HUNGARIAN UNIVERSITY OF AGRICULTURE AND LIFE SCIENCES

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Impacts of soil tillage on soil physical properties, crop yield and quality: Insights from a long-term experiment in Endo calcic Chernozem soil

By

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1. BACKGROUND AND OBJECTIVES

Since the human discovery of tillage post hunter and gathering era, it remained a pivotal aspect of land preparation influencing numerous soil properties and crop productivity. Recent developments in scientific studies are focusing on intricate relationships between soil physical properties, crop yield, and tillage practices, specifically in areas of diverse agricultural landscapes such as Hungary and South Africa.

Soil penetration resistance (SPR) is a physical characteristic of soil that reflects the combined effects of various soil properties, including bulk density (BD), soil moisture content (SMC), porosity, and permeability. These properties are influenced by the distribution of particle sizes, soil structure, and the presence of mineral and organic matter (Soane et al., 1980). Soil penetration resistance serves as a key indicator of soil compaction (Mohieddinne et al., 2019). Compacted soil increases resistance to root growth (Correa et al., 2019; Unger and Kaspar, 1994), hinders soil fauna movement (Dekemati et al., 2019b, 2021; Plum, 2005), diminishes porosity (thereby slowing water and air movement), and reduces nutrient mineralization rates (De Neve and Hofman, 2000). Furthermore, it promotes surface runoff over infiltration, which can be critical for soil moisture retention during dry periods.

In anthropogenic soils, compaction often results from technological processes (Zadorozhnaya et al., 2018; Zhukov and Zadorozhna, 2016), such as the use of land preparation machinery. Tillage operations can significantly modify soil structure, potentially affecting SPR and, as a result, plant growth. However, tillage can preserve, enhance or degrade soil health (Birkás et al., 2015; Madari et al., 2005). Frequent ploughing of the soil to the same depth and outside the recommended moisture range can induce plough pan (Eliasson, 2005; Gerasimov and Katarov, 2010; Han et al., 2009; Sakai et al., 2008; Salokhe and Ninh, 1993). Contrastingly, conservation tillage (CA) is characterized by its holistic approach to enhance and preserve soil health by reducing soil disturbance and retention of crop residues, consequently improving crop yield (Busari et al., 2015; Sanaullah et al., 2020).

Similarly, SMC is crucial for crop development and is affected by tillage practices through alterations in soil porosity (Blanco-Canqui and Ruis, 2018; Mehra et al., 2020), water retention capacity (Mwiti et al., 2022), and evaporation rates (Strudley et al., 2008; Unger and Cassel, 1991).

The quantity of moisture is crucial in crop production in sense that excessive moisture cripples' gaseous diffusion in the soil leading to anaerobic conditions for crop roots, while deficient induces crop drought stress. The latter phenomena contribute negatively to crop output.

The climate in Hungary is characterized by a humid subtype of the continental climate, featuring extended warm periods and notable temperature variations throughout the year (Mezősi, 2017). And the different soil types present an interesting area for investigating the effects of tillage on soil properties and crop productivity. The study area located near the town of Hatvan, is in an agriculturally important region characterized by its fertile soils (Chernozem) and production of different crops.

The topic of tillage effects on soil physical properties has been extensively studied globally (Moraes et al., 2014; Nunes et al., 2015). From these (Bogunovic et al., 2015; Dekemati et al., 2021, 2019b, 2019a; Jug et al., 2024) different studies a myriad of response has been observed to have been influenced by specific location factors such as climate, soil type and type of tillage equipment utilized. To develop sustainable agricultural management strategies in Hungary, it is crucial to examine how tillage methods, SPR, SMC, and crop productivity interact with one another in this specific region.

1.1. Study objectives

1.1.1. General objective

To investigate the influence of tillage practices on soil physical properties and sustainable crop yield in Hungary using a multidimensional analysis comprising meteorological and soil-specific variables.

Specific objective 1: Investigate the impact of tillage practices on soil physical properties.

