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Long-term effect of soil conservation tillage on soil water content, penetration resistance, crumb ratio and crusted area

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Abstract: Conservation tillage harmonizes soil protection with demands of the crop, soil and climate. The continuous conservation tillage improves soil properties and modifies impact of weather extremes. The aim of the paper was to investigate the changes in four soil physical states affected by soil conservation tillage and to evaluate soil water content in a critical period. The study was carried out on Chernozems applying six tillage treatments, that are loosening, ploughing, tine tillage (a deeper, and a shallower), disk tillage and direct drilling. The investigation suggested that soil conservation was the major solution resulting in the balanced water content (SWC) and penetration resistance values in both treatments under peculiar weather conditions. However, the crumb ratio and the crusted area resulted in significant differences between the treatments, presumably due to the level of surface preservation. Soil water content differed significantly between months, with higher contents in spring and lower values in the end of summer. The higher SWC expected at the beginning of the growing season was reliably fulfilled, but the SWC level for workabilty differed from the optimum.

Keywords: climate extreme; soil management; water conservation after overwintering; crumb formation; crusting

Soil tillage can improve or deteriorate soil physical properties (Bogunovic et al. 2018). Poorly managed soils become vulnerable to the climate extremes (Jug et al. 2018). Therefore, excessively wet or too dry soil requires adoption of appropriate soil management (Szalai and Lakatos 2013). Current research reveals that in the rainy season intensity of rains on ploughed soils cause physical soil deterioration (Jug et al. 2018), like settling, reducing the depth of the loosened layer, crumbs disintegration and surface siltation (Gallardo-Carrera et al. 2007). After drying, conventionally tilled soils rapidly lose moisture, while soil compaction increases with higher content of dust (Morris et al. 2010, Dekemati et al. 2019). On the other hand, no-tillage (NT) or conservation tillage practices preserve soil quality (Rodrigo-Comino 2018). Such management in long-term improves soil aggregation (crumb to dust ratio), soil organic matter, while topsoil compaction could increase or decrease (Bogunovic et al. 2018) depending the climate and soils. Moreover, Dexter et al. (2007) noted that in extreme seasons, penetration resistance varies widely under the soil water dynamics, which affects soil physical state and crop performance. When the drought becomes persistent, soil continuously loses its moisture content, penetration resistance increases, crumbling declines, but the proportion of dust increases (Morris et al. 2010). When soil becomes too wet or too dry, the penetration resistance (SPR) varies widely (Dexter et al. 2007), between the seasons. The crumbling process tends to drop in the extreme seasons; however, crust formation occurs more frequently (Gallardo-Carrera et al. 2007). Studying the soil physical factors (e.g. crumb ratio (SC) and crusted area (CA)), they are highly exposed to the weather

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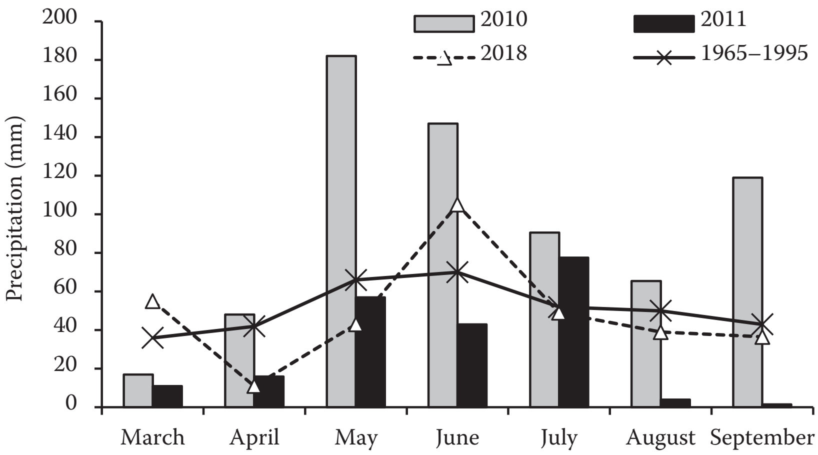

Figure 1. Monthly rainfall values of the experimental area for the trial and the long term periods

phenomena and require more attention in the future (Bogunovic et al. 2018, Jug et al. 2018).

There is a lack of investigations regarding the optimum soil tillage in the Central Europe. Regional soils are endangered by inappropriate management and frequent climatic extremes to ensure water balance and crop productivity. Considering this, the aim of this paper was to investigate the long-term impact of tillage-induced changes on soil physical factors and water conservation after overwintering and in the tillage season.

