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RESEARCH ARTICLE

# Short-term effects of double-layer ploughing reduced tillage on soil structure and crop yield

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## Abstract

Soil tillage is widely acknowledged to affect soil characteristics and agricultural productivity. This research investigates the short-term effects of various tillage methods on soil physical properties and crop yields at a Central German field site with a dry climate (mean temperature 9.5°C; annual precipitation 470 mm). Three tillage approaches were evaluated: conventional plough tillage (25 cm depth), cultivator tillage (18 cm depth), and double-layer plough tillage (15 and 30 cm depth). We assessed soil physical properties through standard laboratory analyses, compression tests, soil pore structure via X-ray computed tomography (X-ray CT) and crop yields over 3 years. The results indicate that cultivator tillage approach increased soil bulk density relative to conventional tillage, especially in the second year, though this effect diminished over time. Double-layer plough tillage emerged as a viable short-term alternative to conventional tillage, achieving comparable soil bulk density. Saturated hydraulic conductivity values were generally higher for soils under conventional tillage or double-layer plough tillage than for cultivator tillage, highlighting their soil loosening effect. Classical soil analysis methods combined with X-ray computed tomography provided valuable insights into tillage induced changes to soil structure. Cultivator tillage resulted in a distinct pore structure with reduced macroporosity and pore connectivity. Despite notable soil property variations, crop yields remained consistent across the tillage methods. Overall, double-layer plough tillage presents a sustainable option, moderately improving soil physical properties while maintaining crop yields. This study highlights the need to assess the short-term effects of tillage on soils and contributes to the broader dialogue on optimizing tillage strategies for effective soil management and crop production.

**KEYWORDS**

bulk density, double-layer plough, macroporosity, pore connectivity, pre-compression stress, saturated hydraulic conductivity, X-ray CT

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# 1 | INTRODUCTION

Soil tillage has long been recognized for its profound influence on soil properties, water dynamics, and crop productivity. Conventional tillage (CT), involving the complete inversion of topsoil, renders short-term benefits such as weed control, soil aeration, increased water infiltration, and improved nutrient release (Idowu et al., 2019). In contrast, reduced tillage (RT) methodologies are characterized by minimized soil disturbance leaving the subsoil relatively undisturbed, with the purpose of preserving soil structure and aggregates (FAO, 1993). These practices have gained attention owing to advantages including cost savings, improved energy efficiency, reduced soil compaction, and enhanced ecosystem functions (Idowu et al., 2019; Palm et al., 2014; Rücknagel et al., 2017).

The practical suitability of reduced tillage hinges on various factors, including soil type, climate, and specific practices. Although the longer-term effects of reduced tillage on soil structure and crop productivity are increasingly well-documented (Büchi et al., 2017; de Carcer et al., 2019), there is a lack of evidence on the short-term effects, which are of particular interest to farmers seeking economic viability (Salem et al., 2015). Early-stage effects, such as soil compaction, moisture retention, and nutrient availability caused by the transition to reduced tillage methods may significantly influence crop establishment and growth, thereby impacting yields and economic returns (Chen et al., 2005). Recent studies have focused on various aspects of soil behaviour, including soil penetration resistance (Alesso et al., 2019), greenhouse gas emissions (Alskaf et al., 2021), microbial biomass (Alvarez & Alvarez, 2000), CO2 fluxes, nematode communities, and more. These studies have demonstrated the influence of factors such as location, climate, soil type, and experimental design (Alskaf et al., 2021; Idowu et al., 2019; Khorami et al., 2018; Ren et al., 2019).

In this study, we sought to evaluate the short-term effects of conventional tillage (CT), reduced tillage (RT), and a hybrid approach using double-layer ploughing (CRT) on soil properties and crop yields. Our objectives were (1) to elucidate the extent of short-term tillage effects on soil properties and (2) to assess the viability of CRT as an alternative to CT and RT. To frame our research, we hypothesized the following: (1) CT will exhibit lower bulk densities and distinct soil properties compared to RT; (2) variations in soil properties will be observed with depth, particularly with an increase in bulk density; (3) CT will maintain consistent soil properties over time, while RT may exhibit minor fluctuations; (4) soil properties in the inversed zone will align between CRT and CT, with CRT displaying distinct properties below; (5) crop yields will be consistent across all tillage variants, primarily influenced by climatic conditions.

The need for this study arises from the desire to comprehend the short-term impacts of different tillage systems and provide insights for farmers seeking to optimize their soil management practices. We recognize the complex interplay of soil, climate, and management practices and aim to contribute to the ongoing dialogue surrounding sustainable agriculture.

# 2 | MATERIALS AND METHODS

## 2.1 | Trial site

The short-term tillage trial at the Agrar- und Ernährungswissenschaftliches Versuchszentrum (AEVZ) Merbitz (Germany, federal state Saxony-Anhalt, 11°52′60″ E, 51°37′0″ N; 160 m above sea level) was established in autumn 2017. The average annual temperature is 9.5°C and the average annual precipitation is 470 mm. The soil type is a Chernozem (FAO, 1998). The texture of the top soil (0–30 cm) consists of 120 g $kg^{-1}$ sand, 790 g $kg^{-1}$ silt and 90 g $kg^{-1}$ clay, constituting a silt loam (Gee & Bauder, 1986). The total organic carbon content in the top soil is equal to 23 g $kg^{-1}$ and the pH value is 7.3.

The field experiment was organized in a completely randomized block design (Figure 1). There were three tillage variants. First, conventional tillage (CT) was carried out with a mouldboard plough turning the soil over down to 25 cm. Second, reduced tillage (RT) was carried out with a cultivator loosening the soil down to 18 cm. Third, a combination of the previously described variants was carried out (CRT) using a double-layer plough which was turning the soil over down to 15 cm and loosening the soil below down to 30 cm depth. Each tillage variant had three repetitions, resulting in a total of 9 plots. Each plot measured 24 × 9 m. The crop rotation on the three experimental blocks was summer barley (*Hordeum vulgare*), winter oilseed rape (*Brassica napus* ssp.) and winter wheat (*Triticum aestivum*) for all tillage variants. Row spacing was 12 cm in summer barley, 24 cm in winter oilseed rape and 12 cm in winter wheat. N-fertilization was site-specific. The trial was managed according to conventional and reduced farming and good professional practice.

