

**Szent István University**

**Compliance of climate-sensitive and climate-protective  
tillage systems on different soils**

Thesis of doctoral (PhD) dissertation

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## 1. INTRODUCTION AND OBJECTIVES

According to the data of the World Bank, the Earth population is gradually increasing (**World Bank, 2018**), thus, the production area per capita in the world is 0,192 hectares and this number is decreasing year by year.

There are several reasons for the decrease in the crop production area. The most important ones among these are climate damage and the negative effects of climate change on the plant-soil relationship. Consequences of climate change include rising average temperatures and uneven rainfall distribution (**Pant, 2009**). **Bogunović et al. (2016)** highlighted that 33 million hectares of arable land are strongly degraded in Europe.

The main objectives of soil tillage have changed three times since the 1970s. First, the goal was to maximize the yield, which was achieved by improving the tillage technology for a given period. In the following period, between 1970 and 2000, the improvement of soil quality became the primary goal, and since the beginning of the 2000s, soil protection has been supplemented with the tasks of climate damage mitigation (**Birkás, 2015a**).

The increase in climate extremes exists not only in climate models developed by researchers, but can also be felt continuously in agricultural production. Climate damage such as rain-stress, water-stress, hail, heat-stress, and drought have a direct adverse effect on soil conditions, and an indirect effect one on soil quality, and thus on the profitability of agricultural production.

The progress of tillage has been slowed down by several factors, e.g. wartime, low levels of mechanization, lack of expertise and adaptation. In Hungary, the conservation tillage – processes adapted to soil moisture content, soil condition and with reasonably reduced number of passes – application demands became prevalent in the last 15 years (**Birkás, 2015a**) – however, in Croatia, traditional tillage technologies that are not suitable for climate damage alleviation still take precedence (**Jug et al., 2005**).

Being born in Slavonia, Croatia, where agriculture is one of the main sources of livelihood, I saw it necessary to set up experiments similar to that taken in Józsefmajor. The results of the Lukács experiment, in tribute to my homeland, were presented earlier than those achieved in my new homeland.

Agriculture plays a major role in both countries based on their natural and soil conditions. According to the soil types, there are 36 soil types in Croatia. Among them 12.1% of all areas

are Luvisols, 9.87% are Pseudogley, and 9.62% are Gley amphigley (**Husnjak et al., 2011**). In Hungary, according to **Micheli et al. (2014)**, more than 70% of the soils are dominated by Luvisols, Chernozems and Vertisols.

As the condition of the soil influences how the weather factors affect the soil, I considered it expedient to carry out studies comparing conventional and conservation tillage systems in connection with the reasons described above. The objectives of the research were as follows:

- to compare the effects of adaptable and traditional tillage on soils based on some soil physical parameters (soil penetration resistance, soil moisture content, surface cover, agronomic structure, and earthworm abundance) in two sites (Luvic Stagnosol [Siltic] in Croatia, and Endocalcic Chernozem [Loamic] in Hungary),
- to compare the effects of covered and uncovered soil surface based on the soil exposure (soil penetration resistance, soil moisture content in 0-10 cm layer, agronomic structure and earthworm abundance)
- to evaluate the adequacy of ploughing and mulch tillage systems in extreme years, in order to reduce damages and to maintain production safety
- to evaluate and rank the tillage systems that are suitable to mitigate climate damage based on their suitability.

## 2. MATERIAL AND METHODS

### *2.1. Information about the experiments*

The experimental work was conducted at two different production sites, in three growing seasons, between 2015 and 2018. The first experimental tillage experiment was set up on the border of Lukács (in Croatian: Lukač) in Virovitica-Drava county – Croatia. The other study area was at the site of the long-term experiment set up in 2002 of Szent István University, GAK Ltd., Józsefmajor Experimental and Farm (Heves county – Hatvan).

The Lukács area can be classified as a lowland, which determined the homogeneity of the climatic characteristics. The climate of the region is continental. The average annual temperature is between 10°C and 10.7°C and the average annual rainfall for the period 1965-1995 is 815.5 mm. During this time, the lowest measured average precipitation was 552.6 mm (1971), while the highest one was 1114.8 mm (1972). Geologically, the soil consists mainly of loess, aeolian sand and organic-waterlogged sediments (waterlogged clay, sand, peat). The soil of the experimental area is Luvic Stagnosol (Siltic), the texture is silty clay with unfavorable water management. The precipitation data (Virovitica station) presented in Chapter 3.1., were obtained from the National Meteorological Service of Croatia.

The experimental area of Józsefmajor is located in Cserhátalja, on the edge of the Great Hungarian Plain and the Northern Central Mountains, and is considered flat. The average annual rainfall for the period 1961-1990 is 520-570 mm, of which 395 mm falls during the growing seasons (April-September). The average annual temperature is 9.5-10.3°C, which is between 16.3-17.5°C during the growing season (**Dövényi, 2010**). According to the World Soil Reference Base (IUSS Working Group WRB, 2015), the soil in the experimental area is Endocalcic Chernozems (Loamic) with a loam texture with favorable water management.

### *2.2. Data of the experiments*

The location of the Lukács tillage experiment and the possibility of its high-quality construction was provided by the Katanacsics (croatian: Katančić) family farm. It is a three-generation farming family, they have been farming on 210 hectares on nearly 150 fields since 1959. The soils are mostly gleyey forest and meadow soils, medium textured, endangered by water inundation.

The experimental plot was 375 m long and 125 m wide. In the experiment, we studied two tillage treatments in the first year, and three tillage treatments in the second and third years, at

random sampling points. Conventional ploughing, shallow and deep cultivator applying, were set up at the same depth as in the Józsefmajor experiment. In the last year of the research, a Väderstad Tempo F was used to sow soybeans into wheat stubble without tillage.

The tillage treatments, depth of tillage, working width and tillage equipment used are shown in Table 1.

Table 1. Tillage treatments in Lukács, working depth, working width and used tillage equipment

Tillage treatments	Tillage equipment	Depth of working (cm)	Width of working (cm)
No-till (NT)	Väderstad Tempo F	4-6 (depth of sowing)	300
Shallow tine cultivation (SC)	Väderstad Cultus 300	18-20	300
Deep tine cultivation (DC)	Väderstad Cultus 300	22-25	300
Moldboard ploughing (P)	Vogel&Noot 1050	30-32	160

The Józsefmajor tillage experiment was set up in 2002 by the staff of the Department of Soil Management, led by Professor Márta Birkás, to improve soil quality and humus content and to study the effects of weather phenomena. In the experiment, six different tillage treatments were applied in four replicates, in a random arrangement. The width of the plots was 13 and the length was 168 m (2180 m<sup>2</sup>). The number of plots is 24, the total area is 5.8 hectares. The tillage treatments, depth of tillage, working widths and tillage equipments used are shown in Table 2. The crops grown – maize, winter oats, soybeans – were identical to those of Lukács.

Table 2. Tillage treatments in Józsefmajor, working depth, working width and used tillage equipment

Tillage treatments	Tillage equipment	Depth of working (cm)	Width of working (cm)
No-till (NT)	Väderstad Rapid 300C / Kuhn Maxima 6	4-6 (depth of sowing)	300
Disking (D)	Väderstad Carrier 500	12-16	500
Shallow tine cultivation (SC)	Kverneland CLC Pro	18-20	300
Deep tine cultivation (DC)	Kverneland CLC Pro	22-25	300
Moldboard ploughing (P)	Kverneland LM100 + packomat	28-32	160
Loosening (L)	Vogel & Noot TerraDig XS	40-45	250

### **2.3. Methods of research**

Soil condition studies were performed for three growing seasons, from early spring to late autumn. Soil moisture content and soil penetration resistance were measured simultaneously, on all plots at random, in triplicate, 5-10 m apart. Measurements were taken at 30-day intervals, except when the weather did not allow it. In the Lukács experiment, I performed the measurements five times at each growing season, taking into account the setup of the experiment, sowing and harvesting.

