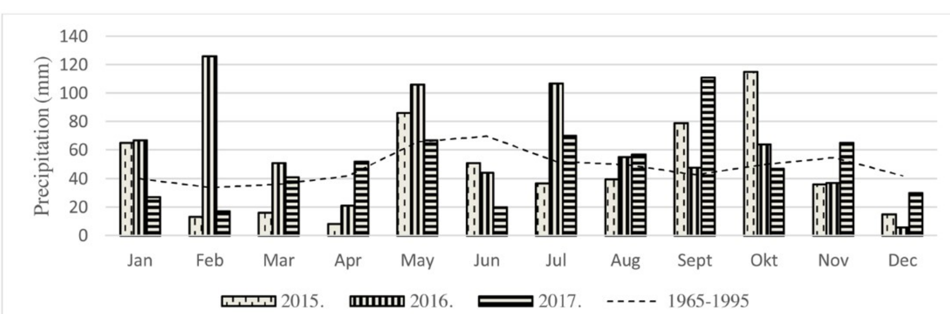

Fig. 2. The average precipitation between 1965–1995, and the measured monthly precipitation data between 2015–2017.

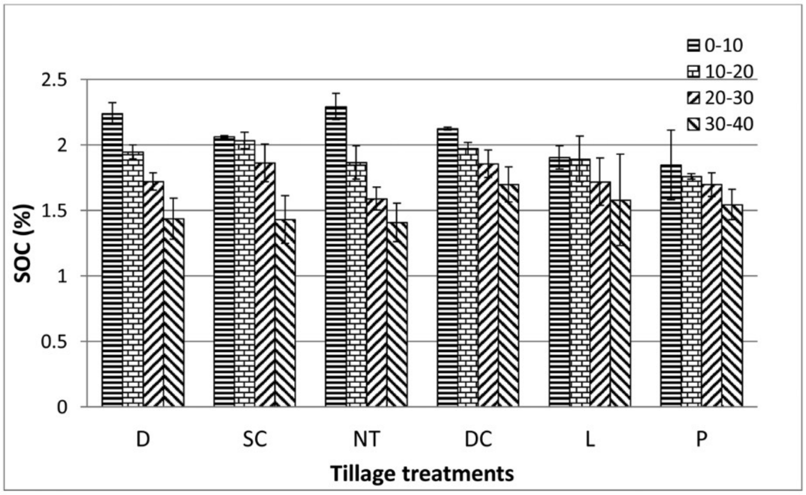

Fig. 3. Soil organic carbon content of soil under different tillage treatments (D – disking, SC – shallow tine cultivation, NT – no-till, DC – deep tine cultivation, L – loosening, P – ploughing).

tillage treatments at 10 cm, except for March, when D had the highest SMC (21.89% at 10 cm) compared to L (20.47%). In April, the lowest SMC (10 cm) was measured in L (24.29%) and the second lowest in DC (25.18%). The SMC was the highest for all treatments in May. The SMC data in June and July did not show any significant differences, therefore they are not shown in Fig. 6. In September, the highest SMC was measured at D (28.95%) and NT (26.46%) at 10 cm depth, while DC (18.95%) had the lowest value. According to the SMC between the lowest value of DC (18.95%) and P (21.70%) there was no significant difference. At 20 cm depth, the lowest SMC was measured at P (24.10%) and L (25.48%) and the highest at SC (28.12%) and NT (28.41%) (these values are not shown in the article). Significant differences were observed among the measurements in June and September. It was found that in June, DC (11.22%) had the highest SMC and the same treatment showed the lowest SMC value in September. However, NT (9.62%) and P (9.30%) showed the lowest SMC in June, whereas in September the same treatments gave the highest SMC.

Soil penetration resistance (SPR) was measured in 2016 and 2017, in fourteen times (Figs. 7 and 8). All measurements were carried out in areas where there was no soil compaction due to traffic.

Since there were no significant differences found among the tillage treatments on SPR in 2016, at 10 cm depth, thus this figure was not included in this article. D (1.74 MPa) and NT (1.68 MPa) had similar values in **May** (10 cm). In June (10 cm), D had the highest (4.04 MPa) and P had the lowest (2.17 MPa) value. The trend for July and August did not change significantly. In September NT was the greatest and SC was the lowest. In October, L (2.17 MPa) had the highest value compared to NT (1.83 MPa) and D (1.79 MPa), and P was the lowest.

In April 2016, at 20 cm depths significant differences were observed between D (2.06 MPa) and NT (1.99 MPa) in comparison to P (1.01 MPa) (Fig. 7). There were no significant differences between P and L. The tendency was the same in May, however, the difference was