Yields (dt $ha^{-1}$, dt = 100 kg) were measured every year in duplicates per plot (total of 6 harvest plots per crop and tillage variant, for summer barley and winter wheat 13.2 $m^2$ and for winter oilseed rape 15.0 $m^2$, threshed with

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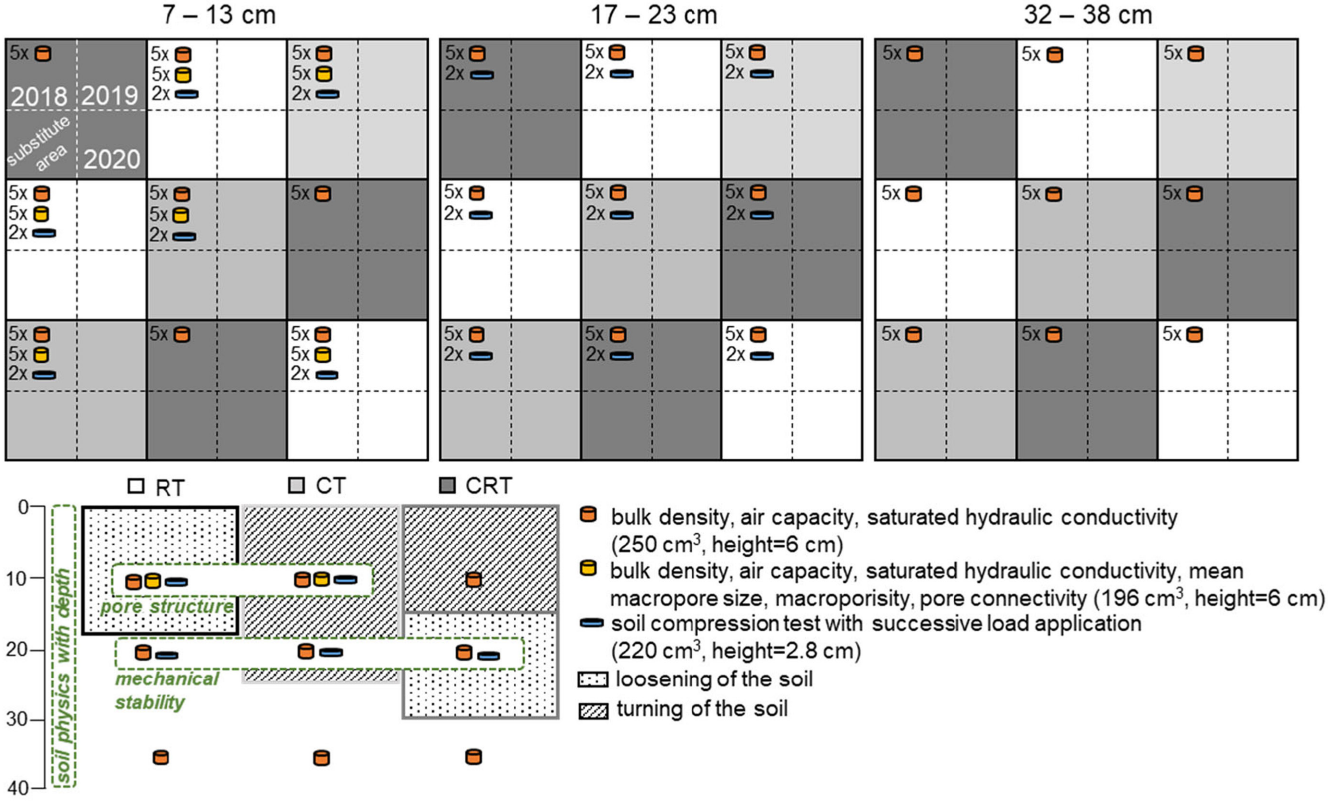


**FIGURE 1** Sketch of soil sampling strategy in conventional tillage with plough (CT, grey) and double-layer plough (CRT, dark grey) and reduced tillage with cultivator (RT, white) in 7–13, 17–23 and 32–38 cm sampling depth. Different volumes of soil sample rings and replicates were used for different soil physical analyses. Sampling alternated clockwise over the years starting at the top left of each block. Different sample constellations are used for a differentiated analysis of the development of soil physical properties with depth, soil pore structure and mechanical stability of the tillage variants.

a parcel harvester). Grain yields are reported here as averages with 86% and 91% moisture content for cereals and winter oilseed rape, respectively.

## 2.2 | Sampling design

Soil sampling took place in plots of summer barley, winter oilseed rape, and winter wheat in April 2018, April 2019, and March 2020, respectively, with the sampling strategy shown in Figure 1. Soil conditions at sampling were the same for all three sampling years (i.e., soil moisture was close to field capacity, corresponding to a matric potential of −6 kPa) and took place 15 days after sowing (summer barley), 7 months after sowing (winter oilseed rape) and 6 months after sowing (winter wheat).

To determine the development of dry bulk density (BD), air capacity (AC) and saturated hydraulic conductivity ($K_s$) between tillage variants and soil depths, undisturbed soil samples (250 cm$^3$, height = 6 cm) were taken in five replications per tillage variant and field block from soil depths 7–13 cm (5 × 3 × 3 = 45), 23–17 cm (5 × 3 × 3 = 45) and 32–38 cm (5 × 3 × 3 = 45).

To conduct pore structure analysis with X-ray computed tomography, we took undisturbed soil samples (196 cm$^3$, height = 6 cm) in five replications from soil depth 7–13 cm for the CT and RT plots (5 × 2 × 3 = 30). Afterwards, analysis of the same soil physical properties followed as previously described. The purpose of this was to (1) determine how reproducible average physical properties are among independent sets of samples in the presence of considerable soil heterogeneity (determined to be very reproducible) and to (2) compare image-derived macroporosity with the very similar, but independently measured parameter of air capacity for the same soil cores. Since the CRT plot was also ploughed at a depth of 7–13 cm as the CT plot, soil structure was assumed to be identical and no further soil samples were taken for this analysis.