MATERIAL AND METHODS

A long-term tillage experiment was initiated at the Training Farm of the GAK (Gödöllői Agrár Központ) Ltd., nearby the Hatvan town (47°41'31.7"N, 19°36'36.1"E, 110 m a.s.l.) in 2002. The terrain is flat, with soil of a clay-loam texture classified as Endocalcic Chernozems, Loamic (WRB 2015), with organic carbon content of 1.86% C. Sand, silt and clay contents of the top 20 cm layer are 10, 54 and 36 vol %, respectively (Tóth et al. 2017). Soil water content at field capacity is 35% on average and vol 51% at saturation (Tóth et al. 2009), that is 26 wt % and 38 wt %, respectively. The mean annual precipitation at the Training Farm is 580 mm (1965–1995); during the examined period it was 538 mm with diverse distribution (Figure 1).

The experiment was arranged in a randomised block design with four replicates. Plot size was 13 m × 185 m. Six tillage treatments (loosening, 40–45 cm, L), tine tillage (deeper: 22–25 cm, T, and shallower: 18–22 cm, ST), disk tillage (12–16 cm, D), direct drilling (DD), and the mouldboard ploughing (30–34 cm, P). Primary and secondary tillage were carried out in a single pass for spring oat (2011) and soybean (2018), and seedbed preparation was applied for maize (2010). Preceding crops were winter wheat (2009), maize (2010) and winter oat (2017).

Table 1 contains information on the timing of management events during the study period and the

Table 1. Management events affecting soil condition in the experiment

Season 2009/2010		Season 2010/2011		Season 2017/2018	
Date	operation	date	operation	date	operation
19. 09. 2009	stubble tillage	28. 10. 2010	maize stalk chopping	21. 08. 2017	chemical stubble treatment, Machete 5 L/ha
22. 10. 2009	primary tillage	29. 10. 2010	primary tillage	29. 10. 2017	primary tillage
03. 05. 2010	seedbed preparation and maize sowing, PR37D25 I.	12, 14. 03. 2011	seedbed preparation and spring oat sowing Salvador I.	26. 04. 2018	seedbed preparation and soybean sowing, ES Mentor
10. 06. 2010	chemical treatment, Lumax, 5 L/ha	29. 04. 2011	chemical treatment, Granstar SuperStar, 50 g/ha + 0.3 L/ha	06. 06. 2018	chemical treatment, Pulsar 40SL, 0.5 L/ha
27. 10. 2010	maize harvest	17. 07. 2011	spring oat harvest, straw chopping	17. 09. 2018	soybean harvest, stalk chopping

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cultivated plants. Post-emergence herbicide was applied in the spring. Nitrogen was applied for crops at a rate of 100 kg N/ha in two doses, while phosphorus and potassium at 100 kg P/ha and 50 kg K/ha.

Soil measurements were taken in 30-day intervals between mid of March (after winter) and mid of September (in the end of summer) at each plot, in five repetitions per plot (20 per treatment). Soil moisture (SWC) was determined by the PT-I type gauge (Kapacitiv Kft, Budapest, Hungary), based on a TDR (time domain reflectometer) principle. The soil is categorised as dry, humid or wet when its moisture content ranges between 14.8–18.9, 19.0–23.9 or > 24.0 wt %, respectively (Csorba et al. 2011). Core samples were taken in 2011 (100 cm^3) at depths of 0–10, 10–20, 20–30 and 30–40 cm randomly at each treatment. Total number of soil cores was 288 (6 treatments × 4 depth × 4 plots × 3 repetitions per plot). Bulk density (BD) of samples was determined after drying in the oven on 105°C. Penetration resistance was measured by a handheld-type dynamic penetrometer (Szarvas, Mobitech, Hungary). It consists of 60° hard steel cone with 10.0 mm diameter base on a 550 mm long, 8 mm diameter shaft at each 0.05 m increment. The total number of measurement was 120. Number of samples was 240. According to Chen et al. (2014) the limit value of 2.0 MPa can be considered as a limit for normal root growth in humid soil conditions.