Soil moisture content (m/m%) was measured with a PT-I type measuring instrument (Kapacitív Kft., Budapest), up to a depth of 0-60 cm, every 5 cm.

The depth of the loosened soil layer was checked by measuring the penetration resistance of the soil. The instrument used for the measurement was the force meter from Szarvas manufactured by Mobitech Bt., in 2015-2016 and 2016-2017 (**Daróczy, 2005**), and in the last research year (2017-2018) it was Eijkelkamp Penetrologger. For both instruments, a cone with a cone angle of 60° and a cross-section of 1 cm<sup>2</sup> is used for the measurement, which must be pushed into the soil at a speed of 2 cm/s.

The examination of the agronomic structure of the soil was performed according to the classification of **Stefanovits (1992)**. Sampling was done from the top 10 cm, as this layer is primarily exposed to climate phenomena. The soil samples were air-dried and then carefully sieved manually (60 shakes/min) on an agronomic sieve line.

The earthworm population was counted on all plots in four replicates. The size of the soil block is 25 × 25 cm with a depth of 30 cm. The duration of the manual sorting is about 30-40 minutes, depending on the physical condition of the soil. The location of the soil block was chosen at random from the repetitions at a distance of 5-10 m. The earthworm abundance in the samples was recorded in number of individuals/m<sup>2</sup>.

The soil surface covering was performed digitally with Adobe Photoshop CC 2019. The process consisted of two parts. First, I marked the stubble residues (color sampling) and then the color range command was applied several times in succession to refine the selection, and it was also necessary to set the „tolerance” for the color range to be selected. The „tolerance” setting determines the width of the selected color range (you can increase or decrease the number of selected pixels by adjusting it). The selected range is marked in white, so the number of pixels was read on a histogram, so the value of the white range had to be analyzed. In the second part, the number of pixels of the selected stubble residues was divided by the number

of pixels of the total image and multiplied by one hundred. I present the soil surface coverage in percentage. All treatments were tested in four replicates. The recordings were done after tillage as well as sowing. The photos have a resolution of 2272×4608 pixels and cover a minimum area of 6 m<sup>2</sup>.

#### **2.4. Statistical analyses**

To examine the significant differences between the tillage systems and the cover categories, I used the one-way analysis of variance of the agronomic structure, soil moisture and soil resistance parameters, as well as for earthworm abundance. In case of the significant result of the analysis of variance, the groups with significant differences were determined by Tukey HSD (Honestly Significant Difference) post hoc test. The normality of the data was checked by *Kolmogorov-Smirnov* test and the homogeneity of variances by Levene test. As the two-sample t-test may be sensitive to damage to normality, and the result of the Kolmogorov-Smirnov test was significant in most cases, to compare the mean of the two groups - for example, two countries or two tillage methods, – I accepted the proposal of **Kao-Green's (2008)** and used the F-test (F-statistic) which forms the base of the analysis of variance. The correlations between the different soil parameters the amount of precipitation and the number of earthworms were examined on the basis of Pearson's linear correlation coefficients. The significance of the correlation coefficients was checked based on the empirical significance levels (p-values). The significance level used in the statistical studies was 5%. Statistical data processing was performed using the IBM SPSS Statistics 25 software package.



### 3. RESULTS

Since the beginning of the new millennium, we have witnessed climate phenomena that have increased the uncertainty of crop production. This difficult situation is often exacerbated by using practices that are not adapted to climate/climate change.

In recent years, profitable crop production has been taking place in very larger areas, despite extreme climatic conditions. At the same time, the amount of precipitation over time and space, as well as the temperature, can be considered significantly variable nationwide. For this reason, both excess water and water shortage must also be taken into account. In areas where irrigation cannot be implemented, soil- and moisture conservation tillage can help maintaining crop production safety.

#### 3.1. Precipitation conditions during the studies

Around Lukács, the average rainfall for 30 years (1965-1995) is 815.5 mm. During the years of the experiment (2015-2018), precipitation became more (867.6 mm) than the multi-year average (Figure 1). The amount of monthly precipitation fluctuated greatly, so I also took the annual effect into account when evaluating the results.

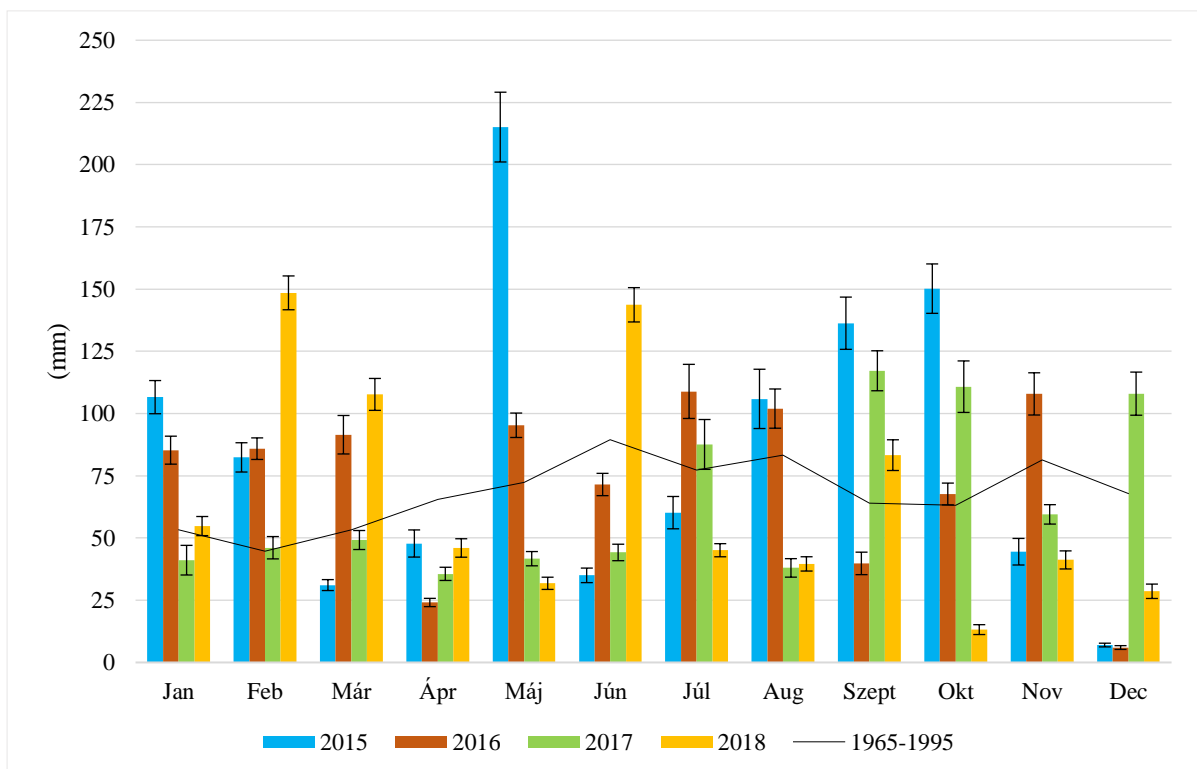


Figure 1. Annual precipitation (mm) between 2015-2018 on a monthly basis and the average of the 1965-1995 period (Lukács)

The precipitation data of Józsefmajor are shown in Figure 2. The 2015 and 2018 experimental years showed a negative trend compared to the multi-year average, while 2016 and 2017 showed a positive trend. During the experimental years (2015-2018), the average precipitation proved to be slightly higher (604.8 mm) than the multi-year average.