In order to assess the mechanical stability of the tillage variants, undisturbed soil samples (220 cm$^3$, height = 2.8 cm) were taken at 17–23 cm depth from each tillage variant per plot (6 × 3 × 9 = 162) for the soil compression test. These samples were successively subjected to nine load steps (10, 25, 50, 100, 200, 350, 550, 1250 and 2500 kPa) (Bradford &Gupta, 1986) for the determination

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of the pre-compression stress of bulk soil to complement the X-ray computed tomography analysis.

## 2.3 | General soil physical investigations

After sampling, each soil sample was first slowly saturated by capillary rise before being drained for at least 7 days in a sandbox with a hanging water column to a matric potential of −6 kPa (Klute, 1986) and then weighed, followed by either soil physical analysis, X-Ray computed tomography analysis or compression testing.

AC was calculated from the difference in total pore volume and water content at field capacity with a particle density of 2.6 g $cm^{-3}$. $K_s$ (cm $d^{-1}$) of the soil samples was measured by means of a stationary system with a constant head method (Klute & Dirksen, 1986) with a flow duration of 4 h. The BD (g $cm^{-3}$) of the same samples was subsequently determined by drying at 105°C for 48 h and then weighing them (Blake & Hartge, 1986).

## 2.4 | X-ray computed tomography and image processing

Using an industrial X-ray scanner, soil samples (volume = 196 $cm^3$) were scanned using at energy of 140 kV and a beam current of 380 µA (X-Tek XTH225, Nikon Metrology). Each scan comprised 2748 projections with an exposure time of 0.5 s (scanning time was 2748 × 0.5 s = 1374 s). A CCD detector panel with 2000 × 1750 diodes recorded the projections. Beam hardening artefacts were reduced with a 0.5 mm copper filter. The CT scans were reconstructed with a spatial resolution of 40 µm and an 8-bit greyscale resolution using the X-Tek CT Pro software package (Nikon Metrology). The results pertain to pore sizes larger than 40 µm, with pores larger than two-three voxels accurately detected (Vogel et al., 2010). In our X-ray imaging analysis, we focused on the macropore network, which comprises pores larger than 40 µm. Conversely, micropores are considered as pores smaller than this threshold. Image processing was performed with the Java software ImageJ 1.50e (Rasband, 1997–2015). To reduce scatter and noise the CT scans were filtered using the "Non-local Means Denoising" plugin in Fiji (Buades et al., 2005).

In order to exclude artefacts at the edges of the sample and reduce the data volume, a cylindrical region of interest (ROI) with a diameter of 50 mm was used in the middle of the reconstructed X-ray scan.

Otsu thresholding (Otsu, 1979) was applied to separate the image into pores and soil matrix. The ImageJ plugin "BoneJ – Thickness" (Doube et al., 2010) was used to determine the pore size distribution by means of the maximum inscribed sphere method. The mean macropore diameter was calculated as the weighted mean of the measured macropore diameters with the frequency of a given diameter range as the weighting factor.

Macroporosity (here pore diameter > 40 µm) was quantified as the ratio of the number of pore voxels to the total number of voxels within the ROI.

The ImageJ analysis tool "Particle Analyser" (Ferreira & Rasband, 2010–2012) was employed to calculate pore connectivity, which represents the connection probability between two arbitrarily chosen pore voxels, i.e. the chance to belong to same pore cluster. This dimensionless number is also denoted as the Γ indicator (Renard & Allard, 2013; Schlüter et al., 2014) and has a value between 0 and 1, where the latter indicates that the soil pores are perfectly connected.

## 2.5 | Soil compression tests

Fully automated oedometers and software (WINBOD32, Wille Geotechnik, APS Antriebs-, Prüf- und Steuertechnik GmbH, Göttingen-Rosdorf, Germany) were used to determine the stress–strain relationships under drained conditions. Load application was uniaxial. Each load step was applied with a load time of 120 min and a subsequent relaxation time of 15 min with a 2 kPa load. The oedometer records settlement with an accuracy of 0.01 mm.

After the compression tests the soil samples were dried at 105°C for 48 h and then weighed (Blake & Hartge, 1986). The dry mass was then divided by the initial sample volume to compute the BD prior to the compression tests ($BD_0$). Using the settlement (s), the initial height of the soil sample ($h_0$), and $BD_0$ the resulting BD after each load application ($BD_{xi}$) was calculated as follows: $BD_{xi} = BD_0 \times h_0/(h_0 - s)$.

A semi-logarithmic stress-$BD_{xi}$ curve was then created. The mechanical pre-compression stress was determined based on these curves using the graphical method of Casagrande (1936). It was applied by a number of experimenters to minimize subjectivity (Rücknagel et al., 2010).

## 2.6 | Statistical analysis

The statistical analyses were carried out with the statistics program 'R Studio' (version 0.99.893, R Foundation for Statistical Computing).

For the variance analyses all soil properties were tested for normal distribution (Shapiro–Wilk test) and variance homogeneity (Levene's test). The arithmetic mean values for BD, mean macropore diameter, macroporosity and pore

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connectivity were calculated separately for each tillage variant and depth from the site repetitions. The means of the log-normally distributed $K_s$ and pre-compression stress values were calculated based on the logarithmized values.

For the soil physical properties BD, AC and $K_s$, an analysis of variance was conducted with soil tillage, depth and year as independent factors. In terms of statistical analysis, similar to the soil properties, yield data were subjected to the same statistical tests. An analysis of variance was conducted for the pre-compression stress of bulk soil and aggregates for the respective tillage variant and year. For the morphometric properties an analysis of variance was conducted with soil tillage and year as the independent factors. Using Tukey's honestly significant difference test differences among group mean values were identified and considered to be significant at a significance level of $p \le .05$.