Specific objective 2: Assess tillage effects on crop yield.

Specific objective 3: Explore the combined effects of weather, tillage, soil physical properties, and crop yield.

Specific objective 4: Identify tillage methods for soil health and water dynamics.

Specific objective 5: Determine tillage methods enhancing overall crop productivity.

2. MATERIALS AND METHODS

2.1. Study location

The study was conducted at the Józsefmajor Experimental and Training Farm (JM) of the Hungarian University of Agriculture and Life Sciences near Hatvan (47°41′30.6″ latitude N, 19°36′46.1″ longitude E; 110 m above sea level), established in 2002. The research area covers 5.05 hectares. The topography is level, with a clay loam texture, classified as Endocalcic Chernozems (IUSS Working Group WRB, 2022). The soil contained a humus content of 3.12% in the top 20 cm layer, with corresponding sand, silt, and clay contents of 36%, 27%, and 37%, respectively (Mohamed et al., 2024). As described by Ács et al. (2015), the climate in Hungary consists of warm, dry summers followed by dry, wet winters, referred to as a continental climate. The weather conditions are classified as continental, with annual temperatures ranging between 10.3 and 15°C during growing periods (New et al., 2002). The mean annual rainfall period from 2018 to 2021 ranged between 500.98 and 643.36 mm (**Figure 1**). During the duration of the study, the annual rainfall was 117.55, 43.72, and 95.24 mm lower in 2018, 2020, and 2021, respectively, when compared to the average long-term rainfall (1991–2020). Whereas in 2019, the study area received 24.33 mm more rainfall compared to the long-term average (1991–2020).

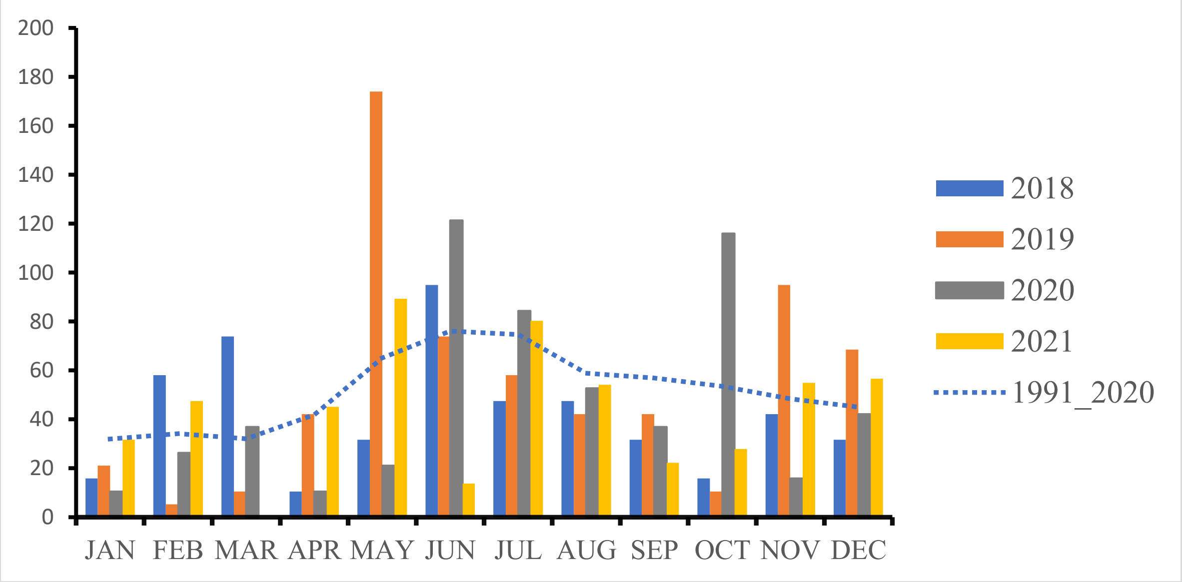

Figure 1. Monthly average rainfall received between 2018 to 2021 and the long-term monthly average rainfall between 1991 and 2020.

