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ORIGINAL PAPER

Contrasting Long-Term Tillage Treatments and their Spatio-Temporal Effects on Soil Physicochemical Signatures in a Cropping Season Under a Temperate Climate in Central Europe

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Abstract
Soil tillage is mostly done to enhance parameters that improve the soil environment. As governments yield toward encouraging farmers to opt for more sustainable options, different soil management systems ought to be studied to expand the knowledge base for decisions. Location specificity of tillage effects requires more representative studies for geographical regions such as the temperate region in Czechia that was experimented with. This study sought to compare conservation tillage systems to conventional tillage to explore variabilities and similarities and, inform on alternatives. In this study, selected soil physicochemical parameters (dry bulk density, hydraulic conductivity, soil water content, soil organic matter, soil pH, and soil electrical conductivity) are analyzed under four different soil tillage practices, namely: reduced till (RT), strategic till (ST), no-till (NT), and conventional till (CT). Measurements were carried out for four experimental phases: July 2021 (summer), October 2021 (autumn), April 2022 (spring), and August 2022 (summer). This was done to capture spatial variabilities by applied tillage type, and temporal variabilities by experimental phase on the observed soil properties. The cultivation plan on the experimental plots follows a crop rotation of oil seed rape (*Brassica napus* subsp. *Napus*), winter wheat (*Triticum aestivum*), and peas (*Pisum sativum*). The experiments captured the period from the harvest of oilseed rape in July 2021, to the harvest of the preceding crop, winter wheat in August 2022. The results showed that temporal variability was more pronounced on the CT plot than other plots, while the CT operation affected soil organic matter. Low saturated hydraulic conductivity values observed on the NT also hinted at some compaction caused by the NT. However, coupled with residue inclusion within the top layers, RT and ST showed outcomes in saturated hydraulic conductivity comparable to those of CT. As time from tillage increased, unsaturated hydraulic conductivity (h at -5) under CT improved significantly, hinting at mesopore development from disintegrating macropores. Dry bulk density could not significantly define the variability by applied tillage, while the variability in dry bulk density could also not be directly linked to the hydraulic properties studied. Findings here suggest that natural regenerative processes and soil residue inclusion can influence sustainable soil water dynamics under conservation tillage systems in the long term.

Keywords Conventional tillage · Conservation tillage · Hydraulic conductivity · Dry bulk density · Soil organic matter

1 Introduction

Many agricultural land use systems have undermined soil quality, eventually resulting in the underproduction of crops and herbs. For example, without a break from frequent plowing, a total breakdown of soil structure, an initial loss of productivity, and moderate levels of erosion occur (Angon et al. 2023). Several mechanical manipulations of soils for crop production—tillage (Mwiti et al. 2022)—can significantly affect soil transport and chemical processes (Dugan et al. 2022). Thus, unveiling the effects of different tillage options is pertinent to maintaining soil composure for effective agricultural land management, especially in these unmarginalized patterns of environmental issues resulting from climate change. Furthermore, experiments within marginalized areas for conservation agriculture could provide new insights.

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For temperate conditions, tillage could provide an enormous ecological benefit in soil properties, hydraulic potential, and relative efficiency in crop productivity (Hausherr Lüder et al. 2019). Soil tillage represents an influential manipulation of soil properties due to its repetitive application, depth range, and influence on the type of residue management or even fertigation practice to be applied (Farahani et al. 2022). Agricultural management strategies applied as events have their effects across different temporal scales. These changes in soil physicochemical, mechanical, and biological properties could be evident within a single season, between cropping seasons, or between years (Obour et al. 2024; Pearsons et al. 2023; Scarpare et al. 2019).

To preserve the integrity of the soil, management practices adopted in agroecosystems ought to follow patterns that ensure sustainability and resource conservation (Liang et al. 2024). Hence, the use of conservation tillage practices has been advocated both as an environmentally friendly and cost-effective option compared to conventional tillage (Abebrese et al. 2023; Sharma et al. 2024).

The principle of conservation tillage embodies crop residue retention as soil surface cover while practicing zero tillage or minimal mechanical soil disturbance to shallow depths (Corsi et al. 2012). In the last decade, mainly due to erosion control policies, conservation tillage practices in Czechia have shown an increasing trend. This is because they are linked with the criteria to fulfill requirements for direct support and subsidies for most farmers (Poláková et al. 2024). Hence, research studies about the impacts of these relatively newly adopted practices on soil properties are vital to understanding their influences and sustainability on soils. As tillage attempts to loosen soils, its effects on bulk density are often well-confined to the tilled depth of the specific practice applied (Topa et al. 2021). Findings from short- to medium-term studies on legume-cereal rotation systems in Czechia showed that conservation tillage practices (no and reduced till) increased soil bulk density within the surface layer compared to conventional till practices (Báťková et al. 2020; Naeem et al. 2021). Meanwhile, under similar conditions, Mühlbachová et al. (2015) reported that high dry bulk density on conservation tillage does not impact soil water functions. In a 15-year field experiment on the influence of no-till and conventional till on bulk density by Li et al. (2007), observed values were only significantly higher on no-till in the first six years of the experiment. The preceding five years showed no significant differences, whereas the remaining years showed slightly lower no-till values than conventional till. Li et al. (2020) suggested that improvements in bulk density on no-tilled plots often occur under long-term (> 12-year) practices, possibly from bio-pore processes. However, considering their experiment was conducted in a dryland farming area cropped with winter wheat, outcomes may differ for contrasting climates. Significantly higher contents of organic carbon (OC) in reduced and no-till plots compared to conventional ones have been reported (e.g., Xu et al. 2019; Zhu et al. 2022). For temperate conditions in Asia and North America, higher concentrations of OC have been observed within the tilled depth on reduced till plots where residue stubbles are incorporated (Wuest et al. 2023; Zhang et al. 2019; Zhu et al. 2022). While some studies further identified no-till as a potential strategy to act as a carbon sink based on observed OC content in the upper soil layers (Breil et al. 2023; Somasundaram et al. 2018; Wang et al. 2020), others associate conventional till with improved or similar OC contents compared to no-till (Blanco-Canqui et al. 2011; Govaerts et al. 2009; Sainju et al. 2008). These previous experiments did not capture the within-season temporal changes in OC as affected by tillage, leaving a gap in assessing the impact of the tested tillage options on OC as time from the tillage operations advanced.

Due to the high content of soil OC often associated with conservation tillage systems, soils under no and reduced till are commonly associated with higher acidity relative to conventionally tilled systems (Li et al. 2020; Sithole and Magwaza 2019). However, variations in soil pH may be subject to other factors such as the buffering capacity of the soil, the magnitude of change in soil organic matter contents, fertilizer management systems, and climate (Page et al. 2020). For example, on sandy-clay soils cultivated with peas under temperate conditions in Poland, although Woźniak (2019) detected OC content to be significantly higher on reduced till compared to conventional till, pH on the reduced till was higher than the conventional till. While under semi-arid conservation tillage systems in Brazil, high pH declinations were observed under legume-based crop rotation systems (Vieira et al. 2009). Hence, the changes in soil pH could vary due to the influences of applied soil management systems or climate.

Long-term conservation tillage systems may improve soil moisture content (Du et al. 2022). However, most often, the effectiveness of these systems in influencing positive changes in soil–water relationships is linked with residue incorporation (Kiboi et al. 2019; Leharwan et al. 2023). This can be a limiting factor for low residue cropping systems. Conservation tillage operations involve a residue retention of at least 30%. These residues improve soil organic matter and widen the range of soil water content for soils (Zhao et al. 2022a, b). Likewise, conventional till could create loose soils and allow more moisture availability (Burger et al. 2023) but successive operations could leave soils in deplorable states (Ndegwa et al. 2023), raising concerns about the environmental sustainability of the system. Porosity benefits gained by intensive plowing are likely to be lost in the short term due to rainfall effects, and drying and wetting cycles

(Zumr et al. 2019). Several measurements beyond the tillage operation could help capture and analyze the effects on properties linked to soil water transport.

Therefore, it would be beneficial to assess varying tillage approaches and their effects on soil physicochemical signatures throughout the season to make reliable inferences on the choice of tillage. Especially because the implementation of Good Agricultural and Environmental Condition (GAEC) standards by the European Union in 2020 encouraged the adoption of conservation practices to boost soil quality in the Czech Republic. In a review study, Blanco-Canqui and Ruis (2018) highlighted important knowledge gaps in researching conservation tillage practices, especially for European soils. They specify: 1. RT and NT effects on soil physical properties are mostly analyzed under monocropping systems, hence the need to study changes in soil properties subject to tillage under complex crop rotation systems, 2. Researching occasional/strategic tillage across different soil types and climates would fully capture the effects of occasional/strategic tillage on soil properties, and 3. More studies on the temporal changes in soil properties within a given season of the same year would be beneficial, considering that previous studies have primarily assessed these variabilities at one point in time or annually (Blanco-Canqui and Ruis 2018). These research gaps form the hypothesis of this study, seeking to answer the following research questions: 1. Can in-season variations caused by applied tillage method under a long-term crop rotation system of oil seed rape (*Brassica napus* subsp. *Napus*), winter wheat (*Triticum aestivum*), and peas (*Pisum sativum*) be monitored to understand the implications of each practice for this climate region? 2. Would comparisons between conventional and multiple conservation tillage options expand the scientific knowledge base and offer farmers more information on management options in this region? Consequently, farmers and policymakers within this region can make informed decisions in the wake of agricultural incentives being tied to the adoption of GAEC.