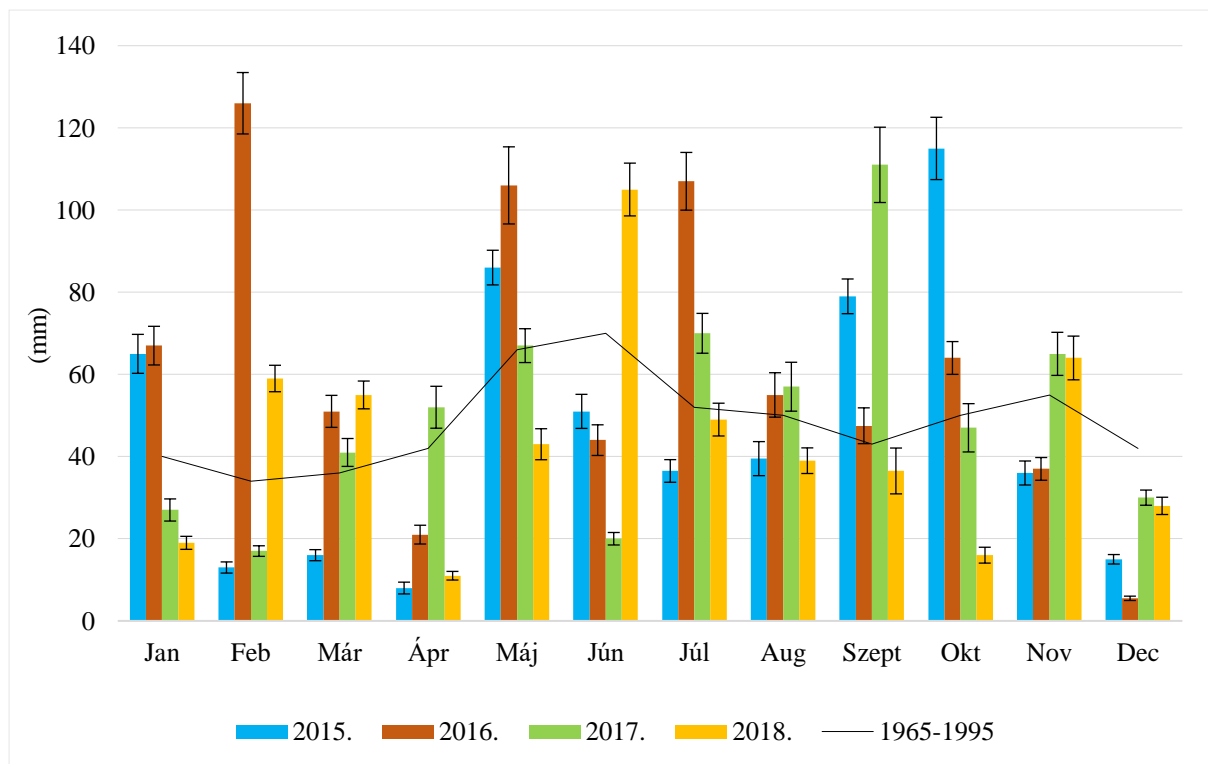


Figure 2. Annual precipitation (mm) between 2015-2018 on a monthly basis and the average of the 1965-1995 period (Józsefmajor)

In the Lukács area, compared to Hatvan-Józsefmajor site, more precipitation (+235 mm) falls on an annual basis. As a result, the tendency for settling is also stronger, so the time interval of soil loosening efficiency is shorter.

### 3.2. Estimation of the depth of loose layer based on soil penetration resistance data

For the sake of comparability, the soil resistance and soil moisture measurement data were executed to the same depth (0-50 cm).

In the year following after the experimental set up, in 2016, I did not find a statistically significant difference between the treatments ( $p < 0.05$ ). The lowest soil resistance value (1.74 MPa) was measured in the 0-5 cm layer in the deep tine cultivation treatment, while the highest (4.71 MPa) was measured in the 45-50 cm layer of ploughed soil. Harmfully-compacted condition ( $> 3$  MPa) was measured in the ploughed soil in the 15-20 cm layer, and in the deep

tine cultivation treatment in the 20-25 cm layer, which also resulted in a statistically proven differences ( $p < 0.05$ ). I considered it important to compare the depths of tillage and the depths of harmfully compacted layers. I did not find a decrease in the depth of the loosened layer in the deep tine cultivation treatment, while I found a 33.3% decrease in the ploughed soil. In the spring of 2016, the effect of tillage in the ploughed soil under maize was still observable, which later has decreased in time and space.

In 2017, based on the average soil resistance values, for the 0-50 cm layer, we found a statistically significant difference only in the 25-30, 30-35, 35-40 and 40-45 cm layers ( $p < 0,05$ ). The soil resistance at the depth of 0-5 cm was 0.93 MPa for deep tine cultivation, while it was 0.96 MPa for ploughing and shallow tine cultivation treatments. Compacted soil state ( $>3$  MPa) was measured at a depth of 30-35 cm in ploughed soil, 25-30 cm during deep tine cultivation, and 20-25 cm in shallow tine cultivation treatments. Based on the results, it can be concluded that the depth of the loosened layer exceeds the tillage depth in all three treatments. The extent of depth of the loosened layer for ploughing was 14.28%, for deep tine cultivation it was 16.67%, and for shallow tine cultivation it was 20.0%.

In 2018, harmfully compact conditions developed in four tillage treatments under soybean, in ploughing (20-25 cm), in no-till and deep tine cultivation treatments (25-30 cm), and the shallow tine cultivation treatment (40-45 cm). In the deep tine cultivation treatment, I measured the lowest soil resistance value (0.81 MPa) in the 0-5 cm layer and found a higher value in no-till at the same depth (1.44 MPa). In the shallow tine cultivation treatments, the smallest increase in soil resistance was observed between the 0-5 cm and 45-50 cm deep layers. In ploughed soil, outliers were observed below 20 cm (2.98 MPa at 25 cm). The higher value can sometimes be attributed to tillage and the compaction induced by the applied compression force of the agricultural machinery.

In the year of maize (2016), the first of a total of eight measurements was performed in October 2015. A statistically significant difference ( $p < 0.05$ ;  $p < 0.01$ ) was detected in all layers. In the 0-5 cm layer, the highest soil resistance values were measured in the no-till and disking (2.10 MPa) treatments, while the lowest ones were found in the ploughed (1.50 MPa) and loosened (1.50 MPa) treatments. Regarding the depth of the loose layers, the disking proved to be the worst, as a harmfully compacted layer ( $>3$  MPa) was already detectable in the 10-15 cm layer. The loosening treatments proved to be the best, as the compacted layer was observed at a depth of 40-45 cm.

After maize harvesting in the rainy autumn, proper tillage and sowing of winter oats were also difficult. The curves have a similar course and statistically significant difference ( $p < 0.01$ ) was only detectable in two layers (0-5 cm and 5-10 cm). In terms of the layers, the lowest values (1.88 MPa) were measured in the 0-5 cm layer in ploughed soil, while the highest values (2.40 MPa) were measured in the disking treatment. In wetter soil conditions, a compact layer can be easily formed with a disk equipment, which in our case had a resistance of 3.05 MPa on average in the 0-5 cm layer. Within 2017, the condition of the treatments changed significantly. The results for March and April showed low values, however, compared to the April measurements, the May ones increased drastically, which can be attributed to the increase in temperature and the drying of the soil. During the June and July measurements, the highest measurable values (6.72 MPa) were obtained in the 15-20 cm and in the layers deeper than that in each treatment.