2.2. Experimental design

The research area consists of six tillage treatments arranged in a randomized block design with four replications, and each treatment area has a size of 2340 m^2(13 m × 180 m). The tillage treatments were disking (D, 12-16 cm), shallow cultivation (SC, 18-20 cm), no-tilling (NT), deep cultivation (DC, 28-32 cm), loosening (L, 40-45 cm), and ploughing (P, 28-32 cm). Primary tillage was performed in correspondence with soil workability.

2.3. Experimental measurements

Soil moisture content (SMC) was measured from 0 to 60 cm depth at 5 cm increments in four replications per treatment, and the data were aggregated to 0–10, 10–20, 20–30, 40–50, and 50–60 cm depths. Measurements were performed in 30-day intervals between March and November of the 2018–2019 and 2020–2021 cropping seasons. A PT-I type gauge (Kapacitiv Kft, Budapest, Hungary), which is based on a time domain reflectometry (TDR) principle, was used to determine SMC. The SMC was shown on the LCD of the instrument as water by weight, %, m/m% (Dekemati et al., 2021). The specified soil is classified as dry, humid, or wet when its moisture content ranges between 14.8–18.9, 19.0–23.9, and >24.0 m/m% SMC, respectively (Csorba et al., 2011).

Soil penetration resistance (SPR) was measured at 5 cm intervals from the surface to a depth of 50 cm, with four replicates per treatment. The collected data were subsequently consolidated into depth ranges of 0–10, 10–20, 20–30, 40–50, and 50–60 cm. Measurements were conducted at 30-day intervals from March to November during the 2018–2019 and 2020–2021 growing seasons. A Szarvas-handheld type and an Eijkelkamp penetrologger instruments were utilized for SPR measurement. The device employed a conical point with a 1 cm^2 area and a 60° angle.

2.4. Measured crop parameters

To obtain the fresh root weight, three sunflower plant roots per treatment were randomly selected, collected, then washed, and measured using a digital scale, and the resulting weight was converted to t ha^{-1}. A similar procedure was followed to collect wheat roots with an auger. After collecting, they were washed and weighed with a scale. A 12-row combine harvester was used to harvest sunflower heads. Similarly, wheat was harvested with a 6.6 m width combine, equipped with a straw chopper.

The grains were ground for chemical composition of protein determination using the near-infrared (NIR) spectroscopy Product Analyzer (INSTALAB 600). The protein content was expressed as percentage. To determine the thousand kernel weight (TKW), 1000- grains per crop were counted and a weighing balance was used to measure their weight. The HLW was measured determined using a chondrometer. This was done by measuring the weight of the empty chondrometer followed by filling it with winter wheat and winter oat grain to the brim and the weight of the full chondrometer with grain was taken down for each sample, which equals 1 litre of grain. For this measurement each crop's HLW was determined separately. All seed samples were analysed at the Crop Production Laboratory at the MATE Institute of Agronomy. The number of spikes square meter was determined in the field by randomly selecting and measuring the area then followed by enumerating the number of spikes within the selected area in four replications.

2.5. Statistical analysis

Data collected was recorded in excel sheet followed by data curation. The final curated data was subjected to R-software version 4.3.1 for statistical analysis. Firstly, before data analysis, the skewness of the data was checked by computing the Kolmogorov– Smirnov test and the Shapiro–Wilk test (Shapiro and Wilk, 1965; Massey Jr, 1951). The results indicated that the following assessed parameters SPR, SMC, hectoliter weight (HLW) (for both wheat and oat), wheat grain yield (GY) and root weight (RW) data were not normally distributed ($p<0.05$). Hence, to assess the relationship of tillage on SPR and SMC a generalized mixed effect model was employed to account for random effects, including depth and season. While for hectoliter weight (HLW), wheat grain yield, and (RW) data wer subjected to square root transformation and means were separated using analysis of variance at 5% level of significance. Mean separation was done with Tukey HSD post-hoc test at $p = 0.05$. The correlation relationships of the parameters assessed were calculated based on skewness of the data. For instance, the normally distributed parameters were subjected to Pearson correlation while a Spearman's rank test was employed for non-parametric parameters.