2 Materials and Methods

2.1 Description of the Experimental Site

The study was carried out within the area of the arable experimental plots belonging to the Crop Research Institute (CRI), Prague, Czech Republic (50°5′17.264″ N, 14°17′50.024″ E). The site has an altitude of 345 m above sea level and is characterized by a 20-year mean annual precipitation of 522 mm and a mean annual temperature of 9.3 °C. For the two observed years (2021 and 2022), an average precipitation of 543 mm was recorded. Figure 1 details precipitation and average temperature throughout the cropping season studied on the experimental plots in Figure 2.

After its establishment in 1994, different tillage approaches have been followed since 1995 under a rotation of oil seed rape (*Brassica napus* subsp. *Napus*), winter wheat

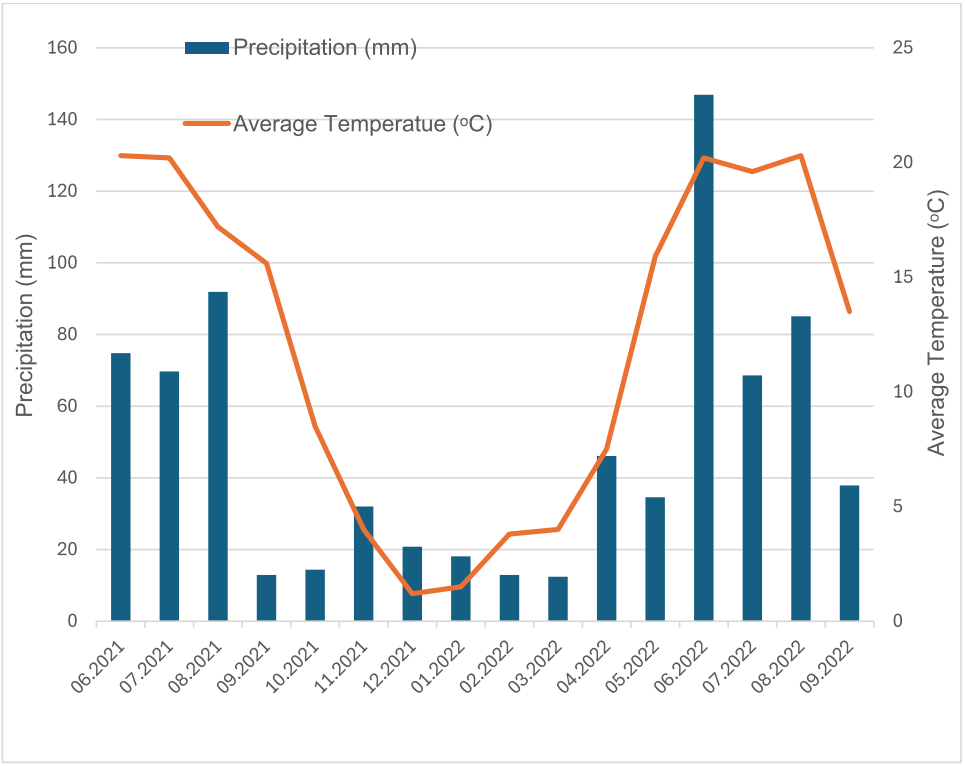


Fig. 1 Weather graph detailing monthly precipitation and average temperature from June 2021 until September 2022. Data was derived from the meteorological station in the Crop Research Institute, Ruzyne – Prague

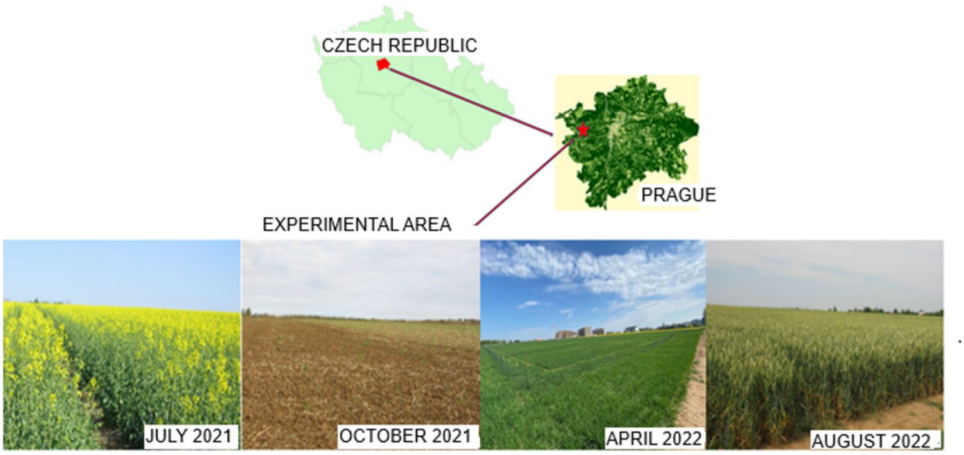


Fig. 2 Localization of the study area in Prague, Czech Republic – with the condition of the field during the experimental phases pictured

(*Triticum aestivum*), and peas (*Pisum sativum*). The study site is well-characterized by Haplic Luvisols (Němeček and Kozák, 2005; IUSS Working Group 2014) on pre-Cretaceous limestone (Chytrý 2012). The soil within the area sampled for this study had a silty clay loam texture.

2.2 Tillage Treatment

The study compared the physicochemical characteristics of four different long-term tillage systems. These were: 1. reduced till (RT), comprising non-inversion stubble breaking into the upper 10 cm soil depth with a chisel plow, 2. strategic till (ST), which is an annual rotational system between reduced till to a 10 cm depth with a chisel plow and no-till. 3. no-till (NT) is represented as a plot without soil tillage (direct drilling), and 4. conventional till (CT) involves preliminary stubble breaking into the top 10 cm with a chisel plow, followed by deep plowing with a moldboard plow to a depth of 22 cm. For all the tillage plots, a direct drilling seeding method using a Farmet Falcon 6 seed drill (working width of 6 m) was used in planting the winter wheat crop on 8th October 2021. A Kvernland ES 95 reversible plow (Soest, Germany) was used for plowing CT. A Lemken Smaragd 7 two-arm sweep cultivator (Alpen, Germany) was used for chiseling RT and ST. Each of the plots comprised a width of 11.85 m and a length of 95 m.

2.3 Sampling Design

The study adopted judgmental sampling (Frey 2018) to cover the variability of soils as representative samples for each tillage treatment. Since the plots are positioned parallel to each other, a transect was measured to cut across all the plots and used as a reference point for the measurements and sampling to allow repetition throughout the experimental phases. Sampling was done around the central points of each plot to avoid the influence of traction wheels on the tilled plots. Soil sampling and field experiments were split into four experimental phases: experimental phase one (Exp Phase 1) in the summer of July 2021, before the harvest of oil seed rape, experimental phase 2 (Exp Phase 2) in the autumn of October 2021, three weeks after tillage and seeding operations for winter wheat, experimental phase 3 (Exp Phase 3) in the spring of April 2022, during the emergence state of the winter wheat, and experimental phase 4 (Exp Phase 4) in the summer of August 2022 at full maturity of the winter wheat. 128 undisturbed soil core samples in total were collected, split between 250 cm3 and 100 cm3 cores equally at depths between 10 to 15 cm. For each experimental phase, 32 samples split evenly for each tillage plot were taken. Disturbed auger samples from four positions on each plot, homogenized to represent each tillage applied, were also taken during each experimental phase for further laboratory analyses.

2.4 Analytical Methods

Soil moisture content by volume was measured in situ corresponding to the experimental phases using a calibrated EC-5 sensor (METER Group AG, USA). The sensor was inserted between the top 10 to 15 cm of depth, positioned to correspond with the sampling points for the undisturbed soil cores on each tillage treatment plot. Soil dry bulk density was derived by drying at 105 C the core ring samples containing undisturbed samples to a constant weight and deriving the ratio of the mass of dry soil to the volume of the soil core (Blake 1965). The laboratory procedure for soil organic carbon estimation involving digestion and titration approaches specified in the Walkley–Black method (Walkley and Black 1934) was employed on 2.5 g of soil (< 2 mm). Soil organic carbon content can serve as an indirect determination of organic matter using an approximate correction factor (ISO 11074:2005). The "van Bemmelen factor" of 1.724 has been used for many

years and assumes that organic matter contains 58 percent organic carbon (Allison, 1965), as shown in Eq. 1. A portion of the soil measured as carbon in organic form was estimated as soil organic matter (SOM).

$$SOM(\%) = 1.724xSOC(\%) \quad (1)$$

In the case of pH determination, the laboratory application of the pH electrode device WTW SenTix 81 (shaft length 17 cm) with a pH measuring range of 0 to 14 and an allowed temperature range of 0 to 100 °C, connected to an output screen device, was used. Soil EC was determined using a combined conductivity and dissolved oxygen (ConOx) sensor (WTW GmBH, Germany). The conductivity range for the ConOx device is 1 µS/cm to 2 µS/cm, with a temperature range of 0 to 50 °C. All the measurements for SOC, pH, and EC were obtained in two replicates for the individual treatment plots (RT, ST. NT, and CT) during each of the four experimental phases corresponding to the sampling design.

Soil particle density was calculated from the ratio of mass to the volume of the soil particles. The mass was determined by weighing the dry soil sample whereas, the volume was determined by calculating the mass and density of water displaced by the soil sample in a 100 cm^3 pycnometer (Blake and Hartge 1986). Four replicates per tillage treatment plot were carried out. Particle density was measured only for Exp Phase 1 and Exp Phase 3 corresponding to the sampling design.