During the season of the soybean (2018), we performed five measurements in which summer measurements (June and July) are not included due to the immeasurable soil condition. A statistically significant difference ( $p < 0.01$ ;  $p < 0.05$ ) was detected in all layers except for the 45-50 cm layer. Interestingly, no value greater than 2.5 MPa was measured in any of the treatments in May, while the June measurement could not be performed with the instrument due to an impermeable dry and hard surface. At the measurable time points, on average, none of the treatments exceeded the detrimental concise value. The curve of the first measurements data for each tillage treatments realistically represents the depth of tillage. In ploughed soil, an increase in soil resistance was observed in the 25-30 cm layer, while in the loosened soil in the 40-45 layer. In no-till treatments soil penetration resistance varied between 1.74 and 1.97 MPa in the depth of the whole profile. The curves of the shallow and deep tine cultivation treatments had a similar course, with a greater increase in resistance in the 20-25 cm layer.

I found that the depth of the loosened layer could be well traced by penetrometer soil resistance measurements. In addition, the state of soil condition was checked to the required depth by spade test each time.

### ***3.3. Soil moisture content in extreme rainfall conditions***

In the Lukács experiment in 2016 we had the opportunity to compare two types of tillage – ploughing and deep tine cultivation.

In 2016, the deep tine cultivation treatment resulted in increased moisture in all layers. A statistically significant difference in this treatment was observed in the following layers: 0 cm, 0-5 cm, 5-10 cm, 10-15 cm, 15-20 cm, 20-25 cm, 35-40 cm, 40-45 cm and 45-50 cm. The highest value was measured in deep tine cultivation treatment (22.18 m/m%) in the 20-25 cm

layer, while in the ploughed soil (20.52 m/m%) in the 15-20 cm layer. The moisture content in the deeper layers was greatly reduced in both treatments. In the layer where moisture loss occurred, not only was the soil settled, it was also dry, impeding upward water flow.

In the winter oat seasons (2017), in addition to ploughing and deep tine cultivation, a shallow tine cultivation treatment was also examined. Mean values were similar in all three treatments, thus, no statistically significant difference was observed. In the 0-50 cm soil profile, the moisture content remained below 30 m/m% on average in each tillage treatment. Compared to the autumn measurement, the soil moisture content was more favorable in spring (March, April and May) due to winter wetting. In April, ploughed soil had the highest moisture content in the 30-35 cm layer (31.9 m/m%). In deep tine cultivation treatment, the highest value (32.67 m/m%) was measured in March in the 40-45 cm layer. With the set in the warmer period, the data in June showed a declining trend compared to May. During arrival of summer, soil moisture content decreased in the upper 30 cm layer, but increased slightly after a few rainfalls.

In the year of soybean (2018), a statistically significant difference ( $p < 0.05$ ;  $p < 0.01$ ) was detected in several layers. The lowest moisture content was measured in the no-till (18.53 m/m%) in July and October. The curves have a similar course, based on which it can be observed that the soil tilled with deep tine cultivator contains on average the most moisture (22.85 m/m%), followed by the shallow tine cultivation treatment (22.17 m/m%) and then the ploughing (20.25 m/m%) and no-till (18.53 m/m%).

In the Józsefmajor experiment in 2016, there was 652 mm precipitation between the first and the last measurement ( $n=8$ ), which had a beneficial effect on the soil condition. At the same time, winter precipitation also had a significant effect on spring soil moisture, in which case the heavy February precipitation (126 mm) also improved. On the surface, the soil moisture ranged from 9.1-10.5 m/m %, but the moisture content exceeded 20 m/m % in the 0-5 cm layer in all treatments. The difference was greater in the upper 5-20 cm layer, and the ploughing resulted in the lowest, the no-till reached the highest values, while the same could not be said for the lower layers (between 25-50 cm). The results suggest that ploughed soil is most exposed to climate impacts, while straw-covered mulched no-till soil is more protected. As a result of temperature rise and soil drying, moisture decreased in June, especially in the upper 0-25 cm layer, although the most significant change was also visible on the surface.

In the year of winter oats (2017), there was no significant difference between treatments. On average, all curves have a similar course, with values averaging between 10.2-29.7 m/m %. Results of moisture in December showed lower values than in October. Between the

measurements in December and March, 72.5 mm of precipitation fell, resulting in greater changes in the upper layer between treatments. Soil moisture content in May was similar to the previous year, and we measured the highest results in all treatments in this month. This phenomenon is due to the 54 mm of precipitation that has fallen in the last 15 days. The lowest moisture (27.9-28.8 m/m%) was measured in the deeper layers (30-50 cm) of the no-till soil compared to the other treatments. In the deepest layer (-50 cm), the ploughed soil contained the highest moisture content (29.7 m/m%).

In the last research year (2018), we performed a total of seven measurements in soybeans. Statistically significant difference ( $p < 0.01$ ;  $p < 0.05$ ) was detected in four layers between several treatments. On the surface, the average soil moisture values were 6.8 m/m% in disking and deep tine cultivation treatments and 8.0 m/m% in the no-till treatment between which there was a significant difference. No-till reached the highest moisture content (13.7 m/m%) on the surface during the March measurement, while the other treatments resulted in 4.6-7.2 m/m% moisture. In contrast, extremely low moisture was measured in the deeper layers, between 18.5-22.2 m/m%.

### ***3.4. Evaluation of surface protection***

#### ***3.4.1. Effect of covered and uncovered surface on soil exposure***

I may state that exposure is threatening soil quality by increasing the vulnerability of the soil surface. The natural factors influencing the exposure are the location of the area as well as the weather phenomena, especially the intensity and amount of precipitation. The most important management factors are soil disturbance (deep, medium, shallow), surface shape (uneven/cloddy, slightly uneven, even), surface cover (good, medium, poor) and agronomic structure, including the ratio of the least vulnerable fraction over time and the moisture of the top layer exposed to rain stress.

In the Lukács experiment, the soil surface coverage is the highest after harvest, exceeding 90% in each research year. This ratio depends on the amount of straw and the quality of the spreading. Ploughing resulted in the lowest (<1%) soil cover each year. In 2016, the deep tine cultivator left 28.6% cover on the surface after sowing, 42.0% in 2017, and 33.4% in 2018. In the shallow cultivator treatment, 36-46% coverage remained on the surface after sowing. In 2017 and 2018, deep tine cultivator left a lower cover compared to shallow tine cultivator due to tillage depth and better mixing.

In the Józsefmajor experiment, immediately after harvest, the soil surface cover exceeded 90% each year, which effectively alleviated summer climate damage. However, we measured

the lowest cover (67.12%) in September 2018, after soybean harvest, which is attributable to the dried and low amount of crop residues. The lowest soil cover was measured on ploughed soil (0.3% in 2016; 1.08% in 2017 and 0.4% in 2018). Compared to stubble cover, no-till treatment had the lowest cover reduction. Thus, soil protection could be considered also good. Irrespective of the plant, the disking treatment gave approximately the same and low cover level in association with the poorer plant stock. Comparing the identical treatments as in the Lukács experiment, the deep and shallow tine cultivation treatments in Józsefmajor are inversely proportional, but the difference between them is negligible in both experiments.