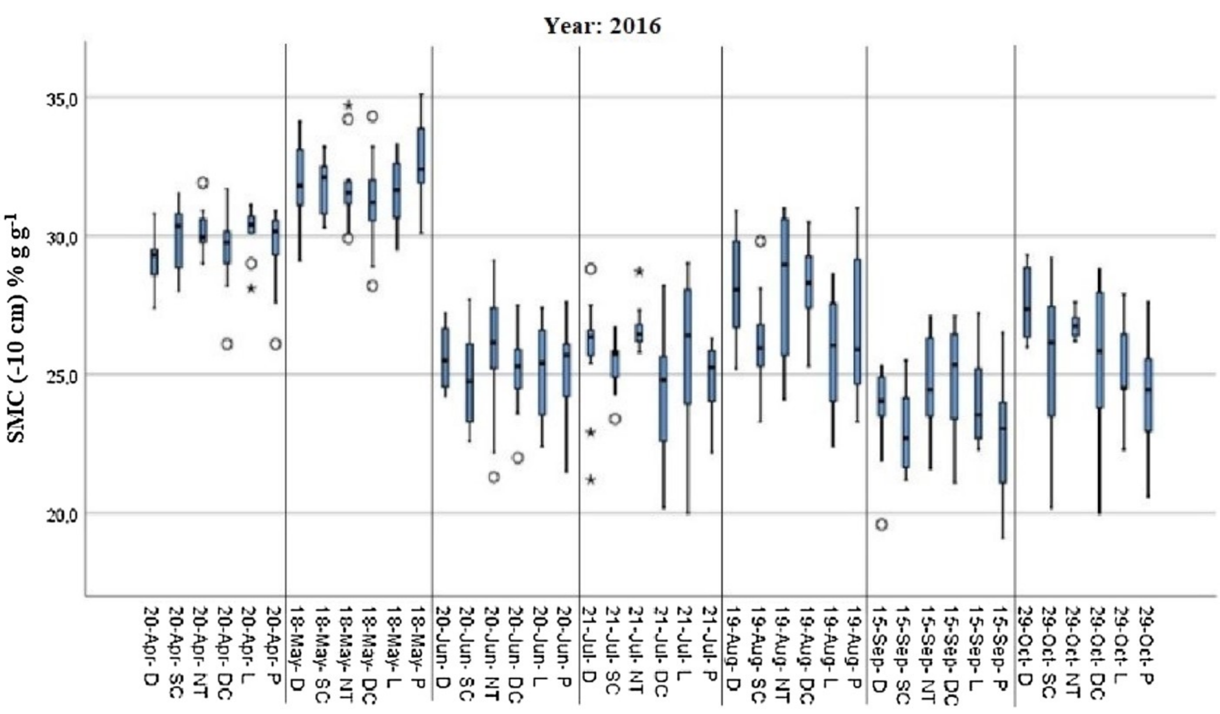

Fig. 4. Soil moisture content values measured at 10 cm depth in 2016 (April to October).

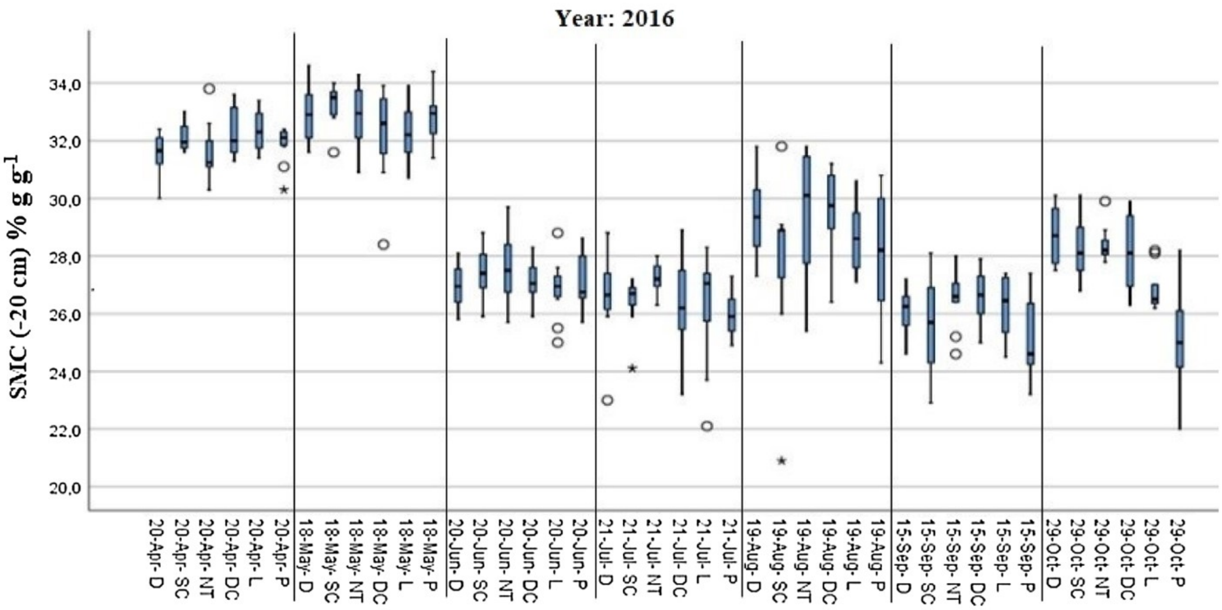

Fig. 5. Soil moisture content values measured at 20 cm depth in 2016 (April to October).

not significant. In June, the SPR value in P (2.45 MPa) reached the NT (2.94 MPa), this tendency continued in the summer (July, August). In September, the highest value was gained in D and NT, and lowest in SC and DC. In October, NT (3.04 MPa) had the highest value, followed by L (2.82 MPa), then D (2.46 MPa). NT was significantly greater than D, SC, DC, and P.

In March 2017, at 10 cm depth, D (1.55 MPa) had the highest SPR value without significant differences to DC (1.20 MPa) (Fig. 8). In April, D and NT had the highest values (1.32 MPa and 1.24 MPa, respectively), which showed a significant difference in regarding to DC, L and P. In May, NT (4.52 MPa) and D (3.74 MPa) values increased compared to the previous measurements, but without significant difference. NT was stronger compacted compared to SC, DC, L and P. In June, there was no significant difference among the treatments. The lowest was 5.75 MPa, and the greatest 6.01 MPa. In July, NT was significantly greater than SC, DC, P and L. (The results of June and July are not included in Fig. 8). In August, the highest was NT (4.36 MPa), and the lowest was P (2.66 MPa). [The following significant differences were found in August: P and L < SC, D, NT; DC < D and NT; SC < NT.] In September, the greatest was D (2.49 MPa), and the lowest was P (0.95 MPa). [Significant differences were found: P, DC, SC, and L < NT and D; NT < D.]