Crumbs are defined as soil aggregates ranging from 0.25 mm to 10 mm in diameter, of which those falling in the range of 0.25–2.5 mm are qualified as small crumbs and < 0.25 mm as dusts (Filep 1999). If the crumb ratio reaches 70–75% it can be considered optimal (Filep 1999). Sampling for aggregate distribution was carried out to the depth of 0–10 cm. The soil samples were air-dried and then they were gently sieved manually (60 shakes/min) through several sieves to obtain the mass distribution between the grades. The ratio of crusted area and the surface cover by crop residues were determined using wooden quadrate device (50 cm × 50 cm) for additional image processing in GIS software (area delineation and calculation of crusted area ratio).

Statistical analysis. The SPSS 23.0 software (IBM Corp., Armonk, USA) was used for all the statistical analyses. Treatment main effects on SWC, SPR, SC and CA and BD (only for 2011) were tested using one-way analysis of variance (ANOVA). Treatment means were compared using the least significant difference (*LSD*) at a significance level of $P < 0.05$. In cases where ANOVA showed significant differences at $P < 0.05$, a Tukey's post hoc test was also applied (data no presented).

RESULTS AND DISCUSSIONS

Rainfall conditions. The year 2010 was classified as rainy, whereas 2011 as dry in the meteorological assessment. The water surplus remained after the wet year had beneficially reduced the precipitation deficit during the first months of 2011. In 2018, weather combined both previously described phenomena. The surplus water that had remained from the former period was sufficient for spring months. However, SWC had gradually shortened during the growing season. Figure 1 reveals different rainfall conditions during the investigated periods. Precipitation distribution was uneven throughout the seasons, particularly in the spring and mid-summer, when most of the high-intensity rains occurred.

Changes in soil moisture content. SWC data were evaluated in relation to tillage treatments and the periods concerned (Tables 2 and 3). No significant differences in SWC were observed among tillage treatments ($P > 0.05$). The mean SWC value for the 2010 period and for 0–60 cm layer was 27.1 ± 0.4 wt %. A positive effect of the previous water retention on treatments was detected till the end of August in 2011, in spite of the precipitation shortage. The mean value of the vegetation period was 26.4 ± 0.7 wt %, which is acceptable for the dry period. By 4.2% lower SWC was observed at P and D treatments ($P > 0.05$). In 2018, soils were sufficiently wet in March and May and drier (20.3–24.3 wt %) in other months. Both wetting and drying had a similar effect on the SWC values assessed in the treatments. The mean value of the period was 23.3 ± 0.6 wt %, which is a bit critical for the period.

SWC data assessed at the end of overwintering and prior to the tillage season arose special attention to differences among the monthly data (Table 3). Significant differences were detected between the monthly SWC data in all selected periods ($P < 0.001$). In March, at the beginning of the growing season, soils were in wet condition (≥ 26.3 wt %). The SWC was quite lower (22.4 wt %) in April, 2018. The mean SWC value in May reached 27.9 wt %, corresponding to the regional requirements for the rainfall amount and the deep soaking of soils in this month. The mean SWC values in June and July were 24.9 wt % and 26.6 wt %, which is sufficient for stubble phase of soils. Droughts often prevail in August as it occurred in 2018, when the mean SWC decreased to 21.6 wt %. SWC in September has an important role in quality of autumnal primary tillage. In 2010, the soil could be classified as wet, sufficiently moistened in 2011 and mostly

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Table 2. Soil water content (SWC); bulk density (BD); soil penetration resistance (PR); soil crumb (SC) and crusted area (CA) under L (loosening); P (ploughing); T (tine tillage); ST (shallower tine tillage); D (disk tillage) and DD (direct drilling) in three selected years