In my opinion, tillage treatments which leave the lowest coverage make the soil the most exposed to the climate phenomena. Based on the three-year data, in the Lukács experiment, the following (decreasing) order was established in terms of soil cover: shallow tine cultivation>deep tine cultivation>ploughing. Based on the data from the Józsefmajor experiment, the (decreasing) order is as follows: no-till>deep tine cultivation>shallow tine cultivation>loosening>disking>ploughing.

I classified the soil surface cover ratios into five categories according to their frequency in the experimental areas. This explains the larger scale of categories 3, 4 and 5. The categories are the following: 0-10, 11-25, 26-45, 46-70 and 71-100%. Their classification from a soil protection point of view is very poor, poor, medium, favorable, very favorable.

The agronomic structure is classified into four categories based on their size, i.e., clod (>10 mm), crumb (2.5-10 mm), fine crumb (0.25-2.5 mm), and dust (<0.25 mm).

In Lukács, in 2016, deep tine cultivation treatment showed smaller proportions of clods (-2.34%), fine crumb (-1.48%) and dust (-5.80%) compared to ploughing. Regarding the crumb fraction, the deep tine cultivation treatment shows a higher proportion (+9.62%) compared to ploughing, thus there was a statistically verifiable difference ( $p<0.01$ ). Ploughing resulted in 5.8% higher dusting, which was also statistically different ( $p<0.01$ ) from that measured in the deep tine cultivation treatment.

In 2017, the lowest clod fraction ratio was shown by the deep tine cultivation treatment (13.12%) and the medium one by the shallow tine cultivation treatment (16.50%). The highest clod fraction ratio was measured in the ploughed soil (23.74%), which differs statistically from the previous two treatments ( $p<0.01$ ). The highest crumb ratio (41.98%) was shown with the shallow tine cultivation. In addition, the highest fine crumbs (44.94%) and the lowest (2.12%) dust ratio were measured in deep tine cultivation treatments.

In 2018, we measured the highest clod (16.20%) and dust (7.78%) ratio as well the lowest crumb (37.38%) and fine crumb (38.64%) ratio in the ploughed soil. There was a significant

difference ( $p < 0.05$ ) between the shallow tine cultivation treatment and the ploughing treatment, while the dust fraction ratios showed a significant difference between the deep tine cultivation and ploughing treatment ( $p < 0.05$ ). In shallow and deep tine cultivation treatments compared to ploughing, a significantly higher crumb ( $p < 0.01$ ) and fine crumb ratio ( $p < 0.05$ ) was found. This observation is due not only to the ratio of surface cover, but also to the favorable characteristics of mulched treatments.

In Józsefmajor, in 2016, the proportion of dust was 4.0% in no-till, 11.6% in disking treatment and 11.3% in ploughing treatment. The treatments containing the finest crumb was the ploughing treatment with 43.0% and shallow tine cultivation with 41.3%, while no-till had the least 35.0%. The highest proportion of crumbs was in deep tine cultivation (42.9%) and no-till (42.4%). In the disking treatment, crumbs showed a significant difference ( $p < 0.01$ ) of 25.9% and ploughing of 26.9% from shallow tine cultivation, no-till and deep tine cultivation treatments. The clod fraction ratios of shallow tine cultivation (11.8%) and deep tine cultivation (11.5%) treatments were found to be favorable, while loosening (25.2%) and disking treatment (24.8%) proved to be unfavourable.

In the winter oat season (2017), the largest harmful clod formation was reached in disking treatment (32.7%) and ploughing (30.4%). However, the lowest ratios were found in shallow tine cultivation (17.0%) and deep tine cultivation (18.6%) treatments. Most soil crumbs were formed in the deep tine cultivator treatment (44.0%). In contrast, compared to 2016, there was a drastic decline (-9.17%) in no-till (33.2%). The lowest fine crumb ratio was measured in the loosening treatment (27.8%), while the highest (35.0%) was measured in the no-till. In the ploughed soil the 8.9% dust ratio was higher than in the other treatments. Nearly the same (5.9-6.0%) ratios were found for disking and shallow tine cultivation treatments. The least dust ratio was generated in no-tilled soil (3.7%).

In the soybean year (2018), the lowest clod ratio occurred in shallow (21.5%) and deep (23.3%) tine cultivator treatments. The crumb ratio in shallow tine cultivation tillage was 41.8%, in deep tine cultivation 39.0% and in no-till 38.2%, in contrast ploughing accounted for 22.0% and disking treatment for 23.0% occupying the last two places in that order. The lowest fine crumb ratio was measured in the disking treatment (28.0%), while the highest (31.5%) was measured in ploughed soil. The lowest dust was measured in no-till treatment (4.7%) and shallow tine cultivator treatment (7.3%) and there was no significant difference between them. The disking and ploughing treatments reached 13.2% and 16.5% dust ratio, which significantly differed from the previously mentioned treatments.



### ***3.4.2. Correlation between surface cover, crumb ratio and earthworm abundance***

The rate of surface cover depends mainly on the weight (sometimes also on the quality) of the stubble residues of the plant species and the method of incorporating it into the soil (mixing or inversion). Surface cover, crumbling and earthworm abundance are key factors in the high functioning of the soil. To ease the examination of the relationship, I treated the crumb and fine crumb together. In the average of the three years, based on the correlation study, a significant difference ( $p < 0.05$ ) can be detected between the coefficients of the crumb ratio and earthworm abundance, but the coefficients do not correlate. In the annual distribution, in 2016, the correlation value was medium ( $r = 0.548$ ), but due to the low number of observations ( $n = 10$ ), the correlation could not be detected.

Based on the averages of three years, it can be observed that the 0-10% category resulted in the lowest earthworm abundance ( $30.5 \pm 8.7$  ind/m<sup>2</sup>), while the 71-100% category resulted in the highest ( $185.7 \pm 40.7$  ind/m<sup>2</sup>). There was a significant difference ( $p < 0.05$ ) in the earthworm abundance between these two categories. In the 11-25% category we counted  $76.3 \pm 9.5$  ind/m<sup>2</sup> earthworms, in the 26-45% category  $156.9 \pm 68.4$  ind/m<sup>2</sup>, and in the 46-70% category  $117.9 \pm 28.5$  ind/m<sup>2</sup>. In the three categories, the earthworm abundance did not increase linearly as did the cover levels.

The crumb ratios of the two experiment sites were also examined for the different cover categories, on the average of three years. Based on the statistical examinations, we could detect a significant difference in both experiment sites ( $p < 0.01$ ). The worst results were in the lowest cover category (0-10%), 71.3% on Lukács soil and 61.8% on Józsefmajor. The highest crumb ratio was measured in Lukács (84.3%), in the 26-45% cover category, while in Józsefmajor (76.1%) in the 46-70% cover category. The crumb ratio did not increase linearly with the cover categories because the cover categories consisted of several tillage treatments.

The temporal dynamics of earthworm populations can be related to climatic and soil conditions, farming, and the presence and cover ratio of plant residues.

In Lukács, on the Stagnosol soil deep tine cultivation tillage provided 11 times more favorable edaphic conditions for the earthworm population than ploughed treatment. Although, at the two early spring dates, ploughing either proved to be better or there was no difference between the values in two measurements. In terms of temporal distribution, the largest earthworm population was observed in June 2016, May 2017 and June 2018 on Stagnosol soil in the Lukács region.