The SPR values in 2017, at 20 cm depth are not shown only discussed in this article. In March 2017 at 20 cm the highest was D (2.01 MPa) and the lowest was P (1.27 MPa). [Significant differences were found: P, L, DC, SC < NT and D; DC < D]. In April, the highest value was obtained in D (1.89 MPa) and the lowest in L (1.11 MPa). [L, P, DC, SC < NT and D]. In May, the highest was in D (4.49 MPa), and

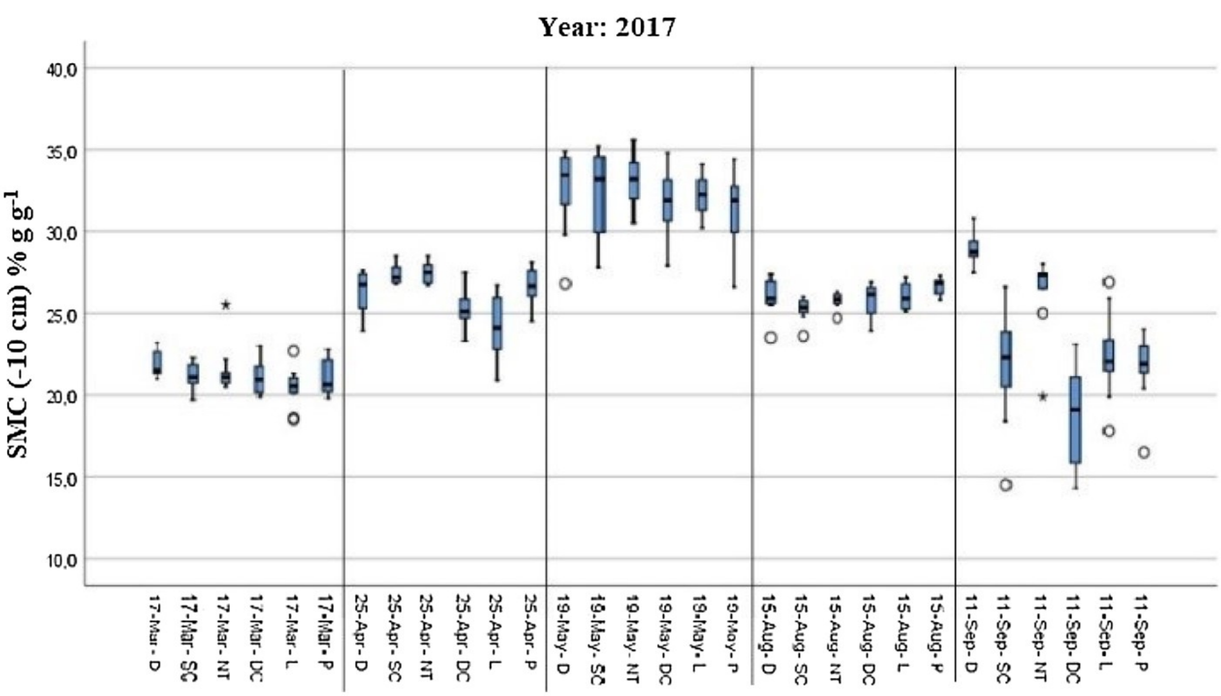

Fig. 6. Soil moisture content values measured at 10 cm of depth in 2017 (March to September).

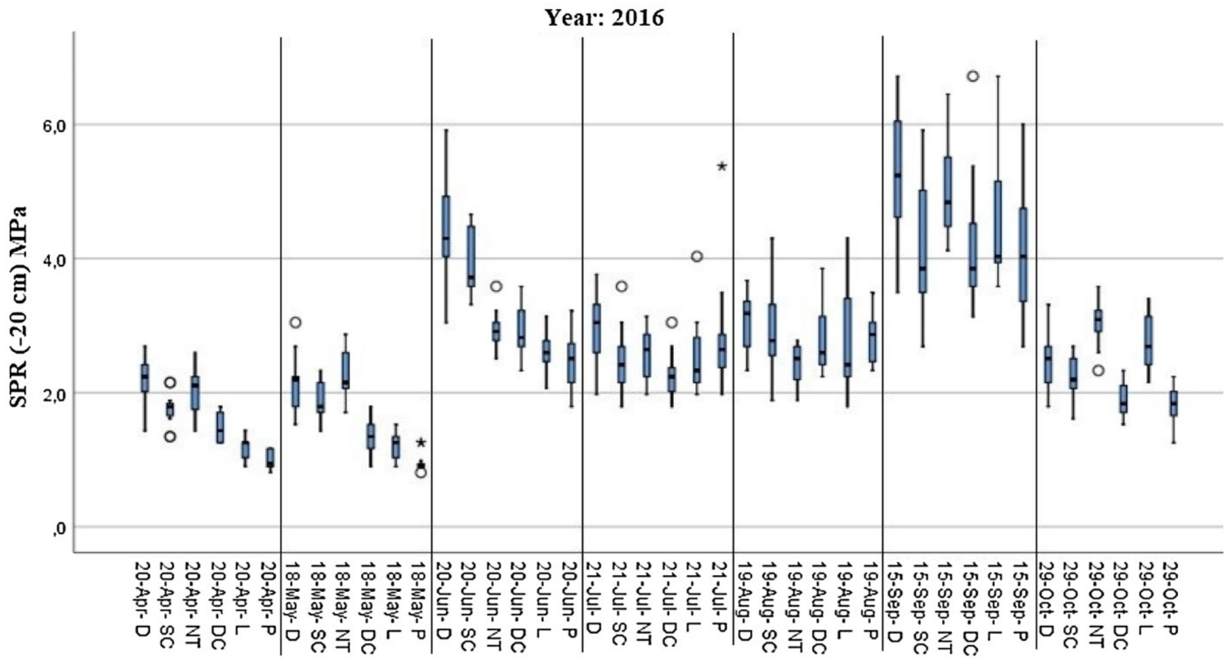

Fig. 7. Soil penetration resistance measured at 20 cm of depth in 2016 (April to October).