Soil property	Year	Depth (cm)	Treatment					
			L	P	T	ST	D	DD
SWC (weight %)	2010	0–60	27.5^{aA}	26.8^{aA}	27.5^{aA}	27.6^{aA}	26.7^{aA}	27.5^{aA}
	2011		26.3^{aB}	25.8^{aB}	27.1^{aB}	26.9^{aB}	25.7^{aB}	27.0^{aB}
	2018		23.3^{aC}	22.6^{aC}	23.9^{aC}	23.9^{aC}	22.7^{aC}	24.2^{aC}
BD (g/cm^3)	2011	0–40	1.28^{b}	1.25^{b}	1.27^{b}	1.30^{a}	1.38^{a}	1.39^{a}
PR (MPa)	2010	0–50	2.10^{aA}	2.09^{aB}	2.20^{aA}	2.17^{aA}	2.46^{aB}	2.42^{aB}
	2011		2.96^{aA}	3.22^{aA}	2.88^{bA}	3.11^{aA}	3.71^{aA}	3.58^{aA}
	2018		2.61^{bA}	2.76^{aA}	2.71^{aA}	2.78^{aA}	3.21^{aA}	3.29^{aA}
SC (%)	2010	0–10	75.2^{aA}	61.4^{bA}	75.8^{aA}	77.7^{aA}	72.6^{aA}	71.9^{aA}
	2011		70.4^{aA}	65.7^{aA}	73.0^{aA}	75.6^{aA}	67.3^{abA}	69.1^{bA}
	2018		62.0^{bB}	50.0^{bB}	66.1^{aAB}	69.0^{aAB}	48.3^{cB}	61.4^{bB}
CA (%)	2010	surface	15.25^{aA}	25.75^{aA}	14.71^{aA}	14.54^{aA}	21.81^{aA}	12.44^{aA}
	2011		3.19^{bB}	7.39^{aB}	2.79^{bB}	2.41^{bB}	7.73^{aB}	2.46^{bB}
	2018		12.8^{bA}	31.2^{aA}	14.0^{bA}	12.7^{bA}	28.8^{aA}	11.8^{bA}

Values followed by the same lowercase letter within a row indicate no significant difference at 0.05 level; values followed by different uppercase letters within a column indicate a significant difference at 0.05 level

dry in 2018. The increasing rank of treatments in average of three periods is as follows: DD > T = ST > L > P = D; however, the difference, in line with expectations, was insignificant.

Investigation of different tillage treatment impact on SWC is a relatively favoured research subject. Chen et al. (2014) and Wang et al. (2019) found favourable changes in soil moisture content stating the positive effects of conservation tillage on soil properties. Other authors outline the rate and amount of straw mulching (Shen et al. 2012, Akhtar et al. 2018); residues in topsoil lower the heat flux into

Table 3. Soil water content (SWC); soil penetration resistance (PR); soil crumb (SC) and crusted area (CA) in months in three selected years in average of six tillage treatments

Soil property	Year	Month						
		March	April	May	June	July	August	September
SWC (weight %)	2010	29.2^{aA}	28.9^{aA}	29.4^{aA}	24.1^{bA}	30.6^{aA}	22.4^{bA}	26.4^{abA}
	2011	28.6^{aA}	28.4^{aA}	26.8^{aA}	26.5^{aA}	27.5^{aA}	25.1^{aA}	22.5^{abB}
	2018	26.3^{aA}	22.4^{abB}	27.5^{aA}	24.3^{aA}	21.8^{abB}	21.6^{abAB}	20.3^{abAB}
PR (MPa)	2010	1.34^{abB}	1.38^{abAB}	2.19^{aA}	2.03^{aB}	2.93^{aA}	2.87^{aB}	2.94^{aB}
	2011	2.48^{bA}	1.95^{abA}	2.94^{abA}	3.94^{aA}	3.06^{abA}	3.86^{aA}	4.41^{aA}
	2018	2.43^{abA}	2.38^{abA}	2.90^{aA}	2.34^{abA}	2.78^{aB}	3.75^{aA}	3.69^{aA}
SC (%)	2010	75.7^{aA}	70.1^{aA}	69.6^{aA}	70.0^{aA}	67.6^{bA}	76.5^{aA}	77.7^{aA}
	2011	78.5^{aA}	69.8^{bA}	74.8^{aA}	69.2^{bA}	68.4^{bA}	66.4^{bcB}	64.4^{bcB}
	2018	71.7^{aA}	74.7^{aA}	63.7^{aAB}	58.5^{aB}	61.3^{aAB}	55.5^{aC}	51.0^{bC}
CA (%)	2010	4.13^{dB}	0.80^{eB}	10.13^{dA}	17.73^{cA}	24.52^{bA}	29.92^{aA}	34.67^{aA}
	2011	7.20^{aB}	2.80^{bcB}	3.70^{bAB}	2.00^{cB}	3.90^{bB}	4.6^{bC}	6.30^{aC}
	2018	20.00^{aA}	22.00^{aA}	13.30^{bA}	15.30^{aA}	18.20^{aA}	19.70^{aB}	21.20^{aB}

Values followed by the same lowercase letter within a row indicate no significant difference at 0.05 level; values followed by different uppercase letters within a column indicate a significant difference at 0.05 level

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soil, increase water infiltration and water retention, reduce evaporation, and minimise the ground water loss. Similar statements were published by regional authors (e.g. Bogunovic et al. 2018, Kisic et al. 2018, Jug et al. 2019). The authors cited above suggested further studies to extend the results for wider application. Moreover, a new task may emerge, that is SWC after overwintering, considering the possible extremes in the growing seasons. In addition, the monthly moisture differences can be explained by the temporal and spatial variations in the amount of precipitation (Szalai and Lakatos 2013).