3. RESULTS AND DISCUSSION

3.1. The effect of tillage on soil moisture content

Soil moisture measured in all cropping seasons at 0-50 cm was significantly affected by soil tillage. The tillage method that showed the greatest SMC was no-till (NT), while the lowest moisture was recorded in ploughing (P). Regarding different soil depths in winter wheat cropping season, significant differences were observed at 10–20 cm during winter wheat cropping period, SMC was significantly higher under disking (D) (26.36 m/m%) compared to loosening (L) treatment. At 20–30 cm, SMC was significantly lower under L and deep cultivation (DC) compared to D and NT. At 30–40 cm, significantly higher SMC was observed at P (29.16 m/m%) compared to the lowest at L (28.16 m/m%). At 40–50 cm, significantly higher SMC was observed at P relative to L. In all assessed treatments, SMC significantly increased with depth. In winter oat cropping period SMC at 0-10 cm was significantly greater in NT relative to P, while at 40-50 cm depth D. Similar observations to wheat SMC regarding SMC at various soil depths were also observed under winter Oat. Sunflower SMC results were measured in the 2020/21 cropping season. At 0–10 cm, a significant SMC increase of 13% and 17% was observed at D and NT, respectively, relative to P. However, at 10–20 cm, NT significantly increased SMC by 66% similar to D. Meanwhile, at 20–30 cm, 30–40 cm, and 40–50 cm, P was significantly lower by 3%, 2%, and 16%, respectively, relative to NT.

Regarding the sampling time, substantial differences were observed during the study period. Under winter wheat, in March under, a significantly higher SMC was observed at P (24.06 m/m%) followed by NT (23.88 m/m%) compared to L (20.53 m/m%) in winter wheat crop. No significant differences were observed between soil tillage treatments in April, June 28, and August. The winter oat cropping period was measured only two times (March and September). Both months did not yield any substantial variations. The differences between measuring time/date showed significant differences in all treatments. Soil moisture content in all treatment plots increased significantly with time. During sunflower season, SMC differences between treatments were observed in the first measurement under. In October, November, and March, NT showed a 7%, 5%, and 4%, respectively, higher SMC relative to P. In September, a significantly higher SMC was observed at D, SC, NT, DC, and L than at P. SMC differences between the sampling dates showed that at P and L, there were no significant differences among sampling dates. Soil moisture content showed a monthly fluctuation (increasing and decreasing).

3.2. The effect of tillage on soil penetration resistance

Soil tillage significantly affected SPR in all cropping (winter wheat and sunflower) seasons $p < 0.05$. Considering all cropping seasons and the 0-50 cm depth, significantly greater SPR was observed in D and NT compared to L treatments which had the lowest SPR. Similar, SPR trends were observed in winter oat and sunflower cropping seasons despite the variations in annual rainfall amounts received per season.

The spatial SPR variation under winter wheat was substantially affected by tillage. Higher SPR was obtained under treatment D at from 0-10 cm to 20-30 cm during winter wheat season. During winter oat results showed spatial significant responses to tillage and depth. Soil depths from 0-10 cm to 30-40cm, had substantially higher SPR was recorded under D and NT. A similar trend was observed for sunflower SPR measurements except for occasional differences observed at some soil depths. Compared to oats results at 30-40 cm SPR was greater under NT while at 40-50 cm it was higher under SC.

Temporal SPR variations under different tillage treatments showed significantly higher SPR under D relative to SC, DC, P, and L in March. While in July, significantly higher SPR was observed under NT and P. Tillage significantly affected SPR during oat cropping season with significantly higher values observed on the 19th of March 2020 under NT and D relative to L. Similarly, in September, NT and D had significantly higher SPR compared to L. In sunflower cropping season, SPR was significantly greater in NT and D from September 2020 to March 2021. While in April 2021, only D significantly increased SPR relative L.