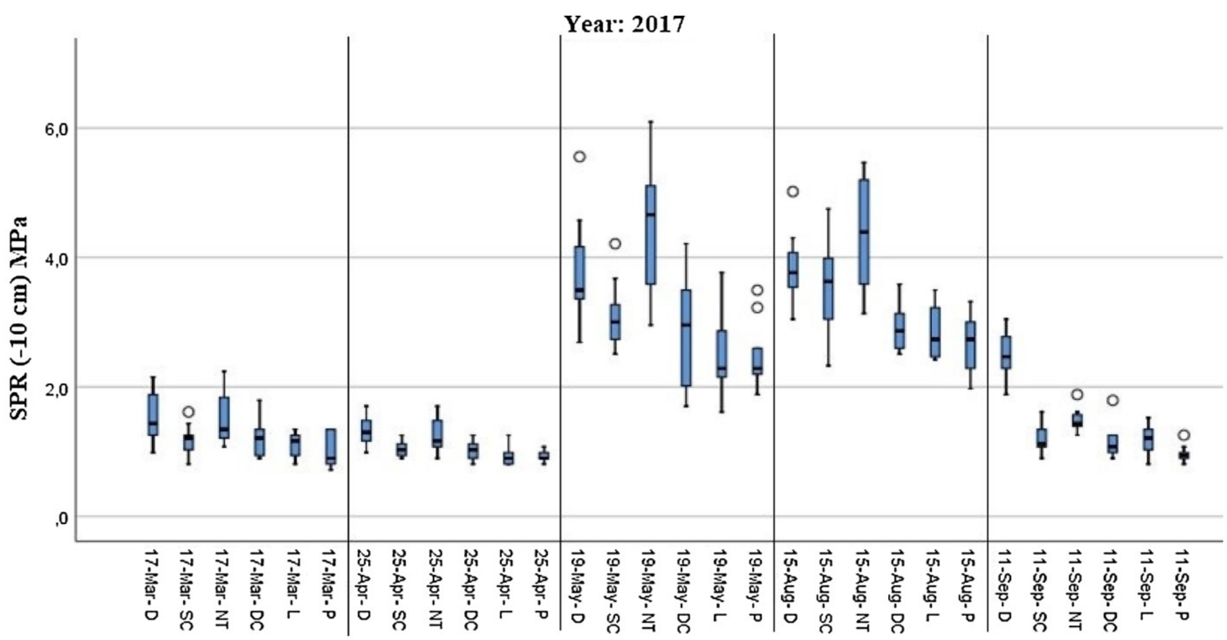

Fig. 8. Soil penetration resistance measured at 10 cm of depth in 2017 (March to September).

the lowest was P (2.89 MPa). [P < SC, NT and D; DC, L < D]. In June and July, there was not any significant difference found, all treatments reached the 6.67 MPa values. In August, the highest was NT (4.74 MPa), and the lowest was L (3.68 MPa). [L, P, DC < SC, D and NT]. In September, the highest was D (2.84 MPa), and the lowest was P (1.23 MPa). [P < SC, NT and D; SC < NT and D; NT < D].

3.3. Earthworm abundance

In April, *2016* the earthworm abundance in NT (117.3 ± 14.9 in. m^{-2}) were similar to D (96 ± 10.7 in. m^{-2}), and they were significantly greater than the other treatments (P, L, SC, and DC) (Fig. 9). In May the earthworm abundance in NT (538.7 ± 29.3 in. m^{-2}) was significantly higher than all the other treatments. This was followed by the SC and DC (346.6 ± 26.8 in. m^{-2}, and 330.6 ± 27.1 in. m^{-2}, respectively), which were also significantly greater than D, L, and P. Under D (154.6 ± 20.9 in. m^{-2}) and L (160 ± 21 in. m^{-2}) the earthworm abundance was about half of SC and DC, and approximately one third of NT. The lowest value was obtained in case of P (42.6 ± 12.4 in. m^{-2}). In June the earthworm abundance was significantly greater in NT (41.7 ± 17.1 in. m^{-2}) compared to P, D, and L. In July it was significantly higher in NT (58.6 ± 15.9 in. m^{-2}) compared to P and D. In August there was no significant difference found among treatments. In September, the greatest abundance was in NT (117.3 ± 14.9 in. m^{-2}), then in DC (106.6 ± 14.2 in. m^{-2}). NT was significantly higher than L, SC, D, and P. In October, the greatest abundances were obtained in NT (154.6 ± 18.6 in. m^{-2}), DC (128 ± 16.7 in. m^{-2}), and L (101.3 ± 15.9 in. m^{-2}). NT was

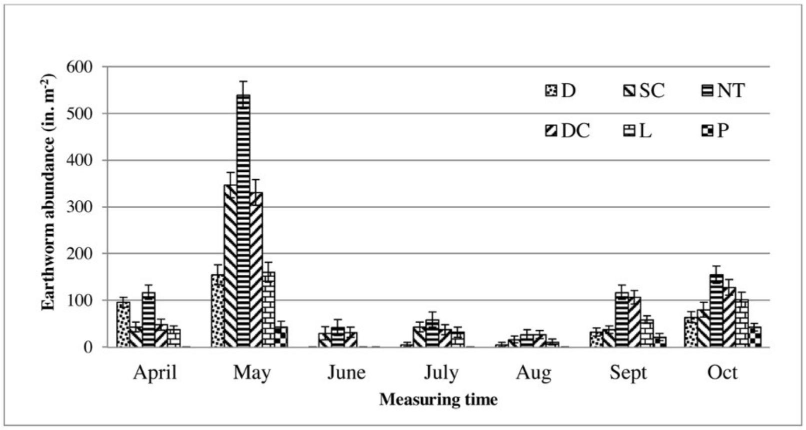

Fig. 9. Earthworm abundance under different tillage treatments (2016) (D – disking, SC shallow tine cultivation, NT – no-till, DC – deep tine cultivation, L – loosening, P – ploughing).

significantly greater than SC, D, and P.