Changes in soil penetration resistance. In the rainy period of 2010, no significant differences were observed between the tillage treatments (Table 2). The possible explanation was uniform and deep soaking of soils. Opposite to this, there was a significant difference ($P < 0.001$) in SPR between months (Table 3), considering the precipitation fluctuation. The mean SPR for the period was 2.26 ± 0.18 MPa. The SPR values in 2011 were probably influenced by high SWC conserved from the previous year and precipitation shortage in the second part of the period. A significant difference ($P < 0.01$) was found between tillage treatments and SPR values for individual months (Tables 2 and 3). The mean SPR for the period was 3.23 ± 0.48 MPa, which refers to higher SPR of drier soils. Higher SPR (> 2.9 MPa) was observed from June, as there were no after-effects of water surplus remained from the previous year. In the study period of 2018, both increase and decrease in SWC affected uniformly the tillage treatments, so there were no significant SPR differences observed between individual treatments. Penetration resistance is mainly affected by the level of soil compaction and its water content (Chen et al. 2014, Gao et al. 2016, Bogunovic et al. 2018). At the same time, there was a significant difference between the SPR values for different months ($P < 0.001$). The mean SPR for the period was 2.90 ± 0.40 MPa, which refers to the restricted root conditions. There were no significant differences between the three periods, considering the SWC and soil state similarities. The rank of treatments is in increasing order: L > T > ST = P > DD > D, referring to soil conditions average of the three periods. Significant differences were detected between the monthly values ($P < 0.001$, Table 2). The SPR from March to June in wet soil (2010) remained at optimal value (2.0 MPa) as described by Chen et al. (2014), but it increased in the next months due to soil consolidation under rainfalls as reported by Busscher et al. (2002). In the third season (2018), higher SPR values (varied from 2.6 MPa to 3.7 MPa) were measured, in relation of the soil drying. Higher SPR indicate that the crop roots paused penetrating the soil (Taylor 1971). In monthly relation, DD and D had significantly higher SPR, on average by 19% compared to L, T and P treatments. Likewise, Gao et al. (2016) documented higher SPR under no-tillage associated with the lower SWC in the root zone. Chen et al. (2014) and Gelybó et al. (2018) drew similar conclusions at ploughless tillage treatments. On the contrary, Chen et al. (2014) and Cay (2018) found that SPR values between 2.0 and 3.0 MPa are suitable for crop production. In our case, the SPR values of 2.0–2.5 MPa corresponded to the requirements of soil management.

Changes in soil crumb ratio. The crumb ratio was influenced by several factors including SWC, i.e. the season and the tillage. The results revealed that crumb deterioration usually occurs in rainy seasons. Both crumb formation and disintegration were assessed in the wet period of 2010. Significant differences were detected between tillage treatments ($P < 0.01$, Table 2). In contrast, no significant differences in SC were observed in monthly values (Table 3). The mean value of period was 72.4 ± 3.4%, which is acceptable for the given period. In 2011, the SC, in line with the SWC, continuously decreased. A significant difference was found between the treatments and monthly values. The mean SC for the period was 70.2 ± 5.4%. According to the national ranking, the crumb ratio above 70–75% is considered to be optimal (Filep 1999). In the 2018 period, the mean crumb ratio was reduced to 59%. A lower ($P < 0.001$) SC was found at P and D treatments (on average 31.5%) compared to other treatments. However, there was no significant difference between the monthly values. The mean SC for the period was 59.0 ± 10.0%, which refers to the unfavourable fluctuation in crumb formation. The mean SC ratio in monthly relation reached the highest value (72%) in March and the lowest (64.3%) in September. Crumb ratio usually reduced during the summer months, both in wet and dry period, although the ratio of decline was moderate on well-attended soils. Significant differences were observed between the periods, due to differences between surface exposures. The rank of treatments was in decreasing SC order: ST > T > L > DD > D > P, referring to soil conditions suitability in three selected periods.