The procedure for determining the fraction of particles (sand, silt, and clay) for fitting the particle size distribution curve based on Stoke's law (1851) was followed. Density of the soil sample suspended in distilled water was measured with a calibrated hydrometer at predefined time intervals (30, 60, 120, 300, 900, 2700, 7200, 18,000, 97,200 and 172,800 s after the start of sedimentation) according to standard ČSN EN ISO 17892–4 (2017). Temperature readings of the samples were simultaneously recorded with the hydrometer readings. This test was done for Exp Phase 1 and Exp Phase 3 corresponding to the sampling design.

The function of unsaturated hydraulic conductivity of the soil was determined in situ using the Mini Disc Infiltrometer (METER Group AG, USA). Two negative pressure heads, specifically −1 cm and −5 cm, were applied to the soil surface to help differentiate the soil pores (Messing and Jarvis 1993). 20 infiltration tests were carried out at each experimental phase corresponding to the sampling design, 5 on each tillage plot. These tests were carried out about 50 cm from the sampling positions on the plots. Unsaturated hydraulic conductivity for each applied pressure head was analyzed following the steady-state procedure proposed by Zhang (1997). Cumulative infiltration and time were derived from the raw readings and fitted with Eq. 2 by Philip (1957):

$$I = C_1 + C_2\sqrt{t} \quad (2)$$

where C_1 and C_2 are parameters relating to hydraulic conductivity and sorptivity, respectively, and, I refers to the cumulative infiltration and t related to time. Hydraulic conductivity for an applied pressure head was then derived from Eq. 3:

$$K(h) = \frac{C_1}{A} \quad (3)$$

where C_1 is the slope of the plotted curve of cumulative infiltration against the square root of time, and the A value is a value derived from the van Genuchten parameters for 12 soil textural classes to the radius of the disk and applied pressure head. The derivation of these texture classes is based on the Zhang (1997) Eqs. 4 and 5:

$$A = \frac{11.65\left(n^{0.1} - 1\right)exp[2.92(n - 1.9)ah]}{(ar_d)^{0.91}} n \geq 1.9 \quad (4)$$

$$A = \frac{11.65\left(n^{0.1} - 1\right)exp[7.5(n - 1.9)ah]}{(r_d)^{0.91}} n < 1.9 \quad (5)$$

where n and a are the van Genuchten parameters, and r_0 is the radius of the mini disk infiltrometer, while h is the applied pressure head. Table 1 shows the van Genuchten parameters and values for the mini disk infiltrometer. For measuring soils with < 1.35, an improved equation was recommended by Dohnal et al. (2010), currently specified in the user's manual of the mini disc infiltrometer from METER Group AG, USA (Devices 2012), to give more accurate hydraulic conductivity estimates. For this study, the van Genuchten estimate for Silty Clay Loam was 1.23; hence, the adjustment (Eq. 6) proposed in the user's manual for < 1.35 to estimate was used.

Table 1 Mean effects of reduced till (RT), strategic till (ST), no-till (NT), and conventional till (CT) on soil particles and soil organic carbon. Duncan's homogeneity test denoted by alphabet indicates 95% significant differences. The standard error for all particle density measurements was within acceptable ranges (< 0.03)

Soil Property	RT	ST	NT	CT
Sand % (0.05–2 mm)	11.3A	12.6A	12.3A	12.5A
Silt % (0.002–0.05 mm)	55.5A	54.8A	54.6A	54.9A
Clay % (< 0.002 mm)	33.2A	32.6A	33.1A	32.6A
Particle Density (g/cm^3)	2.52AB	2.51AB	2.59B	2.46A
Soil Organic Carbon (%)	1.50B	1.54B	1.62B	1.29A

*Using Duncan's posthoc homogeneity test, mean values with the same alphabetical letters were not significantly different, while different alphabets denote significant differences

$$K(h) = \frac{C_1 \left(ar_0\right)^{0.6}}{11.65\left(n^{0.82} - 1\right) exp\left[34.65(n - 1.19)ah_0\right]} \quad (6)$$

Saturated hydraulic conductivity (K_s) measurements using the KSAT device (METER Group AG, USA) were employed: the 250 cm^3 soil core samples were subjected to water saturation by capillary action for 2–3 days. The samples were then transferred to the KSAT device for measurements. Three replicate measurements per sample were done by employing the falling head approach. These measurements were also made to coincide with the experimental phases described in the sampling design. K_s from this approach was derived from the formula for falling head shown in Eq. 7:

$$K_s = \frac{A_f.\Delta_z}{A_s.t}.\ln\frac{h_0}{h_t} \quad (7)$$

where A_f is the cross-sectional area of the measuring tube based on the radius of the tube, A_s is the cross-sectional area of the measured sample based on the radius of the soil sample, t is time, Δ_z refers to the traveling distance through the sample (length), h_0 is the initial water level in the measuring tube at time 0 and h_t represents the water level at the end of the measurement.

Statistical analysis data for physical and chemical properties were tested using the Shapiro–Wilk W-test for normality and met the assumptions for the use of parametric tests. A factorial ANOVA was used to evaluate the differences in soil properties between the applied tillage and experimental phases. Post hoc comparisons using Duncan's homogeneity tests were used to identify significant differences within each treatment for the different experimental phases. To evaluate the relationships between all the soil properties, we used principal component analysis (PCA). Pearson's correlation between the variables was used to obtain the relationship between the tested soil physicochemical parameters. The software package STATISTICA 13.5 (www.statistica.io) was used to perform all statistical analyses in this study.

3 Results

Soil particle size distribution was not variable either by tillage treatments or sampling dates (Table 1). The textural class remained the same for all phases of the experiment, establishing a basis to compare the effects of the physicochemical parameters investigated. On the other hand, the tillage treatments showed varying values ($p \leq 0.05$) of soil OC and particle density (see Table 1). Particle density and soil organic carbon on NT were the highest, while CT recorded the lowest values. Particle density is dependent on organic and mineral components. Thus, changes in soil OC could have influenced the differences in particle density by applied tillage. The observed variabilities could also be linked to the particle movement from tillage-associated soil mixing and soil erosion on the surface soil. The experimental plot is characterized by a slope, which favors the movement and deposit of soil particles in the direction of the slope. While on topsoil characterized by high soil OC and structural stability (NT), differences in particle density over time were negligible.

3.1 Dry Bulk Density

Values ranged between 1.12 g/cm3 and 1.63 g/cm3. The minimum value was recorded on RT, while the maximum value was associated with CT. Besides NT, there was significant variation by experimental phase ($p \leq 0.001$) on all plots with some degree of tillage (i.e., RT, ST, and CT). From Fig. 3, it can be observed that dry bulk density significantly reduced after the tillage operations; however, beyond Exp Phase 3, as the time from tillage increased, the values increased again. In the cases of RT and ST, no significant changes were observed between Exp Phases 1 and 2, but significantly lower values were observed during Exp Phase 3. Variation by applied tillage was significant for all experimental phases, except for Exp Phase 4, where observed values fell within a homogeneous range. On all plots, higher bulk density values were recorded between Exp Phase 3 and Exp Phase 4 (rather insignificant on NT).

3.2 Soil Organic Matter

The highest mean soil organic matter (%) was observed on NT during Exp Phase 3 (see Fig. 4), while the lowest value was recorded on CT during Exp Phase 2. In all the phases, CT had the lowest soil organic matter percentages compared to all the other experimental plots. Generally, soil organic matter on the plots with conservation tillage (RT, ST, and NT) improved significantly after the minimal tillage operations, including the stubble mulch (in the case of NT, residue retention), and remained stable through the course of the season. Under CT, soil organic matter improved only beyond Exp Phase 3 at levels still low compared to the other treatments. There was a significant variation by applied tillage for all the experimental phases but for Exp Phase 4, where variation between mean values observed was rather insignificant.

3.3 Soil pH

Except for Exp Phase 4, soil pH values across the tillage treatments were not significantly variable according to the applied tillage system; however, they showed significant variability with time of measurement through the different experimental phases over the cropping season. A mean value of 7.3 was recorded across all plots, while the minimum of 6.4 and a maximum of 8.2 were both recorded on the RT