In March, *2017* the greatest earthworm abundance was found in SC (224 ± 24.1 in. m^{-2}), followed by NT (160 ± 12.7 in. m^{-2}) and L (149.3 ± 19.6 in. m^{-2}) (Fig. 10). The abundance among these treatments did not differ significantly, however, they were significantly greater than DC, D, and P. In April, the greatest abundance was obtained at NT (501.3 ± 25.3 in. m^{-2}), followed by SC (266.6 ± 27.1 in. m^{-2}), L (202.6 ± 19 in. m^{-2}), and DC (192 ± 21.5 in. m^{-2}), which did not differ from each other significantly. NT was significantly higher than all the other treatments. In May, the greatest abundance was found in NT (133.3 ± 12.6 in. m^{-2}), which differed significantly from all the other treatments. In June, the greatest abundance was gained in DC (53.3 ± 9.2 in. m^{-2}), followed by SC (26.6 ± 8.2 in. m^{-2}), and NT (26.6 ± 10.6 in. m^{-2}). These three treatments did not differ from each other significantly; however, they were significantly greater than L, P, and D. In July and August, there were hardly any detectable earthworms in the field, the abundance did not differ from each other significantly. In September, the abundance was higher than in the summer months, but the differences were not significant either.

3.4. Crop yield

Crops were harvested each year from each plot with combines and grain weights were taken directly on the combine or before grain transfer to the gatherer wagon. Grain samples from each plot were also collected. The *maize* yields are presented in Mg ha^{-1} at 14.5% grain moisture content (Fig. 11). The greatest yield was gained in case of the SC treatment (9.32 Mg ha^{-1}). All the other treatments showed similar values, between 7.92 and 8.46 Mg ha^{-1}. The difference among the treatments was not significant. In both cropping seasons, the fuel consumption in case of NT and D as crop production was lower than the other treatments, according to the number passes. The lowest yields were measured in D: 7.92 Mg ha^{-1}; and NT: 8.05 Mg ha^{-1} treatments.

The *winter oat* grain yield is shown in Fig. 12. There were greater differences in oat yield among the tillage treatments compared to the maize grain yield in 2016. The first three greatest values were obtained for L (5.87 Mg ha^{-1}), P (5.68 Mg ha^{-1}), DC (5.68 Mg ha^{-1}). The difference among these was not significant. The fourth greatest value was obtained in SC (5.29 Mg ha^{-1}). The lowest yield was measured in D (4.49 Mg ha^{-1}). Generally, tillage treatments had significant effects on winter oat yield, the following order was found: L > P > DC > SC > NT > D. [Significant difference was found among: L > SC, NT, D; P > SC, NT, D; DC > NT, D; SC > NT, D].

4. Discussions

The *SOC values* showed gradual decrease with increasing depth under different tillage treatments (Fig. 3). The greatest SOC content was found in NT (2.3%), which was significantly greater ($p = 0.005$) than SC, L, and P (0–10 cm). The remaining plant residues could contribute to the accumulation of SOC at the top of the soil (Gál et al., 2007) in

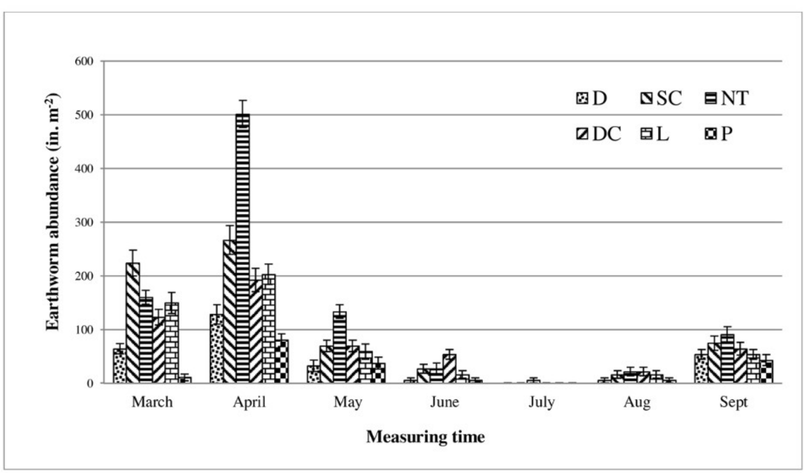

Fig. 10. Earthworm abundance under different tillage treatments (2017) (D – disking, SC – shallow tine cultivation, NT – no-till, DC – deep tine cultivation, L – loosening, P – ploughing).

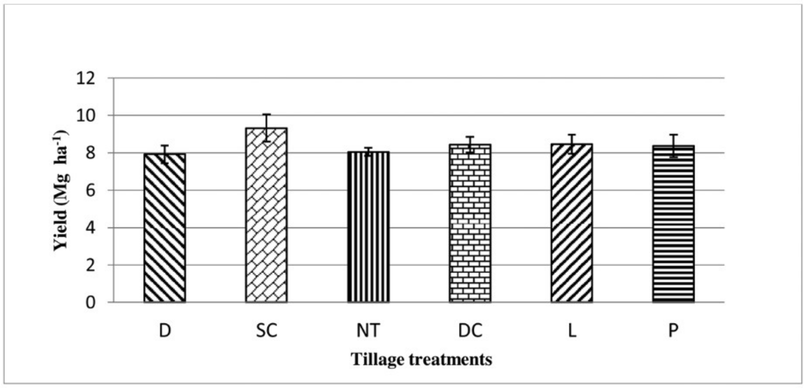

Fig. 11. Maize grain yield in 2016 (D – disking, SC – shallow tine cultivation, NT – no-till, DC – deep tine cultivation, L – loosening, P – ploughing).

case of such an undisturbed system. Eriksen-Hamel et al. (2009) found that the SOC values were affected by the tillage, ie. NT resulted in highest SOC, followed by reduced tillage, then CT.