# 3 | RESULTS

## 3.1 | Development of soil physical properties with depth

Bulk density was significantly affected by tillage practices at all sampling depths in all trial years except for 2018. In 2018, there were no significant differences in BD between CT and RT at any sampled depths, with BD values around ~1.45 g cm$^{-3}$ (Figure 2). In 2019, RT (~1.50 g cm$^{-3}$) had significantly higher BD compared to both CT and CRT (~1.30 g cm$^{-3}$) at all soil depths. In 2020, RT again had the highest BD values among the tillage treatments (~1.40 g cm$^{-3}$), although it was lower than in the previous year. The decrease was most notable in the top 25 cm, so that the difference with CT and CRT became insignificant apart from at the lowest sampling depth (32–38 cm). CRT had very similar bulk densities to CT at all depths and years, with the only exception being a significantly lower BD at 32–38 cm sampling depth in 2018, owing to a few very loose soil cores.

CT had significantly lower BD at all sampling depths in 2019 and 2020 (~1.32 g cm$^{-3}$) than in the initial trial year 2018 (1.46 g cm$^{-3}$). For CRT, there was no significant change in BD at 7–13 cm (turned soil) or 32–38 cm (beyond reach) sampling depth over the trial years, while BD at 17–23 cm sampling depth (loosened soil) decreased significantly. RT only showed significant differences in BD at sampling depths of 7–13 cm (loosened soil) and 17–23 cm (beyond reach), with the former being significantly highest in 2019 (1.52 g cm$^{-3}$) and the latter being significantly lowest in 2020 (1.38 g cm$^{-3}$). But for

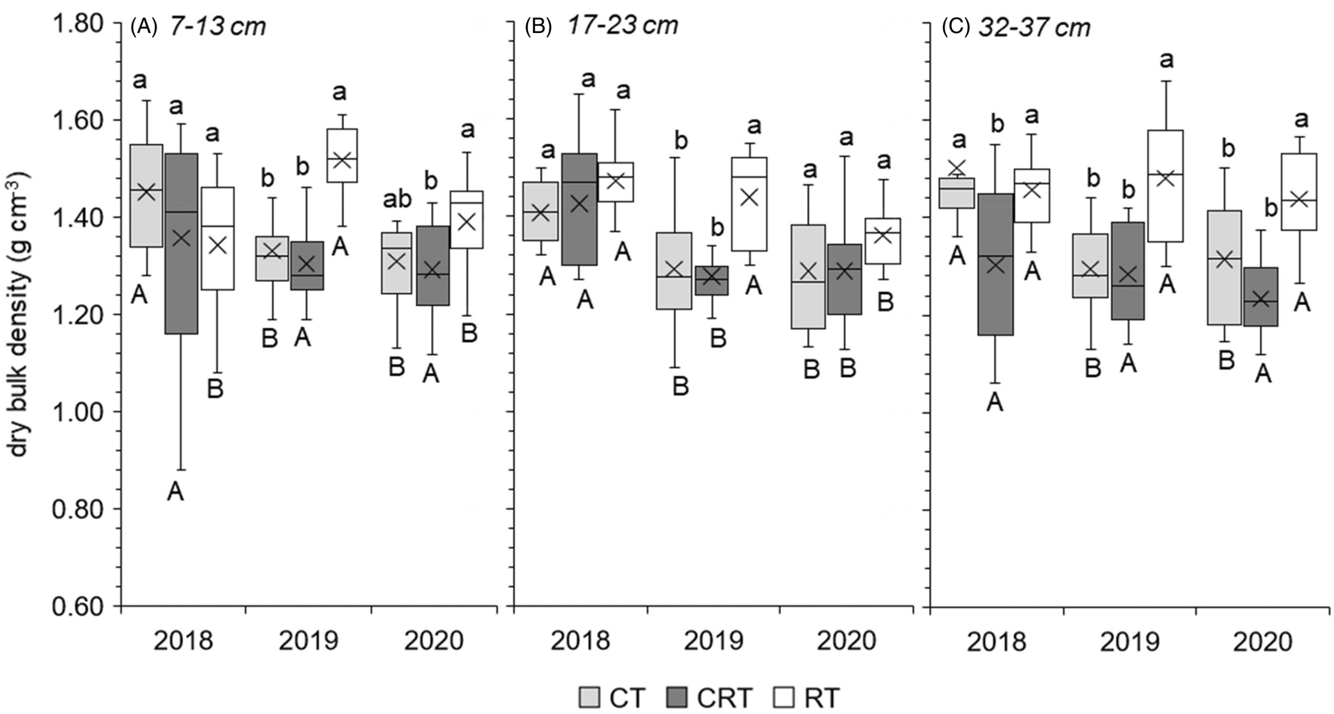


**FIGURE 2** Dry bulk density (g cm$^{-3}$) for the trial years 2018, 2019 and 2020 in conventional tillage with plough (CT, light grey) and double-layer plough (CRT, dark grey) and reduced tillage with cultivator (RT, white) 7–13 cm (A), 17–23 cm (B) and 32–38 cm (C) sampling depth. The median is indicated by the line inside the box and the mean is indicated by the cross in the box. The end of a whisker shows the smallest or largest data value of the data set without outliers. Lowercase letters represent significant differences between tillage in the respective year and uppercase letters represent significant differences between the trial years ($p < .05$) within one tillage variant. There were no significant differences between sampling depths in the respective tillage variant and trial year.

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all tillage treatments, sampling depths and years average BD values were always lower than the site-specific root-limiting BD of 1.55 g $cm^{-3}$ (Kaufmann et al., 2010). In summary, while CT and CRT were indistinguishable, a general trend toward higher BD in RT across all investigated soil depths was apparent that was, however, partially disguised by inter-annual variability, especially in the top 25 cm.

The values of air capacity AC exhibited an inverse relationship to BD, i.e., a lower bulk density was associated with a higher AC. In addition, AC typically had a much higher variability, as the effect of individual macropores and plant residues contained in a soil core was stronger. Because of this high variability, there were hardly any significant differences in AC between tillage treatments or years (Figure 3). In line with BD, RT (~8%) had significantly lower AC at all sampling depths compared with CT (~16%) and CRT (~17%) in 2019 (Figure 3), but these differences vanished again in 2020 because of increased AC in RT. CRT had very similar values to CT. In general, for all tillage treatments, sampling depths and years AC was ≥8 Vol.-% at pF1.8 (pores > 50 μm) to maintain ecological functionality of the soil and $K_s$ values were always higher than the 10 cm $d^{-1}$ minimum stated in Werner and Paul (1999).