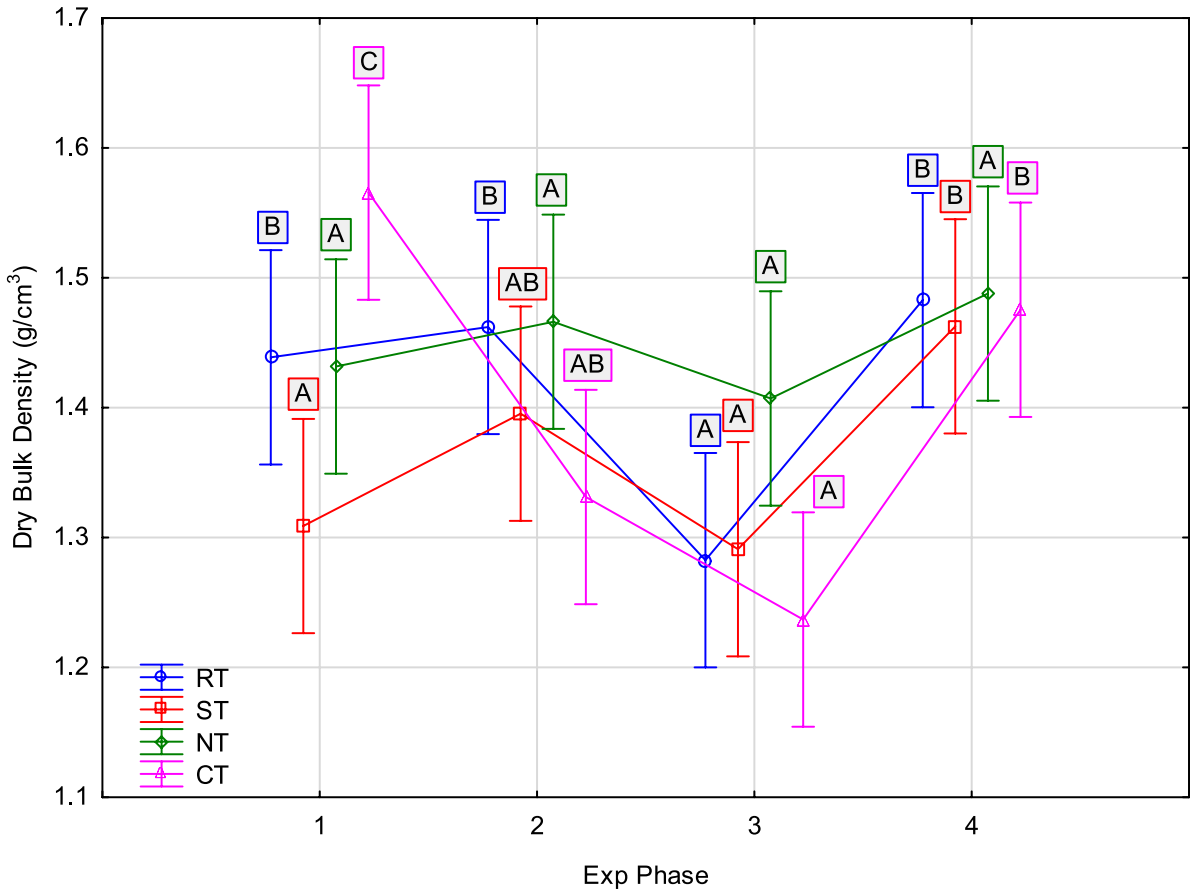


Fig. 3 Effect of tillage (RT- Reduced till, ST- Strategic till, NT- No-till, and CT- Conventional till) on dry bulk density in g/cm^3 through the experimental phases (Exp Phase). Using Duncan's posthoc homogeneity test, mean values with the same alphabetical letters were not significantly different by experimental phase, while different alphabets denote significant differences

plot (see Fig. 5). The largest variation was observed on the RT plot, with values dropping from alkaline to neutral and acidic as time from tillage increased. A slightly acidic reaction was also observed on ST during Exp Phase 3, whereas all other observations were rather neutral to slightly alkaline.

3.4 Soil Electrical Conductivity (EC)

Soil EC ranged from 62 to 191 *u* S/cm. The highest EC was observed on RT, while the lowest value was associated with CT (Fig. 6). Throughout all the phases, CT had the lowest values of EC. EC on RT increased significantly with time through the experimental phases, while for the other plots (ST, NT, and CT), this increment was true for the first 3 experimental phases, with a decline in values between Exp Phases 3 and 4. Variation by applied tillage was significant only for Exp Phase 2, while significant temporal variation through all the experimental phases was observed.

3.5 Soil Moisture Content

Soil moisture content variability by applied tillage system and time of measurement was observed for values ranging between 7.3% of volumetric water content on CT and 37.8% of volumetric water content on ST. Generally, higher moisture values were measured on all tillage plots for Exp Phase 1, while lower values were measured for Exp Phase 2 (see Fig. 7). Variability by time of measurement (experimental phase) was, however, more significant ($p \leq 0.0001$) compared to variability by the applied tillage system ($p \leq 0.05$). Moreover, during Exp Phase 3, the mean moisture values observed for all the tillage plots were homogenous, as seen in Fig. 7. While NT was associated with the least coefficient of variability throughout all the experimental phases, the trend in the moisture values was more explainable by the precipitation data from the experimental area in Fig. 1.

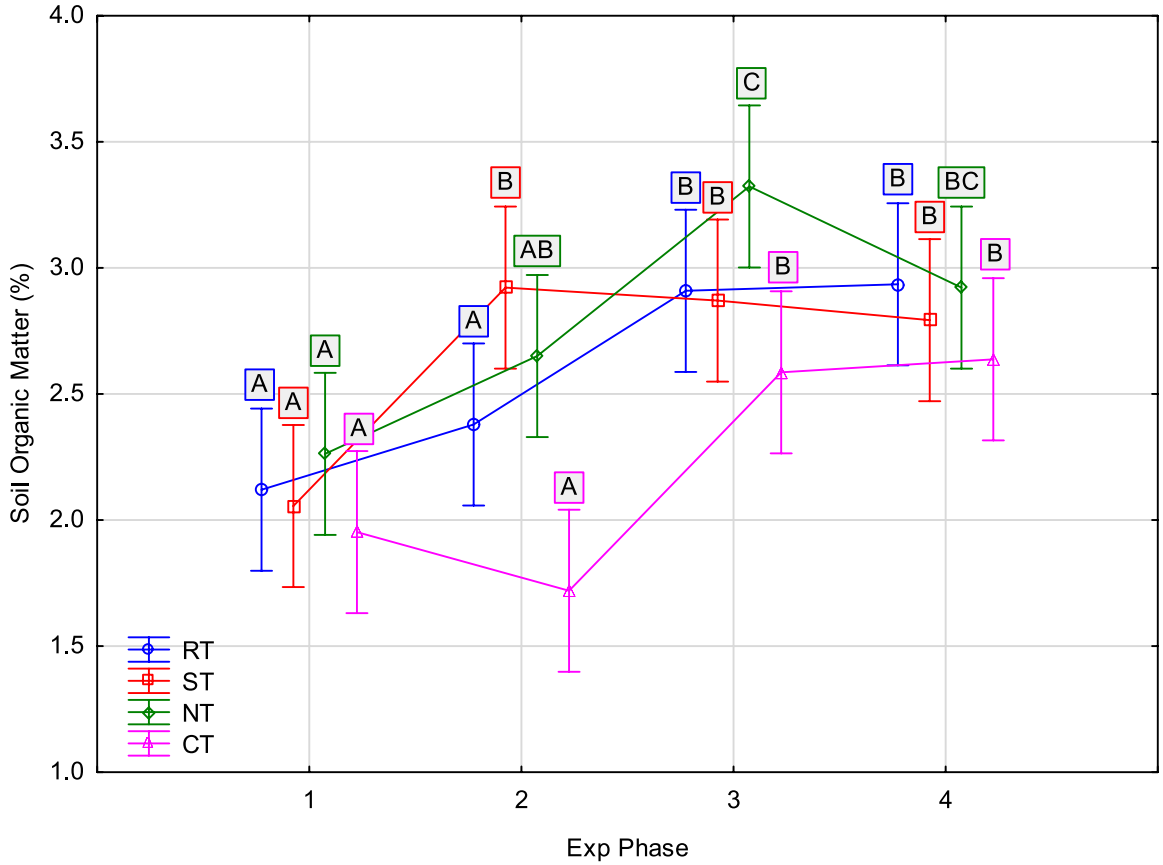


Fig. 4 Effect of tillage (RT- Reduced till, ST- Strategic till, NT- No-till, and CT- Conventional till) on the percentage of soil organic matter content through the experimental phases (Exp Phase). Using Duncan's posthoc homogeneity test, mean values with the same alphabetical letters were not significantly different by experimental phase, while different alphabets denote significant differences

3.6 Hydraulic Conductivity

K_s Did not differ significantly by the applied tillage method considering the data gathered for all the experimental phases (Fig. 8). For the individual experimental phases, only Exp Phase 3 showed a significant variation, mainly because values observed for NT during this period of measurement were rather low compared to the other tillage plots. However, regarding the time of measurement, there was a significant variation ($p \leq 0.001$) considering the different experimental phases. For $K(h)$, two pressure heads were considered for the data analysis as they explain better suction through different categories of pores (specifically suction at −1 cm and −5 cm). The values observed for the two pressure heads varied ($p \leq 0.05$) as well as that of the various experimental phases ($p \leq 0.05$). However, variations by applied tillage were not found to be significant. The combined effect of all three parameters (applied tillage, experimental phase, and applied pressure head) was significant ($p \leq 0.001$). Considering suction at −5 cm characterized with mesopores, all the conservation tillage plots exhibited a similar trend in response to $K(h)$ where they increased between Exp Phases 1 and 2, decreased between Exp Phases 2 and 3, and increased between Exp Phases 3 and 4 (see Fig. 9). CT on the other hand significantly; decreased between Exp Phases 1 and 2, increased between Exp 2 and 3, and decreased between Exp Phase 3 and 4 compared to the other plots. At −1 cm associated with macropores, a drop in $K(h)$ was observed between Exp Phases 1 and 2 for all plots, whereas between Exp Phases 2 and 3, a slight increase was observed for the conservation tillage plots but not CT which rather decreased. Between Exp Phase 3 and 4, a significant increase was observed for all the plots.