Our measurements indicated the lowest SOC in P (1.8%) at 0–10 cm depth, and the SOC value remained relatively constant throughout the four depths. However, in other tillage treatments, the decrease in SOC was very sudden, especially between the first two depths, as in NT, D and DC treatments. These treatments do not disturb the soil, thus leave relatively high amount of plant residues in the top soil, which can result in greater SOC in the 0–10 cm depth as compared to the next depth (10–20 cm). Gál et al. (2007) found that the increase of SOC in P at 30–50 cm depth was probably due to the turning of plant remnants into the 20–25 cm depth by annual ploughing, while in NT plant residues are not incorporated into the soil, thus, remain on the topsoil.

Our first hypotheses, i.e. tillage treatments with no (NT) or shallow disturbances (D, SC, DC) would probably have greater SOC when compared to traditional treatments, was partially justified. In case of NT and DC, significantly greater SOC values were gained in the top layer (0–10 cm), however, in case of SC, we did not get significantly greater SOC compared to the traditional treatments. Furthermore, the SOC in D was significantly greater than in P and L, which might be due to the relatively shallow soil disturbance under D (12–14 cm) as opposed to P (26–30 cm) and L (40–45 cm) treatments.

In the first five measurements (April–August 2016), there was not any significant difference found in *SMC* (Fig. 4). Precipitation (Fig. 2) was erratic during this period, however, it did not have any significant impact on SMC, which disagreed with Josa and Hereter (2005), which pointed out significant differences between NT > minimum tillage > CT from February till May. The amount of precipitation in August and September was average. The SMC was significantly lower in P in both depths (than DC at 10, and NT at 20 cm). The SMC retained in DC probably originated from the rainfall in August and September, in contrast to NT. Since SMC in NT was the greatest in lower depth, we assume that it originated from the rainfall in July, August and September due to the low evaporation through residue cover. Guan et al. (2015) found that NT contributed to the best moisture preservation. In October, our results showed significant differences between D > L = P in both depths. This finding pertains to the low SPR values at L and P, which contribute to the high water infiltration capacity of these treatments. In the shallowest tillage (D) probably the created disk-pan prohibited the intensive water infiltration and percolation. Zsembeli et al. (2015) stated that undisturbed treatments have the smallest surface area for evaporation and relatively high natural soil compaction, which inhibits infiltration. SC, DC and L compared to P had greater capacity to retain moisture. Bescansa et al. (2006); Morell et al. (2011) highlighted positive effects of conservation tillage on SMC and water availability. The P treatment was the most subjected to weather conditions due to the low residue cover (Table 3).

In March 2017, the greatest SMC was at D, while NT in April, which can be explained by the highest SPR (Fig. 8). L had the lowest SMC and lowest SPR in both months, which indicated a better water permeability. The ratio of macropores to micropores decreases, thus soil bulk density and SPR increase (Chen et al., 2014). The difference between the D and L, was 1.42%, and between NT and L, was 3.19%. NT had strong positive effect on soil moisture holding capacity, due to lower evaporation. In May, the greatest SMC values were measured throughout the year, which was caused by the 60 mm precipitation between two measurements. The amount of rainfall was lower (71,43%) compared to the long-term average in June (Fig. 2). The rainfall in July was higher than the average precipitation in 2016 and 2017 as well. In this region the summer months are usually the driest and the hottest. SMC was homogenous and higher than expected in August, due to the higher precipitation (55 mm) between two measuring times. The rainfall in September was twice as much (111 mm) compared to the average values (approximately 45 mm). There was 48 mm rainfall between 1st and 11th of September, which could hardly

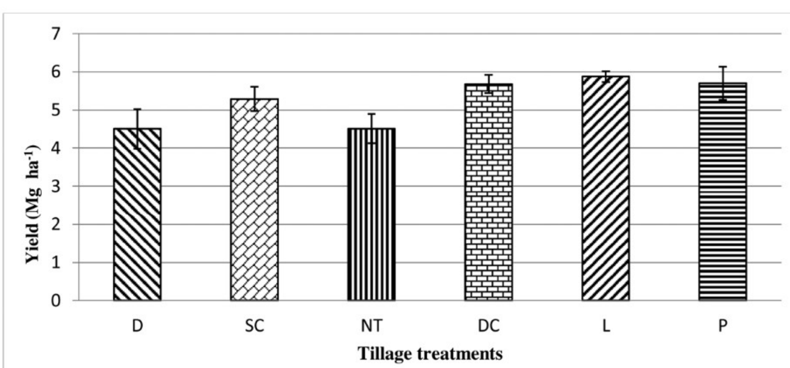

Fig. 12. Winter oat grain yield in 2017 (D – disking, SC – shallow tine cultivation, NT – no-till, DC – deep tine cultivation, L – loosening, P – ploughing).

Table 3
The average amounts of stubble covering on the different tillage treatments.

		Tillage treatments					
	Date	D	SC	NT	DC	L	P
Average (%)	21st March 2016	13,66	41,95	80,54	32,70	41,53	4,93
	17th March 2017	19,60	24,64	46,19	17,63	17,00	2,62

infiltrate in the soil in D and NT treatments, furthermore the evaporation was low due to the mulch cover. Huang et al. (2008), Jalota et al. (2006) and Lampurlanés and Cantero-Martínez (2006) also indicated that crop residues on soil surface decreased evaporation. The deep tillage treatments (P and L) provide greater soil moisture storage capacity, due to the loosened topsoil and greater infiltration rate. These tillage treatments are frequently used in order to infiltrate in deeper layers and store as much precipitation as possible due to the erratic rainfall. The aim is to capture and preserve the moisture in the soil for crop growth especially in drier periods. The extreme climatic conditions are more and more common in temperate region, thus soil moisture preservation is a crucial factor.

Sharma et al. (2009) stated that minimum tillage, straw mulching and polyetilen preserved most of the moisture, ensuring better infiltration of water and enhancement of water-holding capacity.