Variability among samples was even higher for $K_s$ than AC, as individual macropores can act as a shortcut for saturated water flow in soil cores with 6 cm height (Figure 4). Despite this variability some clear trends emerged. In line with BD and AC, RT did also induce significantly lower $K_s$ than CT and CRT in 2019, but these differences vanished again in 2020. In 2018, CT (~1.50 log cm $d^{-1}$) and CRT (~2.40 log cm $d^{-1}$) also differed significantly from each other at sampling depths of 17–23 cm and 32–38 cm, but these differences vanished in 2019 and 2020. The differences between the years were much more pronounced for $K_s$ as compared to BD and AC and indicate a consistent increase with years irrespective of soil depth and tillage type.

## 3.2 | Development of soil pore structure

In line with the soil physical properties, all morphological properties (mean macropore size, macroporosity and pore connectivity) differed significantly between CT (0.70 mm, 0.11, 0.85) and RT (0.35 mm, 0.08, 0.70) in

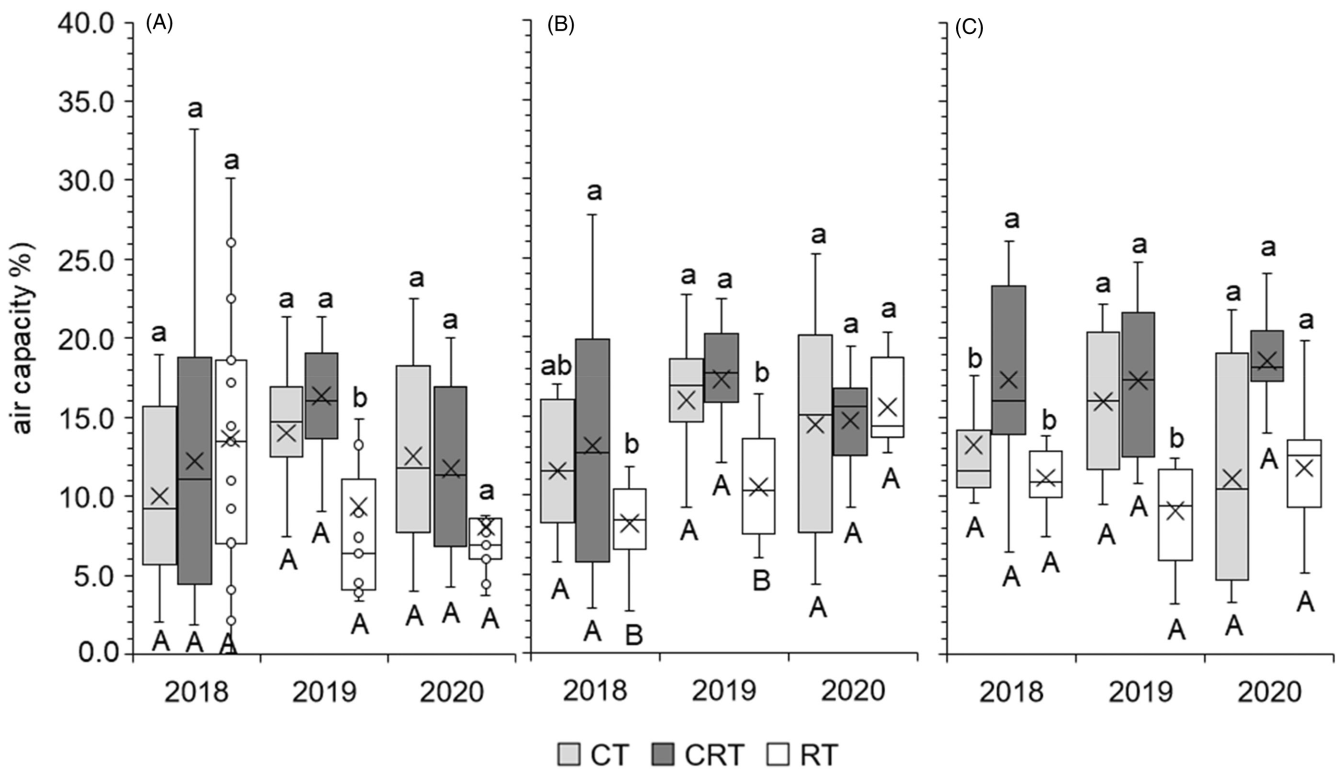


FIGURE 3 Air capacity (%) for the trial years 2018, 2019 and 2020 in conventional tillage with plough (CT, light grey) and double-layer plough (CRT, dark grey) and reduced tillage with cultivator (RT, white) 7–13 cm (A), 17–23 cm (B) and 32–38 cm (C) sampling depth. The median is indicated by the line inside the box and the mean is indicated by the cross in the box. The end of a whisker shows the smallest or largest data value of the data set without outliers. Lowercase letters represent significant differences between tillage in the respective year and uppercase letters represent significant differences between the trial years ($p < .05$) within one tillage variant. There were no significant differences between sampling depths in the respective tillage variant and trial year.

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2019 (Figure 5A–C), but the differences were not apparent in 2020. Despite occasional significant differences between consecutive years, there were no consistent trends over time for CT and RT. The 2D soil images indicated important differences in the soil porous system between CT and RT (see Figure S1). The application of the cultivator in 2019 resulted in major visual changes to the macropore space as a result of the higher initial density compared with 2018. The latter became even more evident as the trial progressed. A more compact structure with fewer isolated biopores developed in RT compared with CT.

### 3.3 | Comparison between classical and morphometric properties

In the simplified capillary tube model, pores >50 μm undergo drainage to a matric potential of −6 kPa, which corresponds to the field capacity. Consequently, macroporosity determination based on CT scans (>40 μm) should correspond with AC (50 μm) determined by water release on a sand bed. Indeed, there was a fairly strong correlation between AC and macroporosity ($p<.001$, Figure 6). The trend lines (although not shown) for RT and CT were close to the 1:1 line, with a slight overestimation for AC (by 2.7% in 2018, 0.5% in 2019 and 2.9% in 2020). The correlation coefficient for the whole data set is given in Figure 6.