3.3. The effect of tillage on crop yield and yield quality parameters

The winter wheat yield was significantly lower in D and NT compared to DC, SC, P and L. During oat cropping season the yield showed fluctuations, with significantly higher yield observed under L and the lowest in P. DC and P were significantly higher to P, while D and NT were lower than L. Similar to wheat, sunflower yield was significantly reduced by treatment D and NT relative to L.

The wheat RW under DC was 22% greater relative to the lowest obtained at D. The wheat root weight was in the following order: DC = L = P =SC > NT > D when considering all treatments. Winter oat RW was significantly increased by L, SC, DC, D, and NT relative to P. The sunflower RW under L (3.89 t ha^{-1}) was 22% higher compared to the lowest at D (3.18 t ha^{-1}). Significant differences were observed between P (3.52 t ha^{-1}) and L (3.89 t ha^{-1}) with greater RW measured at L. Moreover, L was significantly greater than NT (3.31 t ha^{-1}) and SC (3.49 t ha^{-1}). Treatment DC (3.71 t ha^{-1}) produced significantly higher RW than NT (3.31 t ha^{-1}), and D (3.18 t ha^{-1}).

Tillage treatments significantly increased winter wheat protein percentage in the following order D=P>DCSC=NT>L. The TKW showed the following order L>NT=DC>D=SC>L. The Zeleny index was significantly higher under D compared to NT, while the other tillage practices showed the following trend D>P=SC>DC>L. The greatest SW was measured at P (3.91 t ha^{-1}) treatment, while comparisons between SC (3.64 t ha^{-1}) and NT (3.31 t ha^{-1}) showed that NT produced significantly lower SW. The greatest hectoliter weight (HLW) was measured at SC (72.64 kg/HL) and the lowest significantly HLW was measured at P (67.80 kg/HL). Treatment D (70.0 kg/HL) was significantly lower than SC (72.64 kg/HL) but significantly greater than treatment P (67.80 kg/HL). During oat there was no difference on protein% and HLW, meanwhile the measured TKW values differed with the greatest observed under D and the lowest under SC without significant differences. The number of spikes/m^2 were significantly reduced under D, NT, and P relative to L. treatment P and NT significantly reduced the straw weight (ST) while other treatments (SC, DC) significantly yielded significantly greater ST than P and NT.

3.4. Correlation of soil penetration resistance, soil moisture content, crop yield, and quality parameters

According to the results, winter wheat GY negatively correlated with SPR in both D (r = - 0.86) and SC (r = - 0.82), while under NT there was a positive correlation of 20%. Similarly, the correlation between SMC and winter wheat GY was negative, under D and SC. However, under SC the correlation was weak (r = 0.35) while under NT treatments a positive correlation of r = 0.27 was observed. In relation to HLW, stronger negative correlation was observed under NT (r = -90). The RW correlated with GY under NT and D compared to SC. Similarly, under NT and D a strong negative correlation, whereas under SC a positive correlation was observed.

The relationship between GY and SPR under high intensity soil tillage treatments (DC, P, and L) was positively strongest under DC (r = 0.83), moderately negatively strong under P (r = - 0.48) and weakest under L (r = 0.10). The relationship with SMC showed overall weaker correlations in all the soil tillage treatments. The relationship with RW showed the overall strongest correlations in all soil tillage treatments. The strongest correlation was observed under L (r = 0.99*) followed by DC (r =

0.96**) while the weakest among the treatments was observed under P (r = 0.82). The relationship with SW was strong under L (r = 0.88) and P (r = 0.82) whereas the weakest among treatments was observed under DC (r = 0.30). The TKW and GY correlations were also strong in all treatments, however, between treatments the strongest observed under DC (r = - 0.10**), followed by L (r = - 0.92), and the lowest among treatments was observed under P (r = 0.88). The strongest correlation between HLW and GY was observed under P (r = 0.86), while under DC (r = 0.70) there was a moderate correlation and L (r = 0.44) treatments had a moderate correlation. The relationship between GY and number of spikes/m^2 (NOS/m^2) showed an overall of strong correlations in all treatments. However, between treatments the strongest correlation was observed under DC (r = 0.10**) followed by L (r = 0.99*) while the lowest among treatments was observed under P (r = - 0.94).