Considering all the depths and measurements, the greatest SMC values were obtained in most cases in D and NT, while the lowest in P treatment. A layer of crop residues reduced evaporation and preserved SMC, while P was uncovered and subjected to evaporation. Similar findings were also reported by Enz et al. (1988), who found a higher level of evaporation under dark-coloured soil (below 8%) compared to soil surface covered by wheat stubble and residue. Our SPR results also indicated, that water permeability in D and NT was very low near the surface layer (5–15 cm) due to soil compaction (Fig. 8).

Our second hypothesis, i.e. tillage treatments (NT, SC, DC, L) would probably resist the negative effect of summer drought, in terms of SMC when compared to P. In most cases, the highest SMC was gained in NT, DC, D, and sometimes SC treatments. The summer periods had the lowest SMC. Among all treatments, P had the lowest SMC in most cases, probably due to the relatively dark surface and strong exposure to sunlight, which was confirmed by Hungarian (Zsembeli et al., 2015; Birkas et al., 2004) and international findings (Enz et al., 1988; De Moraes et al., 2016).

When both depths (10 and 20 cm) were considered in 2016, the highest *SPR values* were found in most cases in NT and D treatments (maximum mean values: 2,06 MPa and 4.04 MPa, respectively) (Fig. 7). The lowest values were obtained in P (minimum mean value: 1.01 MPa). Hulugalle and Palada (1990) also pointed out that compaction of the soil decreased in the following order: no-till > minimum tillage > ploughing. At both depths, the SPR was low in spring months (April, May), but D and NT raised above these other values. Birkas et al. (2004) stated negative effects of D treatment, especially settling and disk-pan formation, which was established after the fifth year. Bottlik et al. (2013) outlined that soil settling as typical phenomena, which is more noticeable in the first half of the year and greatly depends on soil quality. Cheng et al. (2012) also found that various unfavorable weather conditions and tillage systems had great impact on soil surface porosity, i.e. through time on the soil settling. In the summer months (June, July, August), the SPR values were generally higher than the previous months. The SMC was relatively high in both depths in spring months, which might have caused the low SPR (Figs. 4 and 5). However, in summer months the SMC was low at both depths, and the SPR values were high. In September, SPR reached the highest values in NT and D in both depths, and SC and DC gave the lowest ones. In contrast to our expectations and our previous findings, the greatest value was obtained in case of L (2.17 MPa) in October (10 cm), followed by NT (1.83 MPa) and D (1.79 MPa), without significant differences. (Fig. 6) Notwithstanding, at 20 cm depth, the SPR was the greatest in NT, followed by L and D. These values are not considered high, and they did not have any negative effects on root growth and yield at this phase of the vegetative period. The maize harvest was carried out a couple of days earlier than the SPR measurements (Table 2).

Our experiment indicated that the highest *SPR values* were found in most cases in NT and D treatments (maximum mean values for NT and D: 6.67 MPa) (Fig. 8) when both depths (10 and 20 cm) were considered in 2017. Similar findings were also reported by Lipiec et al. (2012). They found that SPR and bulk density values increased significantly under a compacted headland (Orthic Luvisol) as compared to an uncompacted bulk field. In early spring months (March and April), SPR values did not exceed 2 MPa values, thus there was probably not any negative effect caused to the root development. In May at 10 cm, NT and D values increased by 364.5% and 283.3%, respectively, compared to the previous measurements (April), but without any significant difference between NT and D. In summer months (June, July) there was an extreme increase in SPR, the maximum measured value was above 6 MPa. These high values can be explained by the very low precipitation in June (20 mm), regardless of tillage treatments. This rainfall was about one third of the average monthly precipitation (Fig. 2). In August, the rainfall was above average (63.5 mm), which probably decreased the SPR values in all treatments. Moreover, the stubble residues (winter oat straw) had a positive effect on SPR. In September, the SPR values decreased below the 2 MPa value, except for D, due to the extremely high precipitation (between the two measurements: 70 mm) and the stubble residues. The D treatment can cause disk-pan formation in shallow depth and at the same time, silt film can be formed on the surface.

Our third hypothesis, ie. NT and D had greater SPR compared to P was justified. In case of NT, there was no physical disturbance applied in the soil, thus, after a while it became quite compacted, regardless of the activity of soil organisms. As for D, the depth of disking operation was between 12–14 cm, and after several years disk-pan was formed, which increased the SPR to a great extent. During disking operation, a great amount of silt fraction was produced as the soil structure was broken into smaller units, which later settled and plugged the soil pores. As a result, the disk-pan became gradually thicker by time. That may be the reason why we gained high SPR values and thus greater soil compaction in this treatment. According to the agronomic structure of the visually examined soils, D and P treatment showed the worst agronomic structure (dusting, crusting, and consequently silt leaching, siltation).

Based on all the *earthworm abundance* data in 2016 and 2017, the greatest abundance was gained in NT (in 12 times out of 14 cases), while in two cases other treatments gave the highest abundance (SC - March 2017; and DC - June 2017). In 13 cases, the lowest values were obtained for P treatment, and in only one case D (May 2017) gave the lowest abundance. According to the significance level, NT was significantly greater 8 times out of the 14, while in other cases, either there were no significant differences among the results, or other treatments gave the greatest values (SC and DC). Gerard and Hay (1979) found greatest earthworm abundance in NT, then P and tined cultivation, and the lowest abundance in deep ploughing. Kladivko et al. (1997) found that out of 14 paired sites, in eight sites greater earthworm abundance was obtained at NT compared to conventionally tilled sites. Birkas et al. (2004) found the greatest earthworm abundance under NT compared to P. Eriksen-Hamel et al. (2009) found that earthworm abundances were significantly higher in the NT compared to reduced and conventional tillage treatments in sandy-loam soils. D'Hose et al. (2018) found that both shallow non-inversion tillage and NT had significantly greater earthworm abundance compared to P, while no significant differences were observed in deep non-inversion tillage.

Boone et al. (1976) found that earthworm abundance was three times higher under NT compared to P treatment. Chan (2001) found, based on several international studies, that the total earthworm abundance under NT can be 2–9 times higher than in CT treatments. In our experiment, the abundance in NT was 2–16 times greater than P.