### 3.4 | Development of mechanical stability

In general, when soil BD was low there was no significant differences in pre-compression stress results between the tillage methods at 17–23 cm depth. Soils under RT had significantly higher pre-compression stress in all trial years compared to CT and CRT and the pre-compression stress increased with duration of the trial for RT (Figure 7). In general, the pre-compression curves for RT showed higher BD values compared to CT and CRT. In 2019 and 2020, CRT had the pre-compression curves with lowest BD values.

### 3.5 | Development of yield

Overall, when physical soil properties were distant to critical thresholds for plant productivity reported in the literature. Therefore, tillage had no significant effect on grain yield across the crop rotation. RT tended to have the highest yields in 2018 and 2019 but the lowest yield in 2020 (Table 1). Significant differences between tillage variants regarding further crop properties (not shown) such as spiked stalks, grain weight, grains per ear, protein content, crop density or pod per plant were absent.

## 4 | DISCUSSION

### 4.1 | Effect of reduced tillage on soil physical properties

Our study results align with findings in the literature regarding the effect of RT on BD (Khorami et al., 2018; Mubarak et al., 2005; Palm et al., 2014; Salem et al., 2015). In the second year of the trial, RT led to significantly higher BD at all soil depths, which can be attributed to the lower intensity (7–13 cm) or absence (17–23 cm) of soil loosening. However, in the third year, the BD differences between RT and other treatments were less pronounced. These fluctuations in BD under RT may be influenced by soil spatial variability and differences between tillage and soil sampling conditions (Ren et al., 2019). Contrary to previous results (Gruber & Claupein, 2009), CRT had very similar BD values to CT in the first 3 years of our trial. This suggests that CRT offers a short-term alternative to CT without significantly affecting BD.

Similar to other findings (Lindstrom & Onstad, 1984; Rücknagel et al., 2017), CT and CRT had higher $K_s$ values at all depths compared with RT, particularly in 2019. The loosening of the soil in CT and CRT caused larger interaggregate pores and increased $K_s$. However, it is important to consider the time after tillage when assessing $K_s$ data (Kreiselmeier et al., 2020; Schwen et al., 2011), as natural settlement and increased traffic across the field can affect $K_s$ values.

### 4.2 | Development of soil pore structure

Compared to CT, RT displayed a distinctive pore structure with isolated macropores and lower microporosity as well as low pore connectivity from the second trial year (see Figure S1). This difference is notable, particularly when considering the ecological functionality of cohesive soils (Werner & Paul, 1999). Our results highlight the impact of tillage practices on soil pore structure, demonstrating the ability of X-ray computed tomography to provide valuable insight into structural changes induced by tillage method and highlights that resolution and sample size are important in assessing soil pore properties (Pires et al., 2017; Salem et al., 2015; Schlüter et al., 2018; Strudley et al., 2008).

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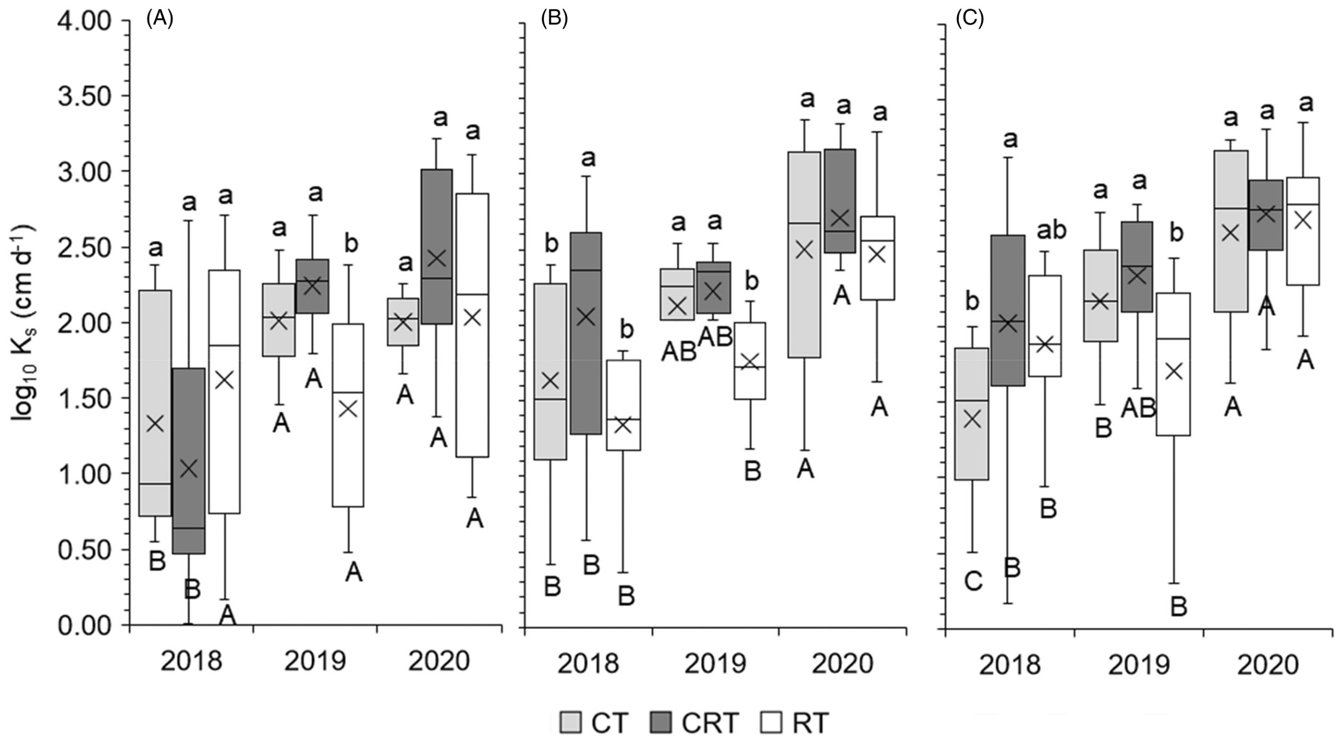


**FIGURE 4** Log-transformed saturated hydraulic conductivity ($\log_{10}(K_s)$, cm $d^{-1}$) for the trial years 2018, 2019 and 2020 in conventional tillage with plough (CT, light grey) and double-layer plough (CRT, dark grey) and reduced tillage with cultivator (RT, white) 7–13 cm (A), 17–23 cm (B) and 32–38 cm (C) sampling depth. The median is indicated by the line inside the box and the mean is indicated by the cross in the box. The end of a whisker shows the smallest or largest data value of the data set without outliers. Lowercase letters represent significant differences between tillage in the respective year and uppercase letters represent significant differences between the trial years ($p < .05$) within one tillage variant. There were no significant differences between sampling depths in the respective tillage variant and trial year.