Low intensity soil tillage correlations for oats. The relationship between RW and GY showed the strongest relationships under SC (r = 0.90) and D (r = 0.87), and the weakest was observed under NT (r = 0.05) treatment. The relationship between SW and GY was strongest under SC (r = 0.80) and D (r = 0.78), while NT (r = 0.22) showed the weakest correlation. The relationship between GY and TKW was strongest under NT (r = 0.94) and under D (r = - 0.40), and SC (r = - 0.49) treatments showed weak moderate correlations. The GY with the NOS/m^2 relationship was weakest under NT (r = 0.07) and strongest under D (r = 0.86) and SC (r = 0.89).

The relationship between GY and SPR under high intensity soil tillage treatments was positively strongest under DC (r = 0.83), moderately negatively strong under P (r = - 0.48) and weakest under L (r = 0.10). The relationship with RW showed the overall strongest correlations in all soil tillage treatments. The strongest correlation was observed under L (r = 0.99*), followed by DC (r = 0.96**), while the weakest among the treatments was observed under P (r = 0.82). The relationship with SW was strong under L (r = 0.88) and P (r = 0.82), whereas the weakest among treatments was observed under DC (r = 0.30). The TKW and GY correlations were also strong in all treatments, however, between treatments the strongest observed under DC (r = - 0.10**), followed by L (r = - 0.92), and the lowest among treatments was observed under P (r = 0.88). The strongest correlation between HLW and GY was observed under P (r = 0.86), while under DC (r = 0.70) there was a moderate correlation, and L (r = 0.44) treatments had a moderate correlation. However, the relationship between GY and protein percentage was strongest under DC (r = 0.91), while P (r = 0.45) had a moderate correlation, and the weakest correlation was observed under L (r = 0.20). The relationship between GY and PD/m^2

showed an overall of strong correlations in all treatments. However, between treatments the strongest correlation was observed under DC (r = 0.10**) followed by L (r = 0.99*) while the lowest among treatments was observed under P (r = - 0.94).

4. DISCUSSION

The study conducted in Hatvan Hungary for a period of three seasons assessing the effects of tillage on SPR, SMC, Grain yield and crop quality parameters yielded informative results. The SMC measurements indicated which tillage methods are suitable to mitigate the effects of extreme climatic conditions. According to the measurements, conservation tillage methods proved more beneficial during lack of adequate rainfall. Such tillage methods include NT and L, they had the highest SMC when considering the 0-50 cm layer, temporal and spatial variations. However, when rainfall is adequate this tillage methods do not vary conventional tillage methods on moisture conservation. This beneficial nature stem from mechanical loosening in L, while NT due to no soil disturbance tends to have a crumbly structure with good moisture conservation. Moreover, the residue retention in NT aid in reducing evaporation ultimately moisture loss.

The substantial differences in SMC between SC, D, and NT at the depth of 40–50 cm compared to ploughing were noteworthy, with respective differences of 3.64 m/m%, 3.76 m/m%, and 3.93 m/m%. Generally, findings in this study underscore the efficacy of conservation soil tillage practices, such as NT, in maintaining higher soil moisture levels at deeper soil depths compared to traditional ploughing methods. Such differences hold significant implications for agricultural management strategies. We posit that improved conservation soil tillage methods hold the potential to mitigate soil moisture deficits and enhance overall soil health and productivity. In contrast, tillage methods such D and P increase compacting thus impeding moisture infiltration. However, such tillage methods can still be utilized without being detrimental to the soil's physical state. This could be possible by performing soil state assessments, whereby the soil moisture state is assessed to avoid compaction.