3.7 Principal Component Analysis (PCA)

A descriptive analysis of soil properties (variables measured) was carried out through a PCA, thus obtaining an approximation of the relationship between properties and the association between the measured properties for applied tillage and time of measurement (experimental phases). For applied tillage type, the first primary components of the PCA managed to explain between (in%) 50–91, 44–88, 35–81, and 34–88 of the total system variability among RT, ST,

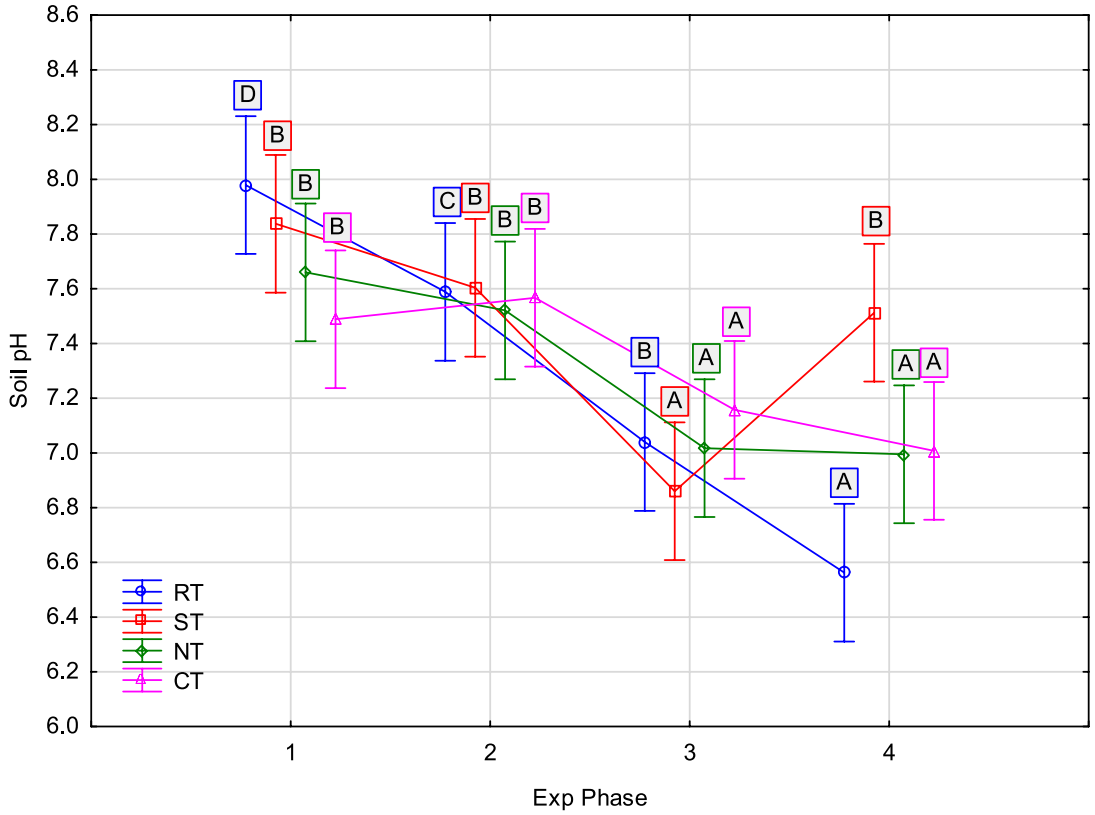


Fig. 5 Effect of tillage (RT- Reduced till, ST- Strategic till, NT- No-till, and CT- Conventional till) on soil pH through the experimental phases (Exp Phase). Using Duncan's posthoc homogeneity test, mean values with the same alphabetical letters were not significantly different by experimental phase, while different alphabets denote significant differences

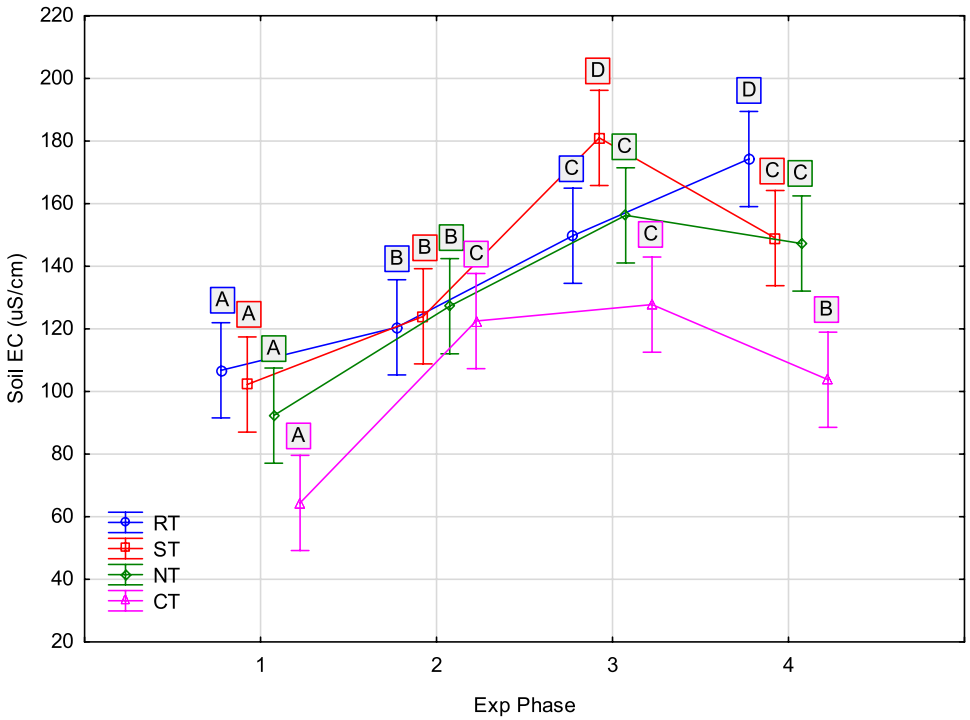


Fig. 6 Effect of tillage (RT- Reduced till, ST- Strategic till, NT- No-till, and CT- Conventional till) on soil electrical conductivity (Soil EC) through the experimental phases. Using Duncan's posthoc homogeneity test, mean values with the same alphabetical letters were not significantly different by experimental phase, while different alphabets denote significant differences

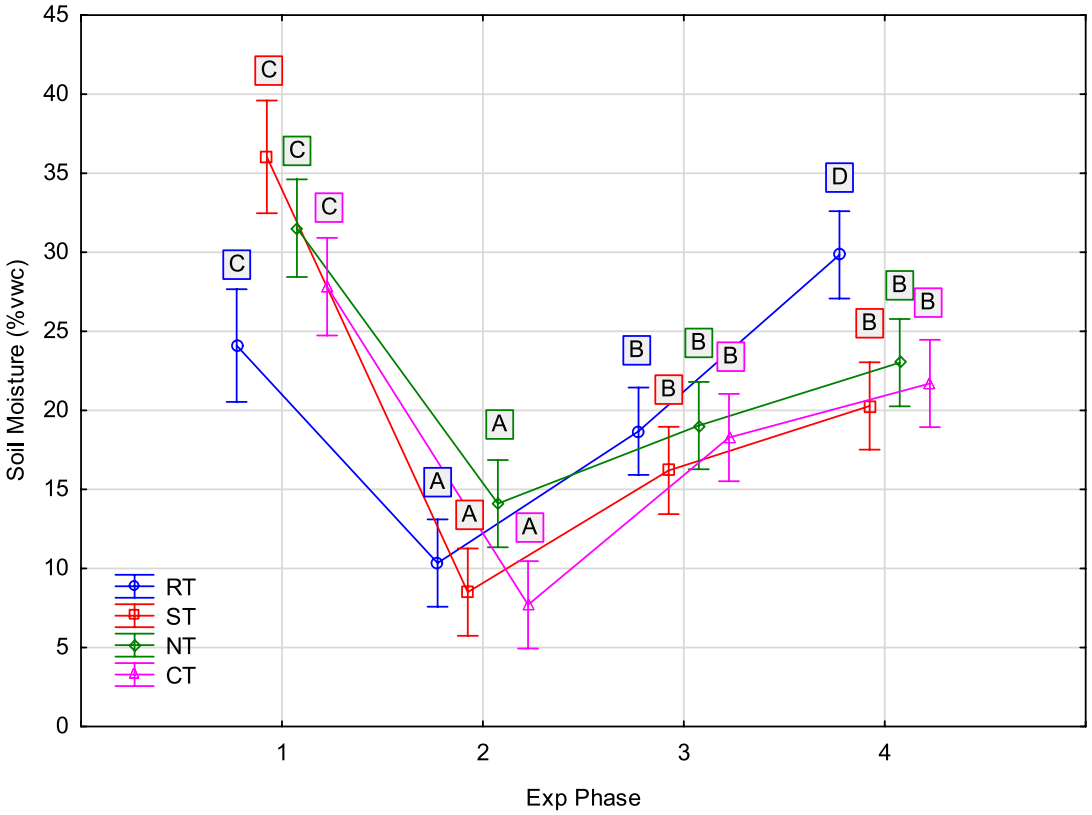


Fig. 7 Effect of tillage (RT- Reduced till, ST- Strategic till, NT- No-till, and CT- Conventional till) on soil moisture content (as a percentage of volumetric water content—%vwc) through the experimental phases. Using Duncan's posthoc homogeneity test, mean values with the same alphabetical letters were not significantly different by experimental phase, while different alphabets denote significant differences