### 4.3 | Integrated assessment of soil physical properties, yield performance, and mechanical stability in response to different tillage practices

There was good agreement between classical soil physical methods and X-ray computed tomography-derived morphometric properties. Despite a slight overestimation of AC derived from image-derived microporosity (~2%), the combined use of classical and X-ray computed tomography methods provided a more comprehensive understanding of soil structure changes resulting from different tillage practices. The ability to visualize soil structure through X-ray computed tomography offers a distinct advantage in assessing soil responses to tillage.

Our findings support earlier studies (Büchi et al., 2017; De Carcer et al., 2019; Idowu et al., 2019; Salem et al., 2015) suggesting that CT and RT can produce similar yields. The limited water supply during the growing seasons in our trial area underscores the importance of water and nutrient supply as limiting factors for crop productivity. According to typical practice in our study area, this study's trial was rain-fed only, and water supply during the growing seasons was low (2018: 293 mm, 2019: 428 mm, 2020: 424 mm). Despite differences in soil physical properties between tillage variants, yield differences were not significant in our study.

RT equipment's shallow working depth can contribute to the formation of a continuous, vertically oriented pore system, potentially enhancing soil stability against machine load (Rücknagel et al., 2017). Our results indicated that CT and CRT had lower pre-compression stresses compared with RT. This aligns with findings from previous studies (Chen et al., 2005; Salem et al., 2015) highlighting the impact of tillage on soil strength and compaction indicators.

### 4.4 | Extent of short-term tillage effects on soil properties

This study focused on the short-term effects of RT on soil properties, which align with the short-term decreases in BD and increases in macroporosity previously noted by Strudley et al. (2008). Our study results affirm these short-term trends. In the second year of the trial, RT led to significantly higher BD at all soil depths compared to conventional tillage (CT) and double-layer ploughing (CRT),

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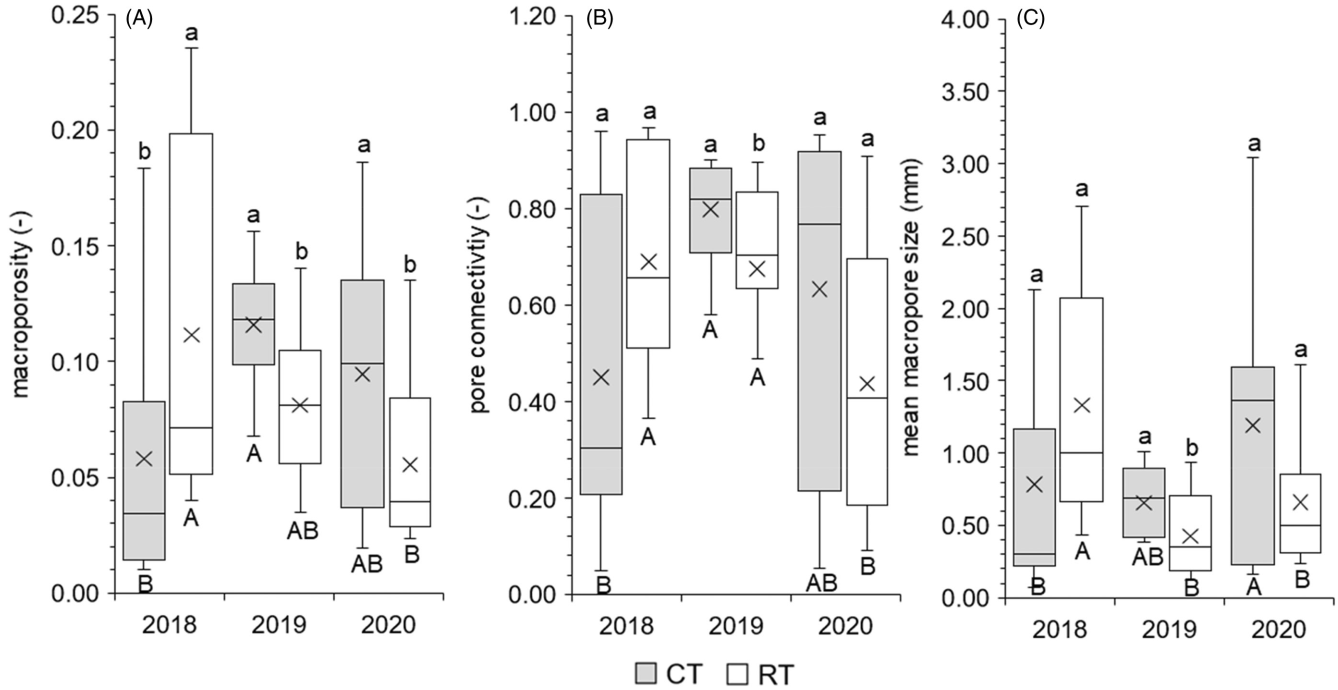


**FIGURE 5** Morphometric properties obtained with X-Ray computed tomography: (A) mean macropore size (mm), (B) macroporosity (−) and (C) pore connectivity for the trial years 2018, 2019 and 2020 under conventional tillage with plough (CT, light grey) and reduced tillage with cultivator (RT, white) in 7–13 cm sampling depth. The median is indicated by the line inside the box and the mean is indicated by the cross in the box. The end of a whisker shows the smallest or largest data value of the data set without outliers. Lowercase letters represent significant differences between tillage in the respective year ($p < .05$) and uppercase letters represent significant differences between the trial years ($p < .05$) within one tillage variant.