Results from this study indicated that D and NT increased SPR. With higher SPR is an indication of difficulty of water to infiltrate the soil layers, secondly it indicates a shallower environment for root growth that is difficult to overcome. This further affects the yield as indicated by yield results under these tillage treatments. However, loosening provides a better and deeper loosened layer that facilitates water infiltration and better root growth. The penetration resistant in this study was lower in L treatment and this enhanced the grain yield results. Furthermore, this was particularly beneficial during Europe's dry year in 2021, when precipitation was 20% below the long-term average. In light of this, it is recommended that periodic loosening be incorporated into NT to reduce higher SPR.

The reduced winter wheat yield observed in D and NT were also reported by other researchers, this confirms the negative effects of higher SPR on crop yield. Other tillage practices that such as P also cause plough pans thus affecting proper crop growth and yield observed indicated by winter oat yield. In 2021, the greatest sunflower yield was obtained at L. This showed that loosening provided suitable growing conditions (depth of the loosened layer). According to records, loosening of the soil is believed to improve the soil's physical condition by alleviating the compact layer.

The crop quality parameters under wheat were significantly affected by tillage. The quality parameters of wheat were more affected by tillage compared to oats. The results varied by tillage as different quality parameters responded to because either tillage affects them directly or indirectly. For instance, loosening may increase nitrogen loss thus affecting protein% this is one of the plausible reasons of low protein% observed in this current study.

Regarding TKW, conservation soil tillage treatment's ability to improve soil chemical and physical conditions for greater and stable crop yields could have been responsible for higher TKW in this study. Although previous studies say tillage has no effect of HLW. Since it is affected by water tillage can be a contributing factor due to its effects on soil moisture dynamics. Ploughing is known for reducing moisture this could be the reason why under this tillage practice the HLW was low. Superior gluten quality and a higher gluten concentration are typically associated with reduced sedimentation rates and increased Zeleny number values (Hrušková and Faměra, 2003).

Although this current study was limited to the protein% only, hence it is plausible that the greater ZN observed under NT is related to a lower gluten content. However, further studies are required to confirm the assumption. Treatments subjected to soil tillage practice with soil disturbance greater than 16 cm depth proved to be better in enhancing SW. Disking soil tillage had the lowest PD/m^2, the assumption is that the nature of D soil tillage encouraged moisture depletion that affected oat seed germination. In addition, seedbed preparation plays a pivotal role in enhancing germination.

. The lower RW observed under P treatments could be a result of multiple reasons. Ploughing could disrupt water infiltration, because unlike NT, P treatment removes the previous crop's roots and also breaks the formed biological soil channels that root can inhabit to explore the horizon in-depth. The latter mentioned thus prevents proper moisture infiltration which may lead to poor aeration affecting proper root growth.

5. CONCLUSION

This chapter provides conclusion derived from the results of the study and recommendations to further enhance and cover areas that need research to contribute knowledge to the scientific world.

Soil tillage plays a significant role in crop production, by modifying the environment that crops grow, it indirectly affects crop growth and yield quality parameters. The results of this study highlight the complex interplay between soil tillage on soil penetration resistance, soil moisture content and crop production. In relation to the physical parameters of the SPR, significant differences were observed among the assessed soil tillage practices. Evidently, the study has shown that disking and no-soil tillage significantly increased soil penetration resistances under an Endocalcic chernozem soil on a Mediterranean climate of Hatvan.

Moreover, for the soil type and climatic conditions that the study was performed I observed that higher SPR resulted in lower root weight and grain yield. These findings suggest that for Endocalcic chernozem soil, periodic deep soil tillage should be considered to prevent excessive compaction when reduced soil tillage systems are employed. Deep soil tillage practices, such as L and P proved more beneficial in eradicating soil compaction. This highlighted that soil tillage depth may be a more significant factor than frequency, as observed in deep soil tillage (40–45 cm) being more effective in preventing compaction than intermediate-depth soil tillage methods (18–25 cm). However, it is equally important to note that, although ploughing can provide a substantial depth of a loosened layer, there is a possibility of plough pan formation below the working depth of the equipment. Hence, further steps should be taken in order to avoid crop yield penalties, such as annual soil condition assessment if ploughing is practiced annually. Furthermore, variation in depth of ploughing could prove beneficial in reducing the extension of a plough pan.