In Józsefmajor the lowest earthworm abundance was measured – due to higher temperature and drier soil – in the summer of all three years, while the highest – due to the more favorable habitat conditions – was measured in May 2016 and 2018, and in April 2017. The high earthworm abundance in April 2017 is presumably due to more favorable habitat conditions as well as 40 mm of rainfall. In the late autumn measurement periods, the earthworm abundance was reduced not only by tillage modes but also by the cooling of the weather. Based on the three-year data set, the following (increasing) order can be concluded: ploughing<disking=loosening<shallow tine cultivation=deep tine cultivation<no-till.

### ***3.5. Evaluation of tillage systems under different precipitation conditions***

#### ***3.5.1. Suitability of the ploughing system on two different soils***

The soil penetration resistance in the Lukács experiment proved to be lower compared to Józsefmajor due to the previously higher moisture content. At the same time, as the depth increased, the soil penetration resistance values increased in parallel at both experiment sites. In the deeper layers, the Józsefmajor ploughing treatment was characterized by higher values due to the lower moisture described earlier. A harmfully compact state (>3 MPa) was observed in the Lukács experiment in the 35-40 cm layer, while in the Józsefmajor experiment this state was already observable in the 25-30 cm layer. The shallower loosened depth in the Józsefmajor experiment is presumably due to the permanent ploughing of almost the same depth and the lower moisture content.

Regarding the soil moisture, on average over three years we measured higher values in the Lukács soil at all depths compared to the Józsefmajor experiment site. This is presumably due to more precipitation (816 mm on average over 3 years) and the limited drying of the deeper layers of gley soil. The lowest value was typically measured at the surface, 7.9 m/m% in the Józsefmajor experiment and 9.4 m/m% in the Lukács experiment. In the Józsefmajor experiment, the highest value was measured at a depth of 30 cm (23.8 m/m%), below this a decrease was observed. In the Lukács experiment, the values continuously increased in the soil profile, so the highest value (29.2 m/m%) was measurable at depths of 45-50 cm.

The results of the agronomic structure analysis show a more favorable distribution of the ploughing in Lukács. The proportion of clod was 18.2% on average in Lukács ploughing, while in Józsefmajor it was 26.2%. In the ploughed soil of Lukács there were 71.3% crumbs and 61.8% in Józsefmajor. In the dust ratios there was no significant difference, however it exceeded 10% in both ploughed soils.

Based on the evaluation of the earthworm abundance, significantly ( $p < 0.01$ ) more favorable living conditions were created by the ploughing in Lukács. In Lukács ploughing the average was  $54.7 \pm 47.6$  ind/m<sup>2</sup>, while in Józsefmajor it was  $21.4 \pm 21.4$  ind/m<sup>2</sup>. In all three years we found more earthworms in Lukács ploughing, the greatest difference was found in the soybean season, under the more favorable humidity conditions.

### ***3.5.2. Suitability of loosening-crumbling-mulching systems on the different soils***

By loosening-crumbling-mulching tillage systems, I mean disking, shallow tine cultivation, no-till, deep tine cultivation and loosening treatments. These tillage systems differ mainly in the purpose of application and the depth of disturbance, and in some cases also in the cover of the soil surface.

Different soil penetration resistance results were measurable both in the two experiments. In the Lukács experiment, there were no high differences regarding the 0-50 cm between deep and shallow tine cultivation treatments. The values measured in no-till differed in the near-surface and deeper layers from the two previous treatments. In the 20-30 cm layer, there were only slight differences between tilled and non tilled soils. In case of the two shallow and deep tine cultivation treatments, larger differences were measured only in the 0-5 cm and 5-10 cm layers ( $p < 0.05$ ).

The results of moisture content in Józsefmajor proved to be generally more favorable compared to the values measured in the Lukács soil. Between the two shallow tine cultivation treatments, Józsefmajor had higher moisture content, in addition, there was a significant difference between four of the layers. The lowest moisture content characterised the Lukács no-till soil. In no-till treatments there was a significant difference between the moisture values of all the layers ( $p < 0.01$ ) except for the surface. The soil tilled by deep tine cultivator in Lukács contained less moisture than that of Józsefmajor. In both cultivator treatments, the highest moisture content was measured in the 30 cm layer, 25.3 m/m% in Lukács, and 29.3 m/m% in Józsefmajor. The disking and loosening treatments in Józsefmajor did not differ from the other treatments in Józsefmajor, and since no such treatments were set up in Lukács, they did not have a comparison pair.

In terms of agronomic structure, in the shallow tine cultivation treatment, in the Józsefmajor experiment a 4.5% more clod and 5.5% less crumb ratio were measured, while the dust was only 1% higher. The deep tine cultivation treatment in Józsefmajor experiment showed

5.8% more clod and 1.8% more dust ratio, and 7.5% less crumbs compared to the deep tine cultivation treatment in Lukács.

Based on the evaluation of the earthworm abundance (ind/m<sup>2</sup>), statistically significant difference ( $p < 0.05$ ) in the loosening-crumbling-mulched treatments of Józsefmajor and Lukács could be detected only in the no-till treatment, which was achieved by non-representative data. Regarding the annual changes, we found a statistically verifiable difference each year. In 2016, in the Józsefmajor deep tine cultivation treatment there were 65 ind/m<sup>2</sup> more earthworms than in Lukács, in 2017 only 6.5 ind/m<sup>2</sup> more, while in 2018 we had 69.6 ind/m<sup>2</sup> less earthworms in the Józsefmajor experiment compared to the deep tine cultivation in Lukács. At the same time, in 2017 in Józsefmajor, due to better habitat, we found 37.7 ind/m<sup>2</sup> more earthworms in the shallow tine cultivation treatment, while in 2018 we found 62.4 ind/m<sup>2</sup> more in the Lukács treatment, presumably due to the wetter soil.

Based on the performed evaluations – depth of loose layer in connection with soil penetration resistance, soil moisture content, surface cover, crumb ratio, earthworm abundance, soil exposure – we had the opportunity to rank the tillage treatments (systems). The figures show the average data for the three years and represent a real difference between the values. As a result, there is a greater or less difference between certain treatments. Regardless of the parameters – higher moisture content or lower resistance value, more crumbs or less clod ratio – I edited the data so that the lower value, the worse it is.

On the Stagnosol soil in Lukács, the suitability of the tillage systems for the given weather conditions – in increasing order – is as follows: ploughing < no-till < shallow tine cultivation < deep tine cultivation (Figure 3). This order proved the beneficial effect of regional tillage even after the years of the experiment.