The higher earthworm population in NT can be explained by several biotic and abiotic factors. These are: (a) disturbance and/or physical injury from tillage operations is minimal, (b) the availability of food (plant residue) (Gerard and Hay, 1979; House and Parmelee, 1985; Curry, 1998; Chan, 2001; Schmidt et al., 2003; Eriksen-Hamel et al., 2009; Postma-Blaauw et al., 2010). Since earthworms were provided different plant residues throughout the year in NT system, they can grow and proliferate more rapidly in these soils. (c) The higher SMC that can be preserved in less disturbed systems is also very important, thus, these factors can provide a good habitat for earthworm growth, with longer periods for feeding and cocoon production (Gerard and Hay, 1979; Chan, 2001). The SMC was also high in NT, SC, D and DC treatments in our experiment; thus, this abiotic factor could also contribute to greater earthworm abundances. Other soil physical factors like (d) soil compaction, which can greatly affect earthworm abundance. However, in our research, the SPR values were highest at NT and D treatments in most cases, but the earthworm abundance was high in these treatments. Thus, the interacting effects of all the above-mentioned parameters are responsible for determining earthworm abundance and not only one parameter by itself (van Capelle et al., 2012).

Our fourth hypothesis, i.e. NT, SC and DC would have the largest earthworm abundances compared to the other treatments was justified. As for NT, as mentioned earlier, it had significantly greater earthworm abundances in most cases. SC and DC also had great abundances, fairly close values to NT data. The reason for this could be less soil disturbance, thus preserving more plant residues on the soil.

Even though, the earthworm abundance was the highest in NT treatment in most cases, we did not gain higher *yield*, as one would have expected. In April 2016, the precipitation (Fig. 2) was about 50% lower than the average between 1965-95. In May, the precipitation (106 mm) was higher than the average, however, in NT treatment the infiltration and storage of moisture was generally low due to higher soil compaction. There was 46 mm rainfall in 24th, May 2016 which is an extreme amount of rainfall within one day. Regarding earthworm abundance in May, NT had the highest value may be due to the appropriate microclimatic conditions (SMC, temperature) and no disturbance. However, the precipitation in NT treatment was not able to infiltrate as a result of high SPR. In June (44 mm), during the critical moisture requirement period, when the pollination mostly occurs, the precipitation was one third less, than the average values. In July, twice as much precipitation occurred, while in August and September, the precipitation was close to the average values. Therefore, this anomaly in rainfall that is more and more typical in Hungary, needs to be considered.

According to the maize yield there was no significant difference among the tillage treatments (Fig. 11). The two lowest yield was gained under D and NT treatments. The working width and depth of D operation was the widest (500 cm) and the shallowest (12–14 cm) (Table 1). In comparison with the other operations, which were narrower and deeper, D operation consumed the least amount of fuel. For NT operation, fuel was not needed except for seeding. Munkholm et al. (2013) found yields of 10.9 Mg ha^{-1} in P, and 10.4 Mg ha^{-1} for NT treatment. Regarding the time necessary for tillage operation, L and P required the longest time (only 160 cm working width) and the highest amount of fuel due to the greatest working depth, but they do not necessarily result in higher yields.

Additionally, SOC was greatest under NT treatment (10 cm), which could have also indicated that higher yield would be gained. However, this was not proved. It contributed to greater earthworm abundance but especially in May 2016. The NT treatment had the highest earthworm abundance in the other months as well but it was not extremely higher compared to the other months. Regarding the maize yield, the spring months provided good soil conditions (high SMC and low SPR) for the germination of the maize. However, atmospheric drought occurred during the summer months (June, July), which discouraged the maize growth, especially in the process of pollination. Presumably, that is why the maize yield was relatively low. The amount and distribution of annual precipitation from the sowing time of winter oat (1st November 2016) was very uneven and leading to drought. As shown in most months (Fig. 2), there was less precipitation compared to the average between 1965-95, (throughout the vegetation there was only 308 mm). For instance, in December 2016 (5.5 mm) and February 2017 (17 mm). Our results showed that winter oat yield increased regarding the depth of tillage (SC < DC < P < L) except D and NT. Results from this study confirmed, that the deeper tillage treatments provide higher water permeability which were identified as beneficial factor for higher yield.

5. Conclusions

The precipitation in the last two years (2016–2017) of our research was erratic compared to the long-term average. The longer drought periods could result in yield decrease. In addition, the great amount of precipitation that the area suddenly received in 24th May 2016 (46 mm) was probably only partially utilized and it could not contribute entirely to plant growth. Regarding the different tillage treatments, there was no significant difference among them in 2016 and 2017. In 2017, during the greatest drought (June, July) the SPR reached the greatest values (above 6 MPa). After winter oat harvest (12th July) the straw cover and the rainfall contributed to the lowering of SPR in the following months. The SOC results from this study in NT confirmed the typical distribution of SOC in the topsoil (10 cm), ie. highest concentration on the topsoils (due to the plant remnant), then sudden decrease in the next layers. According to the earthworm abundance in 2016, the highest abundance throughout the year was achieved later in spring (May 2016) compared to 2017 (April). In 2017, the growing vegetation and the root system of winter oat provided better microclimatic conditions (higher SMC, less evaporation and lower SPR) in the soil, which manifested in measurably higher earthworm abundances. In DC treatment, the SOC content was high and evenly distributed into the soil. The incorporation of the straw remnants occurred evenly. The early harvested crops (winter oat), and their straw cover can have positive effects on earthworm activity, on lowering of SPR, and also on increasing SMC (however, these data are not shown in this article). In spite of the good microclimatic and soil conditions in springtime, the effect of summer drought was more pronounced, thus it could result in the similar yield regardless of tillage treatment. With a goal to the preserve the SMC and maintain the earthworm abundance, we must increase the water-holding capacity and organic carbon of our soils, and we should decrease the number of tillage passes on the field.

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