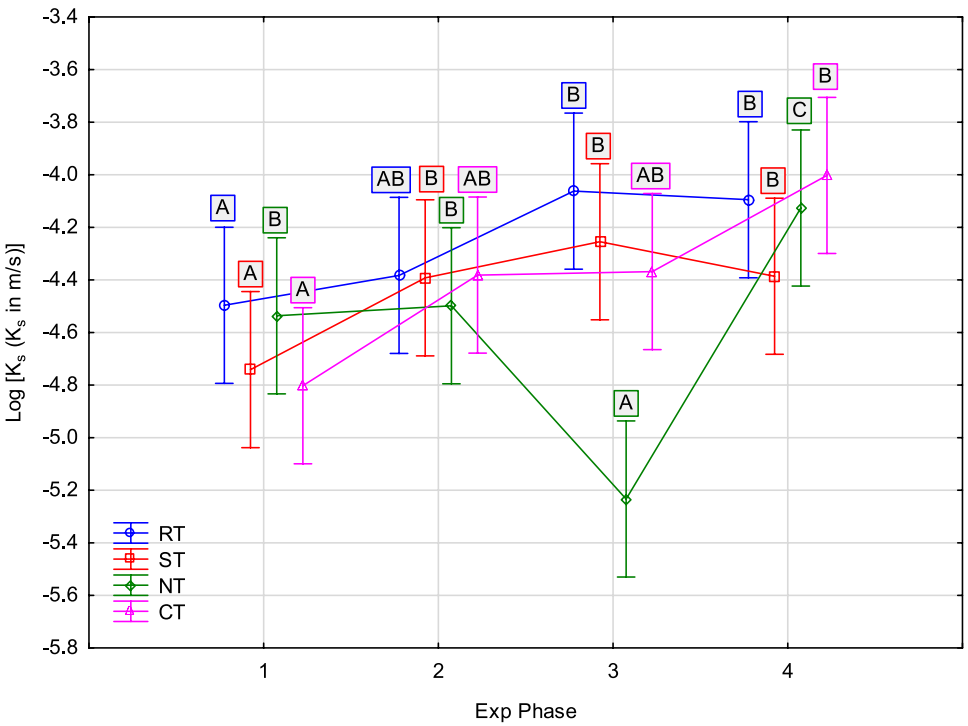


Fig. 8 Effect of tillage (RT- Reduced till, ST- Strategic till, NT- No-till, and CT- Conventional till) on saturated hydraulic conductivity (Ks) expressed in logarithmic through the experimental phases. Using Duncan's posthoc homogeneity test, mean values with the same alphabetical letters were not significantly different by experimental phase, while different alphabets denote significant differences

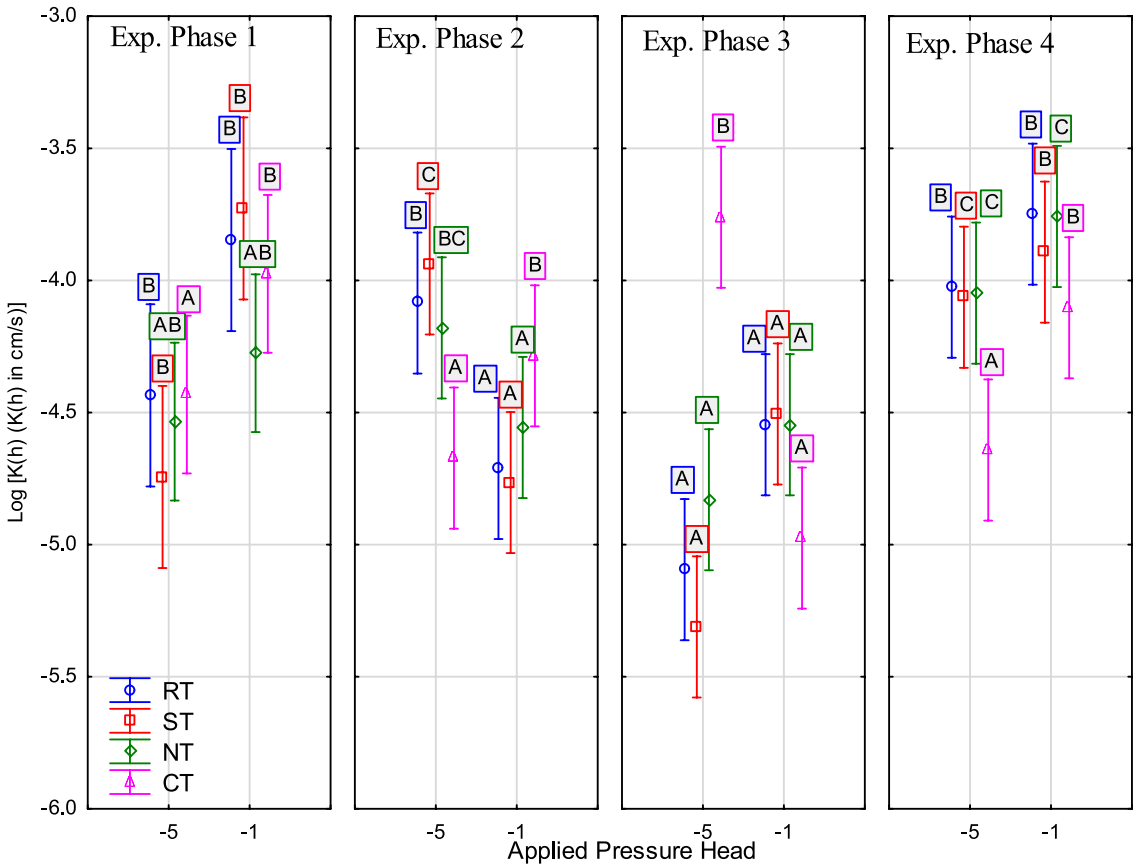


Fig. 9 Effect of tillage (RT- Reduced till, ST- Strategic till, NT- No-till, and CT- Conventional till) on unsaturated hydraulic conductivity K(h) expressed in logarithmic at two pressure heads (h −5, h −1) through the experimental phases. Using Duncan's posthoc homogeneity test, mean values with the same alphabetical letters were not significantly different by experimental phase, while different alphabets denote significant differences

NT, and CT, respectively (Fig. 10). In all cases, the first component explained > 30% of the variability. Soil pH was the only variable that significantly defined the first component in RT. Additionally, volumetric water content defined the second component of RT, ST, and NT, while on CT, this property was defined in the first component. Hydraulic conductivity factors were influential on ST, NT, and CT for the first component, although in the case of NT, it was valid for only unsaturated hydraulic conductivity. Besides RT, soil organic matter was also found to be definitive for the first component amongst all the other treatment plots. Amongst all treatment plots, dry bulk density was neither significantly defined within the first component nor defined in the second component amongst the other treatment plots. These defining variables had a significant correlation ($p \leq 0.05$) with the principal components they defined.

From Fig. 11, dry bulk density was the most significant factor defining the variability of the first component during Exp Phase 1. pH was found to be definitive through Exp Phase 2 until 4 (significant only during Exp Phase 4) for the first component. Similarly, for both Exp Phase 2 and 3, saturated and unsaturated hydraulic conductivity defined the first component. For Exp Phase 4, besides soil water content and saturated hydraulic conductivity, all the variables tested defined the first component factor (significant for pH, dry bulk density, and particle density). For the second component, only soil moisture content significantly defined Exp Phases 1 and 3, while EC defined that of Exp Phase 2. Subject to the time of measurement, between 28 and 75% of the variability was explained by the first two principal components.

4 Discussion

The comparative analyses provided sufficient evidence of different tillage practices on agricultural soils, specifically for this silty clay loam, and the extent to which different tillage practices may alter soil properties concerning soil and water productivity within a given cropping season.

Dry bulk density variabilities on Haplic Luvisols, subject to different tillage practices and simplified rotations under