The ratio of crumb in soils under conservation tillage is one of the basic soil quality indicators (Nimmo 2004). Therefore, the use of proper tillage management (that is ST, T, L or DD) helps create surface state that may

https://doi.org/10.17221/249/2019-PSE

mitigate the exposure to the climate damages including crumb breakdown (Morris et al. 2010). Moreover, Muršec et al. (2018) paid attention to the structural stability of soil aggregates. Investigation of differences in soil aggregation between irrigated and rainfed soils may become a new challenge for future, considering frequency of drought periods in the region.

Crusted area. The crust occurrence was affected by the ratio of siltation in the soil surface, however, it was influenced by the amount and intensity of the rainfalls. In the rainy season of 2010, a higher difference in CA was detected between tillage treatments (e.g. at P 25.75%, and at T, ST and DD < 15%), yet, without statistical justification (Table 2). The mean CA for months differed between 0.8% and 34.7%, with a statistically verifiable difference ($P < 0.001$, Table 3). In the 2011 period, the after-effects of the previous season and the lack of precipitation of the given season had affected the crust formation. There was a statistically significant difference in CA between the tillage treatments (Table 2). CA ratios at the P and D treatments were twice larger compared to the other treatments (Figure 2). The differences between monthly values showed lower reliability ($P < 0.05$). The CA formed in the first months of

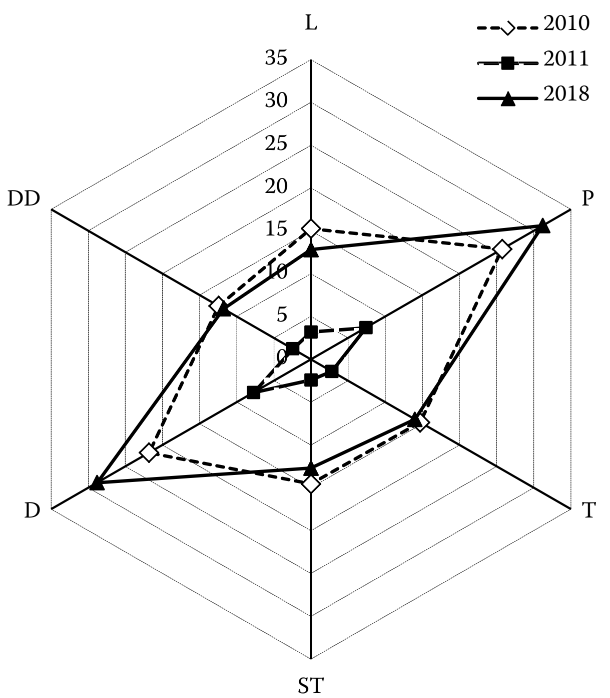

Figure 2. Extension of the crusted area (%) under L (loosening); P (ploughing); T (tine tillage); ST (shallower tine tillage); D (disk tillage) and DD (direct drilling) in three selected years

year 2018 had remained until the end of the growing season, with a slight difference each month. However, tillage treatments resulted in a significant difference ($P < 0.001$) in CA. In addition, the ratio of CA assessed at P (31.7%) and D (28.8%) treatments was significantly higher than at other treatments. The lower crust ratio at L, T, ST and DD treatments may attribute to the protective effect of stubble residues remained from the previous year. Comparing the CA ratio, significant differences ($P < 0.01$) were observed between three selected periods with varying rainfall conditions. The rank of tillage treatments in a three-year average was in increasing order: DD < ST < L < T < D < P, referring to the surface conservation as well as the surface exposure.

Surface crust mainly depends on soil properties and weather conditions, while it often occurs due to the high amount of dusts developed by multi-traffic tillage in the top layer (Gallardo-Carrera et al. 2007). Gallardo-Carrera et al. (2007) outlined that already damaged small soil particles that were transformed into hard crust when the rains were followed by dry period. Our data, received in Endocalcic Chernozems correspond with their assessments. Surface cover seems to reduce the thickness of the surface crust at any examined variant, as noted elsewhere (Cassel et al. 1995, Gicheru et al. 2004, Chen and Duan 2015).

In conclusion, tillage had almost uniform effect on SWC and SPR due to the continuous conservation thoughtfulness under peculiar weather conditions. The surplus water remaining from the former season will be more important in the future and the studies should focus their attention to apply water conservation solutions. SC and CA, considering the soil surface exposure to the weather factors, were affected by tillage treatments, which confirmed again the importance of surface preservation. Our findings suggest that the long-term conservation applying DD, ST, T and L can effectively mitigate the impact of weather phenomena in regional soils.

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