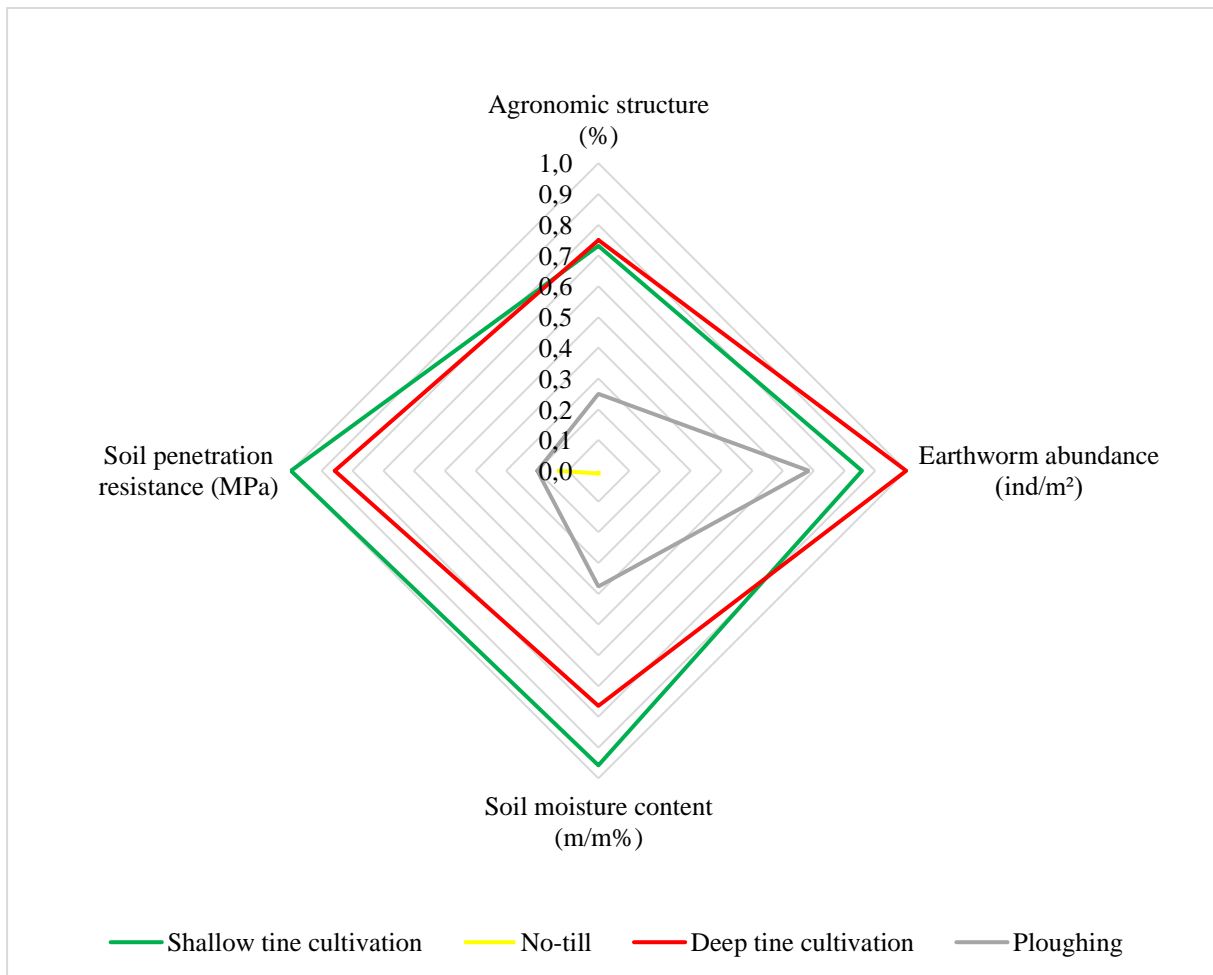


Figure 3. Comparison of tillage treatments based on the four parameters measured in the Lukács experiment (2016-2018), *Note: 0: worst value, 1: best value*

The suitability and ranking of the tillage systems on the Endocalcic Chernozem soil in Józsefmajor in the given weather conditions – in increasing order – is as follows: ploughing<disking<loosening<shallow tine cultivation=deep tine cultivation=no-till (Figure 4).

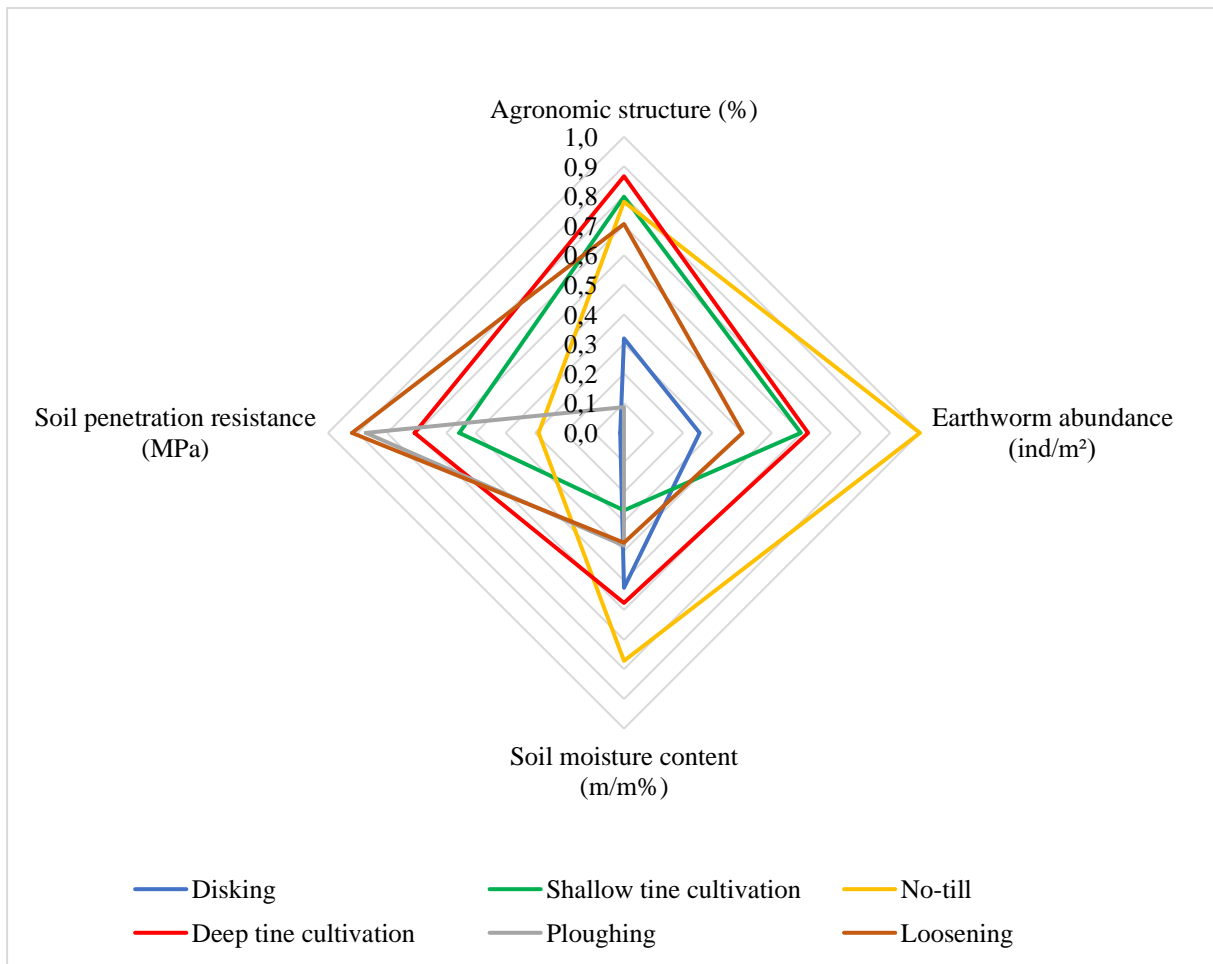


Figure 4. Comparison of tillage treatments based on the four parameters measured in the Józsefmajor experiment (2016-2018), *Note: 0: worse value, 1: best value*

The ranking of compliance based on the above refers to climatic conditions and soil state observed in extreme years. The advantage of no-till soil condition is not yet reflected in the crop yield.

In the case of even more extreme weather conditions, the ranking of tillage systems is also likely to change, but the need to achieve acceptable yield while causing as less damage as possible and regardless of the difficult situations will not change.