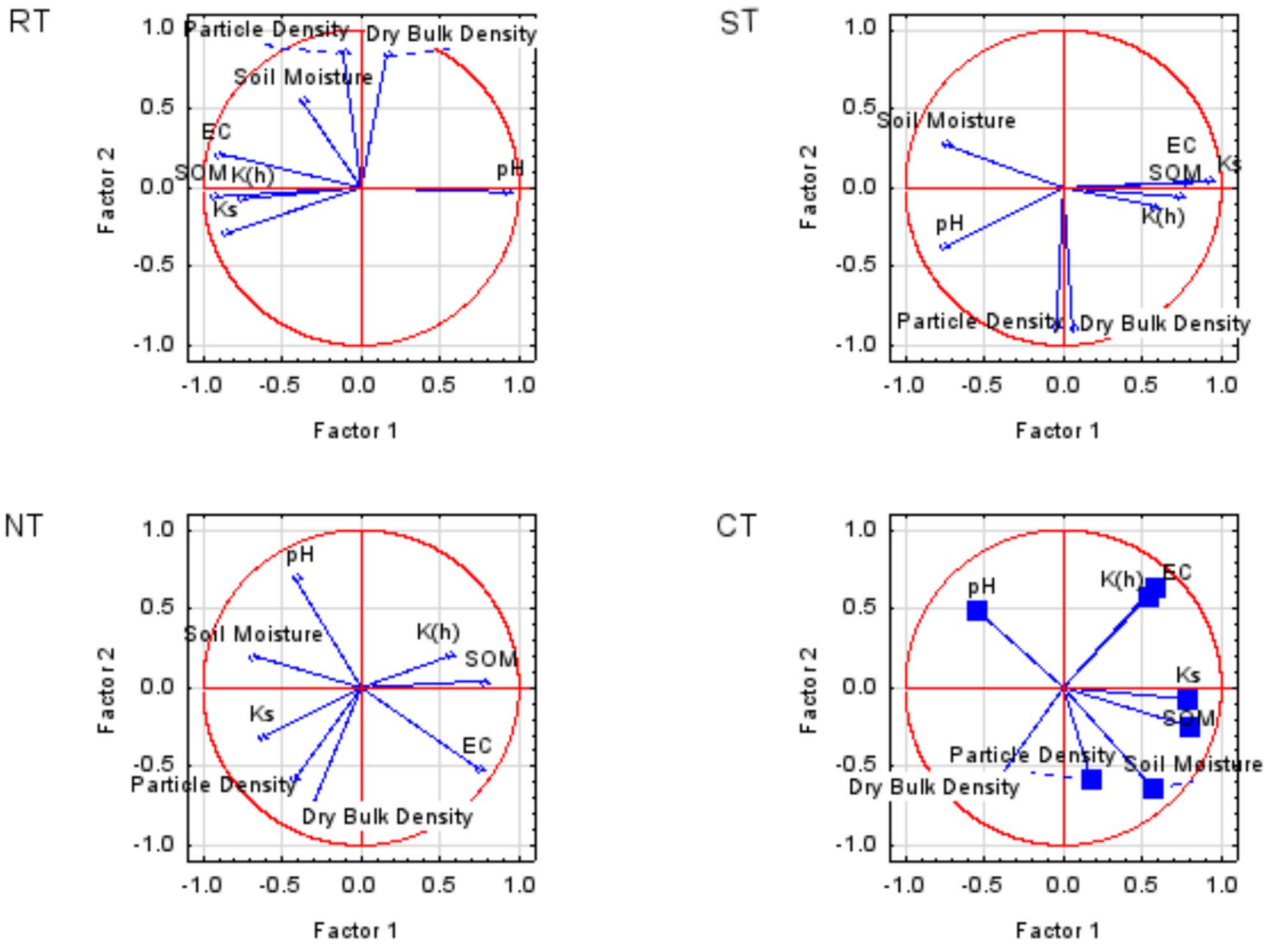


Fig. 10 The ordination diagram shows the results of the Principal Component Analysis (PCA) of the observed soil properties (Soil moisture, Soil pH, Saturated hydraulic conductivity Ks, Unsaturated hydraulic conductivity K(h), Soil organic matter SOM, Soil electrical conductivity EC, Dry bulk density, Particle density) on RT (Reduced till) and ST (Strategic till), NT (No-till), and CT (Conventional till)

temperate climates can occur (Orzech et al. 2021). In this study, there were no significant changes in dry bulk density on NT throughout the experimental phases. On silty clay loams under a similar temperate climate, the negligible disturbance associated with NT stabilized soil physical properties such as dry bulk density (Mestelan et al. 2021). On all plots (besides CT values for Exp Phase 1) the dry bulk density values were within the acceptable threshold for root development for silty clay loam (Nyéki et al. 2017). However, values for CT during Exp Phase 1, coupled with the significant increase ($p \leq 0.001$) between Exp Phases 3 and 4, pose long-term sustainability concerns for this operation. Mainly because during the soil's consolidation phases (Exp Phases 1 and 4), dry bulk density on CT could hinder arable production unless further tillage is carried out (Nyéki et al. 2017). On the other hand, the non-inversion practices can create ideal dry bulk density for crop production all year round. This could be linked to the incorporation of residue stubble and subsequent root development in creating loose soils under these climatic conditions. Klik and Rosner (2020), in their findings on silty clay loams in similar climatic conditions in Austria, found high bulk densities on NT and RT plots; however, for the 0 – 20 cm depth, the observed values were still within the threshold acceptable for arable crop production for silty clay loams. For variability over time, findings were similar to those observed on clay loams experimented under temperate conditions in Sweden (Sandin et al. 2017). Loose soils created by CT could be short-term, with a consequential increase in bulk density after drying and wetting cycles from succeeding rainfall events (Sandin et al. 2017). Given that rainfall events spiraled beyond Exp Phase 3, it could explain why the downside effects of CT took longer for this specific climate and soil type. There is also the possibility of winter freezing and thawing effects on porosity created by CT. Although some variability in bulk density was observed on RT and ST, they were linked to stable soil water and organic matter contents compared to CT, similar to Klik and Rosner (2020).

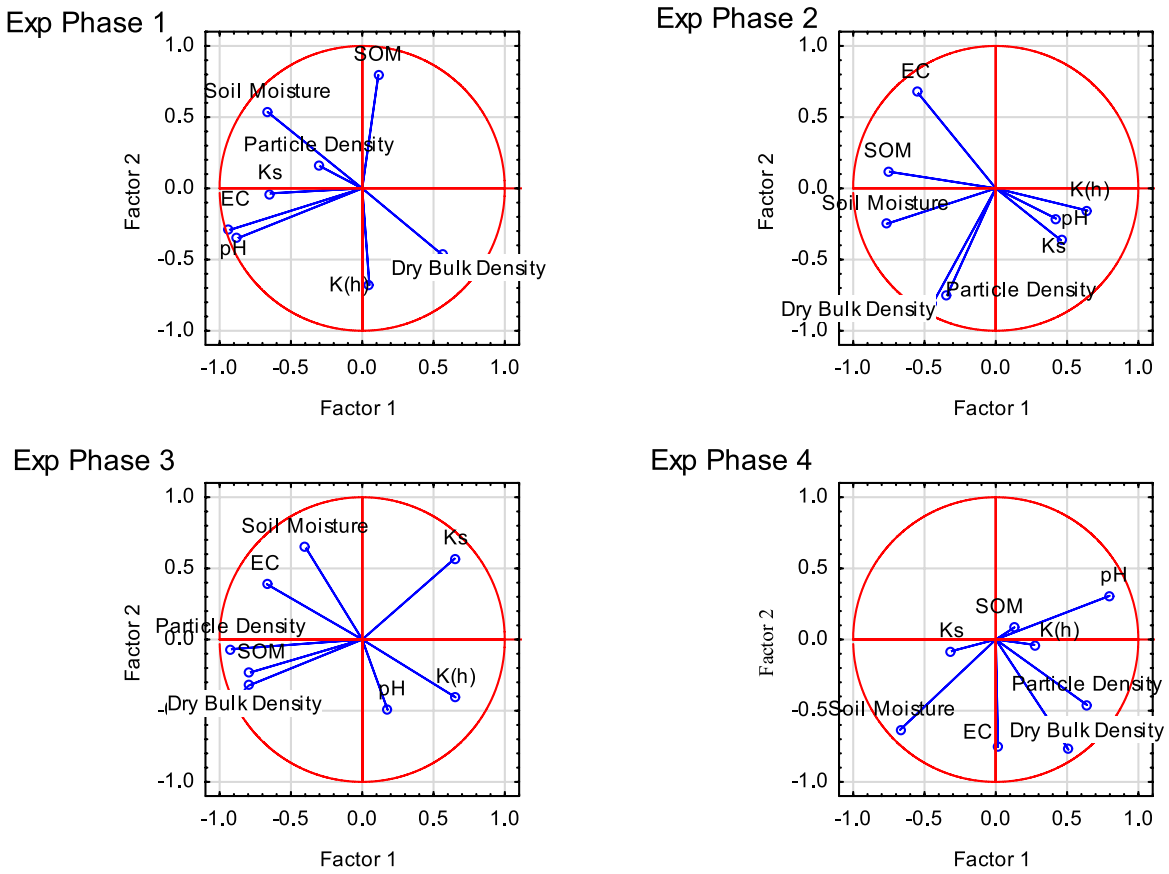


Fig. 11 The ordination diagram shows the results of the Principal Component Analysis (PCA) of the observed soil properties (Soil moisture, Soil pH, Saturated hydraulic conductivity Ks, Unsaturated hydraulic conductivity K(h), Soil organic matter SOM, Soil electrical conductivity EC, Dry bulk density, Particle density) throughout the four experimental phases (Exp Phase 1, Exp Phase 2, Exp Phase 3 and Exp Phase 4)

Enhanced levels of soil organic matter are important in ensuring sustainable soils (Lal 2020). NT increases the content of the organic components of the soil. Similar to observed findings, Sun et al. (2016) from experiments on clay loams in temperate conditions indicate that a combination of crop rotation with NT increases the content of this parameter and contributes to microbial abundance. This was similar to RT and ST, where these practices showed a potential for loosening the soil and storing a considerable amount of soil organic matter within the experimented layer. NT improved soil organic matter content the most; NT in temperate conditions is typically associated with the availability of nutrients in soils, possibly from its consistent correlation with soil organic matter (Perez-Brandán et al. 2012). In a similar study on carbon sequestration on the same plots used in this study, Mühlbachová et al. (2023) associated the conservation tillage plots with high storage of soil OC compared to the CT plot. While high temperatures and repeated rainfall were generally identified as drivers for increased carbon emissions for this climatic area, the presence of mulch on the surface of the conservation tillage plots decreased carbon emissions by 45% to 51%. CT in temperate climates is linked to comparatively low soil organic matter, consistent with previous studies (Rahmati et al. 2020; Stockfisch et al. 1999). The high turnover of macroaggregates under CT soils could potentially disenfranchise the creation of microaggregates, from which new soil organic matter originates (Six et al. 1999). Even for soils under periodic plowing, Yvan et al. (2012) in their study under temperate conditions suggested that natural regeneration could take about two cropping seasons to establish after the last tillage event.