Seasonal changes influence soil penetration resistance trends with variations driven by climate and soil conditions, with notable increases during drier periods. Other studied soil tillage practices did not show clear impacts on soil penetration resistance; however, I observed that on a Endocalcic chernozem soil there was no difference between SC and DC despite the difference in loosening depth (18–20 and 22–25 cm, respectively) in mitigating soil penetration resistance.

To prevent crop loss due to drought in the Mediterranean, arid, and semi-arid regions, the adoption of deep soil loosening or the incorporation of periodic deep soil tillage into reduced soil tillage systems (SC, D, DC, and NT) is recommended to prevent excessive compaction particularly for the current study's soil type and climatic conditions. Moreover, future research should explore the synergy between soil physical properties, crop physiology, and climate variability to optimize soil tillage strategies for sustainable agriculture.

In this current study soil tillage had substantial influence on wheat protein%, which was enhanced by D and P treatments. With winter oat crop irrespective of absence of significant differences the protein % was higher under P, SC, L and DC. These results showed an inconsistency of the response of these quality traits and since the experiment was conducted in a single season, more research is needed to understand better the interplay between these soil tillage and protein%. Thousand kernel weight and hectoliter weight were not significantly influenced by soil tillage during oat growing season. During the growing winter wheat period, the latter were enhanced under minimum soil tillage practice than ploughing. Zeleny sedimentation measured only under winter wheat was also improved by NT. While under winter oat only the PD/m2 also was improved by conservation agricultural practices (L, DC, NT and SC). Lastly, the straw weight was enhanced by P under wheat and L under oat, however it is important to note that the differences under wheat were not substantial. This means that L treatment can be used instead of P to enhance straw weight, thus, this further supports the notion that conservation agricultural soil tillage practices were more superior than conventional soil tillage on the investigated properties.

NEW SCIENTIFIC FINDINGS

1. The study confirmed that despite more than 16 years of NT practice on an Endocalcic Chernozem soil, the highest soil penetration resistance is still obtained in NT treatment compared to ploughing.
2. I confirmed that reduced tillage methods, such as no-till, shallow cultivation and disking lack substantial differences to ploughing, loosening, and deep cultivation when climatic conditions are more humid, particularly when annual rainfall > 600 mm for thousand kernel weight and hectoliter weight.
3. Minimum tillage practices, such as SC and DC equally enhanced and improved SMC, crop quality similar to NT, hence they can be integrated into areas where NT practice have shortfalls or is not effective.
4. I quantified the relationships of SPR, yield and yield quality parameters. The study confirmed a strong negative correlation between grain yield and soil penetration resistance under disk tillage and shallow cultivation. The study further confirmed a strong negative correlation between grain yield and soil moisture content under disking; however, a weak correlation was confirmed for Zeleny sedimentation and hectoliter weight.
5. The study revealed that disking and ploughing outperformed loosening in enhancing wheat protein percentage. However, loosening improved thousand kernel weight relative to ploughing. Furthermore, the study confirmed a pattern of decreasing TKW in DC and P.
6. No-till and disking tillage treatments reduced wheat yield and sunflower yield, while ploughing reduced oat yield. While loosening greatly enhanced yield of all the crops for the whole three examined seasons.
7. Disking treatment greatly diminished root weight for winter wheat and sunflower, whereas the root weight under oats substantially decreased under ploughing treatment.
8. The study revealed confirmed that no-till on an Endocalcic Chernozem does not reduce the penetration resistance even post a decade of practice as reported by other studies. Moreover, I confirmed that the higher penetration resistance under NT had an effect on crop yield as compared to tine tillage implements.

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