### ***3.6. New scientific results***

Based on the results of my doctoral dissertation, I established the following new scientific results:

1. I proved the unfavorable effects of the different precipitation and erratic distribution on certain soil condition factors – depth of loose layer, agronomic structure, earthworm abundance, surface exposure – and the quality of tillage. I stated that the degree of quality deterioration is increased or decreased by the soil condition formed by tillage in a statistically verifiable manner. I have shown that the favorable effect of the amount of precipitation on the soil moisture content occurs only in the case of a soil condition suitable for water uptake and water retention.
2. I verified the deepening of the tillage depth at loosening and tine tillage cultivation treatments that are suitable to avoid compaction occurrence.
3. I proved the beneficial effect of surface protection after harvest ( $\geq 50\%$  cover ratio) and after sowing ( $\geq 30\%$  cover ratio), corresponding to the internationally requirements.
4. I extended the assessment of soil surface exposure with the inclusion of new factors (surface cover, agronomic structure and soil moisture content in the top 0-10 cm layer).
5. I quantified the correlations between surface cover, crumb ratio and earthworm abundance in two different experiment sites. According to the results, in case of  $\geq 30\%$  surface cover, in addition to the development of the required total crumb ratio ( $\geq 70\%$ ), the earthworm abundance is also considered favorable (80 ind/m<sup>2</sup>/0-30 cm).
6. I proved the suitability of the tillage systems adaptively to the site conditions and in erratic climatic factors on the basis of soil moisture content, soil penetration resistance, agronomic structure and earthworm abundance.

#### 4. DISCUSSION

My research work on the compliance of climate-sensitive and climate-protective tillage was carried out in Croatia, in the Lukács region on Luvic Stagnosol soil, and in the Hatvan region, in Józsefmajor on Endocalcic Chernozem soil. During the research period extreme weather conditions were dominant. The highly variable weather affected the quality of tillage and thus the condition of the soils.

The examinations that were used to develop the goals of the study – depth of loose layer in relation to soil resistance, soil moisture content, surface cover, crumb ratio, earthworm abundance, exposure – helped to accurately assess the effects of tillage and climatic factors on soil.

The depth of the loose layer is not necessarily the same as the tillage depth, it can be better than that. Soil penetration resistance measurements proved to be suitable for checking the depth of the loose layer. In the Lukács and Józsefmajor experiments, statistically significant differences ( $p < 0.01$ ;  $p < 0.05$ ) were observed between the resistance of ploughed and non rotated soils. According to the studies, in ploughed soils more often, while in deep tine cultivated soils only occasionally a compacted condition is developed under the tilled layer that prevented root formation. The depth of loosened layer in the deep tine cultivation treatments exceeded the tilled layer by 10-30 cm. In no-till soil, the progression or lack of looseness was a factor that aided or limited rooting. The long-term application of no-till results in better loosening compared to the initial state due to improved biological activity, which also improves moisture storage. Using equipment which produce a compact layer – ploughs, disks – it is especially important to examine the soil condition before tillage.

Soil moisture studies confirmed the combined influence of weather effects and tillage systems at both experiment fields. In case of higher precipitation deeper soaking – and correspondingly higher soil moisture content – was observed in those treatments (loosening, deep tine cultivation and ploughing without compact layer) where moisture infiltration was not or only slightly impeded by the compact condition formed by tillage. Measurements have confirmed that ploughing and disking can be classified as tillage systems that prevent the infiltration of water into the deeper layers due to the formation of compact layers. Loosening and deep tine cultivation treatments, where compact layers are not formed provide more favorable moisture condition. Differences in moisture content (2-5 m/m%) between the tillage treatments were mostly significant. Moisture values typically reflected the given period in non-inversion tillage and no-till, while ploughed soils had lower moisture content. Nowadays, dry



periods also occur during the tillage and sowing seasons, soil conditions and its suitability for water absorption deserve more attention after harvest as well. Furthermore, whether based on moisture content a favorable condition develops by the time of the basic tillage. It is recommendable to use tillage methods and systems that are suitable for absorbing and retaining moisture from harvest to sowing. Regarding this, ploughing without the formation of compacted layers may be acceptable in addition to non-inversion tillage. However, if the moisture content of the ploughed soils is already lower at harvest, there is less chance for a significant improvement. That is, the soil moisture content is only a suitable indicator for assessing the suitability of tillage if data of a longer period of time is available.

Surface cover has become a factor to be assessed in recent years due to the need to reduce climate damage. In our experiments, there was a significant difference between nearly coverless surface tillage (ploughing) and treatments which proved to protect the surface (deep tine cultivation and no-till) ( $p < 0.01$ ;  $p < 0.05$ ) in both experimental fields. The classification of the soil surface cover ratios into five categories was necessitated by their frequency in the experimental fields, i.e. 0-10, 11-25, 26-45, 46-70 and 71-100%. The rating covered whether the surface coverage meets the expected coverage % for a given experimental field and the internationally designated 30% requirement. Deep tine cultivation and no-till treatments fulfilled this requirement. Based on the results, the recommended rate of surface cover is depending on the given period, i.e. in critical (summer) periods higher ( $\geq 50\%$ ), and after sowing the soil protection maintaining rate ( $> 30\%$ ), as recommended by the international expectations is advised.

The crumb ratio ( $\varnothing$  2.5-10 mm) is an important characteristic in the evaluation of soil due to climatic and mechanical stresses it faces. There was significant difference between the given fractions of crumb-destroying (ploughing, disking) and crumb-preserving (deep tine cultivation, loosening, no-till) treatments. More crumbs formed in the soil that was preserved in its physical and biological condition, by using no-till or deep tine cultivation, crumb ratio was 35-45% in the Lukács gley and in the Józsefmajor chernozem soil. To promote crumb formation, reduce clodding and dusting and conservation tillage (not ploughing) is recommended regardless of location.

The earthworm abundance provides information on the biological activity of a given soil. In our experiments, significant differences were found between suitable and unsuitable habitats. Soil conditions during tillage with high disturbance (ploughing) proved to be unsuitable, while during tillage with moderate disturbance (tillage systems without inversion), especially if disturbed only at sowing (no-till) proved to be suitable. Climatic and soil conditions provided

the most favorable habitat for earthworms in the spring. Earthworm abundance was  $\geq 150$  ind/m<sup>2</sup> in gley soil, and  $\geq 200$  ind/m<sup>2</sup> in chernozem in the 0-30 cm top layer. The other period when conditions could be considered favorable were after harvesting, when the soil was covered with stubble residues, earthworm abundance was 75 ind/m<sup>2</sup> in gley soil and 50 ind/m<sup>2</sup> in chernozem soil in the 0-30 cm top layer.

The earthworm abundance is an indicator of the soil condition, therefore it should be examined when the suitability of soil conditions is determined. In order to maintain and increase the biological activity of the soil, it is recommended to establish soil conditions that promote earthworm abundance and activity. Due to this, ploughing is recommended rarely, while tillage without inversion can be recommended in given conditions (tillage system, weather).

Soil condition examinations served as a basis for assessing the suitability of tillage systems. The suitability of the tillage systems on the Luvic Stagnosol (Siltic) soil in Lukács under the given weather conditions – in increasing order – is as follows: ploughing < no-till < shallow tine cultivation < deep tine cultivation.

The suitability and ranking of the tillage systems on the soil of Endocalcic Chernozem (Loamic) in Józsefmajor under the given weather conditions – in increasing order – is as follows: ploughing < disking < loosening < shallow tine cultivation = deep tine cultivation = no-till.

The compliance ranking is valid in the recent climatic conditions and soil conditions observed in extreme years. The advantages that no-till treatments have on soil conditions is not yet reflected in the crop yield.

In the case of even more extreme weather conditions, the ranking of tillage is also likely to change, but the need to achieve acceptable yield while causing as less damage as possible and regardless of the difficult situations will not change.

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