Generally, soil pH values on NT systems are low due to the decomposition of organic matter (Zhao et al. 2022a, b). Although the experiment was conducted on the same Haplic Luvisols in all treatments, there was a slightly alkaline to neutral reaction for both NT and CT, while in the cases of RT and ST, a slightly alkaline to slightly acidic observation was made. In both cases, the decline in pH could be linked to soil organic matter decomposition throughout the cropping season. As soil organic matter increased with time, pH decreased with time. Given the mixing of soils (especially CT), similar observations under temperate conditions

indicate that dynamic pH can occur due to the differences in soil depth characteristics (Neugschwandtner et al. 2014). For instance, pH variabilities by depth when comparing different tillage options are common (Liebenberg et al. 2020; Limousin and Tessier 2007; Neugschwandtner et al. 2014). In this study, the changes in pH could have been a combination of the effects of mixing the soils and the decomposition of crop residues throughout the season. The dormancy period between seeding and germination due to the nature of the climatic region could promote regeneration of soil microorganisms (Lennon and Jones 2011), especially on the conservation tillage plots. For RT and ST, the presence of soil microorganisms observed during sampling could have influenced the nitrification of the crop residues, creating acidic soils. Acidic soils have been associated with an indication of high soil organic matter content; however, the primary cause of acidity in soils can also be linked to other varying factors such as climate (Page et al. 2020). This is because although NT was linked to high soil organic matter content, no acidic pH was observed under these temperate conditions. Generally, at a circum-neutral pH (6.5–7.5), soil nutrients are readily available for crop uptake (Beazley et al. 2011). Beyond Exp Phases 1 and 2, the observed pH values were within the circum-neutral range for the succeeding phases, which also represented the period at which nutrient uptake was crucial.

Nutrient uptake and efficiency are linked to the EC of soils (Havlin 2020). For this study, all EC values observed were below salinity thresholds that may affect nutrient availability. For this climatic region issues pertaining to soil salinity are rather uncommon (Zumr 2023). While for certain soils within this territory (Eutric Fluvisols and Fluvic Gelysols) EC may not be a relevant indicator of soil salinity at sub-saline levels (Valtera et al. 2021). Soils high in EC have been found to contain high amounts of clay and organic particles strongly bonded to cations (Al-Gaadi 2012). Significantly higher OC contents associated with RT, ST, and NT may have encouraged the high EC compared to CT. EC under CT was the lowest for all the experimental phases, yet with a significant temporal variation. Nevertheless, no significant changes in sand, silt or clay particles were observed. This was in contrast to findings from Domsch and Giebel (2004) on soil EC variability in temperate climates in Germany where higher EC values were linked to strongly changing clay soils. These outcomes can be attributed to the differences in soil texture types studied. EC under CT was further observed to have a significant correlation ($r = 0.56$) to bulk density. A potential condition to have caused leaching within the observed layer and consequently resulted in the low levels of soil OC on CT. Comparatively, the neutral correlations between EC and the tested parameters on the conservation tillage plots (RT, ST, and NT) provide the opportunity for stabilized conditions, hindering the transport of soluble minerals below the soil gradient in the presence of water availability. Nevertheless, EC under all studied tillage options were considered appropriate to reduce the formation of nitrous oxide (USDA-NRCS, 2017).

One of the main reasons for introducing soil tillage in agriculture was the premise that it encourages soil moisture availability (Lal 1991). However, the soil moisture changes observed in this study were more explainable with the precipitation dynamics during the experimental phases than the changes in soil properties by tillage. Although CT significantly improved bulk density values through Exp Phases 2 to 3, this did not infer huge variations in soil moisture compared to the conservation tillage plots. Supporting previous findings by Mühlbachová et al. (2015) on these experimental plots where variations in dry bulk density did not impact parameters such as soil moisture and crop yield. This is possibly due to the relatively high organic matter on the conservation tillage plots. Although bulk density variations can be an indicator of structural changes (Tuzzin de Moraes et al. 2016), in temperate climates, residue retention, such as straw residues, can significantly affect soil moisture contents (Alskaf et al. 2021). The absorptive characteristics of soil organic components help to improve water-holding capacities and widen the range of water contents (Obour et al. 2018). Similar to findings from Zhao et al. (2019) on silty clay loam, crop residues under conservation tillage practices have the potential to influence soil moisture contents, offsetting benefits that would have been created by intensive plowing. In most cases, the soil moisture content on the conservation tillage plots was either higher or comparably insignificant compared to CT. This observation questions the sustainability of CT operations in improving soil water welfare, similar to others under both similar and drier climates (De Vita et al. 2007; Hashimi et al. 2023; Lamptey et al. 2020). However, it is worth noting that for this temperate climate, the benefits created by conservation tillage could be negligible under dry conditions (Mühlbachová et al. 2015).

Hydraulic conductivities are affected by applied tillage type due to the potential of specific tillage operations to alter soil pore structure (Schlüter et al. 2020). K_s was negatively affected by NT beyond the seeding operation. Under this temperate climate, plots with some degree of tilling (RT, ST, and CT) may improve K_s over the cropping season (Jabro et al. 2023). While K_s values mostly did not differ by applied tillage, the significantly low values observed on NT during Exp phase 3, coupled with high bulk density pose compaction concerns. $K(h)$ through the mesopores (h at −5 cm) for all the conservation tillage plots behaved similarly, compared to CT. Generally, CT is known to create macropores which further disintegrate into mesopores as the time from tillage increases (Cameira et al. 2003). This phenomenon can explain why on CT, improvement in $K(h)$ at −5 cm was only observed during Exp phase 3. Furthermore, as

CT enhanced $K(h)$, its significant decline by the end of the cropping season suggests that this benefit is short-term and unsustainable, similar to findings from semi-arid Mediterranean climates (Talukder et al. 2024). Beyond the tillage event, a drop in observed values for $K(h)$ −1 was observed for all plots. Cameira et al. (2003) on silty loams in south Portugal reported a significant 45% decrease in macropores created by $K(h)$ after the first irrigation event. Given the precipitation pattern in Fig. 1, the wetting and drying cycles could have affected the macropores created by CT, RT, and ST. Meanwhile, NT showed some stable values during the observed season. Improved values on all plots during Exp phase 4 could have been owed to bio-pore processes such as root development and preferential holes created by soil microorganisms beyond the dormancy and germination period. Similar to findings from Zumr et al. (2019), dry topsoil conditions could have also contributed to the high values observed for Exp Phases 1 and 4. This is because moisture and soil aeration affect soil macropores, especially in this climatic region (Matula et al. 2015).

Given the observation of the most predominant soil properties explaining the variabilities by applied tillage type, soil moisture content was found to be a more defining factor under CT, while it did not show this same effect on the other plots. Similar to findings from Mediterranean climates, soil moisture dynamics on CT throughout the cropping season are more profound compared to conservation tillage plots (Castellini et al. 2020). Generally, hydraulic conductivity properties were found to be a significant cause of variability subject to tillage, as the choice of tillage significantly alters this property (Popolizio et al. 2022). Soil organic matter defined variability for all but RT; soil property variability on RT was rather influenced by pH. Since pH dynamics can be linked to soil residue decomposition (Li et al. 2020), the influence of this variability could be associated with this process. Especially given that on RT, pH and soil organic matter showed a significant correlation ($r = -0.88$). Dry bulk density was not found to significantly define any of the applied tillage systems in the first component, even for CT, where changes in bulk density from intensively plowing the soil could be common for soils in this geographic and climatic region (Zumr et al. 2019). The relationship between hydraulic conductivity and dry bulk density was not self-explanatory from these results. Temporal changes in dry bulk density in temperate conditions have been previously found to not fully explain the temporal changes in hydraulic conductivity for several soil textures (Hu et al. 2012). Variability in bulk density was predominant during Exp Phase 1 and Exp Phase 4, hinting that the variability in bulk density was more pronounced during the consolidated state of the soils (at the end of the cropping season), similar to previous observations on similar soils in Czech Republic (Jirků et al. 2013). As expected, beyond the tillage event, hydraulic conductivity properties were definitive of the variability until Exp Phase 4. This indicates that tillage operations alter water movement through the porous system. Soil moisture variability did not significantly define the first component for any experimental phase. However, for several climates, dynamics in soil moisture have been found to substantially influence hydraulic conductivities (Castellini et al. 2015; Martínez García et al. 2014). This points to the fact that although tillage-induced moisture variability may not exist for this silty clay loam under temperate conditions, water movement through the pores can be altered by the applied tillage system, with temporal dynamics within a given season.

5 Conclusion

Findings from this study suggest that evaluating the temporal variability of the physical and hydraulic properties of soil is crucial for understanding the environmental sustainability of different soil management practices, specifically tillage, in this context. The temporal changes of the observed soil properties during the observed cropping season highlighted the importance of such studies because seasonal variabilities may necessitate the adoption of certain soil management practices to complement affected properties. For instance, for this silty clay loam soil experimented in a temperate climate, conservation tillage was consistent in improving all the studied physicochemical characteristics according to the observed outcomes; even though some indications of compaction under no-till were present. Implying that successful no-till for this soil type and climate may require careful consideration of the production situation (for example, planting crops with dominant roots), the problem to be solved, and then making a good choice of the straw or residue inclusion system to improve soil water dynamics. Findings under these temperate conditions where the improvements in macropore abundance by conventional till were observed to be short-term and diminish as time increases beyond the tillage event serve as interesting perspectives for more quantitative studies to expatiate this observance. Typically, a wide variety of conservation tillage systems are available to farmers, providing opportunities to enhance environmental performance. This study is vital to farmers and agriculturists within this geographical region or with similar climate patterns to consider the merits of conservation tillage practices reported. This would help reassess traditional conventional approaches for a more sustained agricultural system to complement crop production. Moreover, as region-wide regulations near requirements for adopting conservation agriculture, studies such as this could be a vital resource for stakeholders to bridge the knowledge gap between policymakers and farmers.

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Author Contribution David Kwesi Abebrese: Conceptualization, Methodology, Writing (original draft), Visualization, Formal Analysis, Investigation, Writing (review and editing). Matula Svatopluk: Supervision, Funding acquisition. Kamila Báťková: Supervision, Visualization. Recep Serdar Kara: Investigation, Validation. Miháliková Markéta: Formal analysis, Visualization.

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Data Availability Data used in this study is not available for the open public as it subjected to project discovery.

Declarations

Conflict Interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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