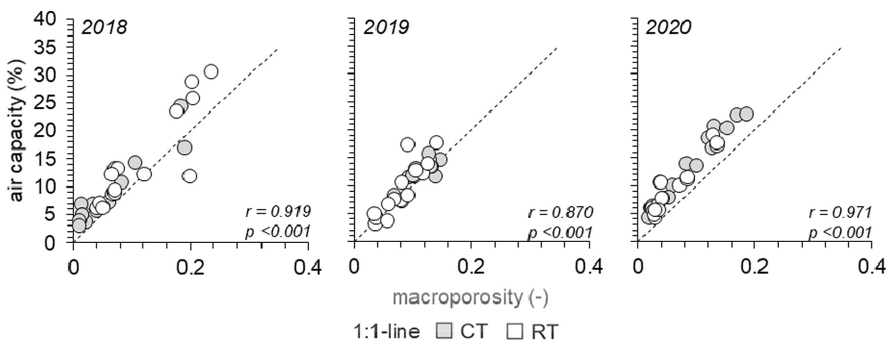


**FIGURE 6** Correlation between macroporosity (−) obtained with X-Ray computed tomography and air capacity (%) obtained in laboratory in the trial years 2018, 2019 and 2020 for conventional tillage with plough (CT, light grey) and reduced tillage with cultivator (RT, white).

consistent with observations by Strudley et al. (2008). Roger-Estrade et al. (2009) reported also differences in ploughed and non-ploughed treatments in Belgium, with the latter having significantly higher mean BD after 2 years, regardless of crop rotation. However, in the third year, the BD differences between RT and other treatments were less pronounced.

The study also examined the impact on air capacity (AC) and saturated hydraulic conductivity ($K_s$), with RT exhibiting lower AC and $K_s$ in 2019. However, these differences diminished in 2020, showcasing the influence of short-term temporal variability. Addressing the interplay of temporal effects and spatial responses in field trials, Chen et al. (2005) emphasized the difficulty in achieving long-term benefits from tillage practices unless the system demonstrates efficacy in the short term.

Bacq-Labreuil et al. (2020) suggested that changes in pore network connectivity develops more slowly than alterations in overall porosity owing to carbon cycling processes being affected by the decomposition of organic matter and rhizodeposition. While long-term tillage impacts on soil texture are well-documented, our focus on short-term changes, particularly in soil pore size and distribution, adds valuable insights (Botha, 2013). Ren et al. (2019) and Strudley et al. (2008) noted challenges in discerning long-term effects from natural variability

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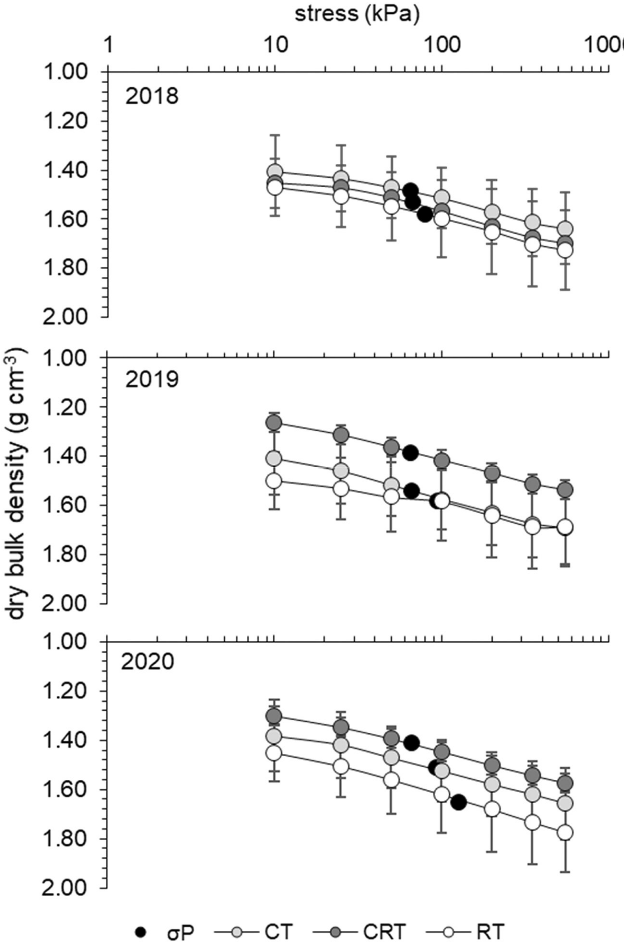


**FIGURE 7** Mechanical pre-compression stress (σP) for conventional tillage with plough (CT, light grey), double-layer plough (CRT, dark grey) and reduced tillage with cultivator (RT, white) in 17–23 cm sampling depth for the trial years 2018, 2019 and 2020.

**TABLE 1** Crop yields (dt $ha^{-1}$) of summer barley (2018), winter oilseed rape (2018/2019) and winter wheat (2019/2020) for conventional tillage with plough (CT), conventional-reduced tillage (CRT) and reduced tillage with cultivator (RT).

| | Summer barley | Winter oilseed rape | Winter wheat |
|---|---|---|---|
| CT | 75 ± 5 | 31 ± 4 | 129 ± 4 |
| CRT | 76 ± 3 | 32 ± 4 | 132 ± 8 |
| RT | 79 ± 5 | 33 ± 2 | 123 ± 10 |

*Note*: There are no significant differences ($p < .05$) between tillage variants in the respective crops.

and the potential overshadowing of management-induced variability by temporal fluctuations. They emphasized that rapid decay in measurable differences in soil hydraulic behaviour can render conclusions from short-term studies less reliable.

Additionally, soil pore structure analysis using X-ray computed tomography revealed distinct differences between CT and RT, confirming the presence of isolated macropores and lower microporosity in RT from the second trial year. This emphasizes the importance of our short-term investigation in capturing nuanced changes in soil structure induced by different tillage practices.

In the context of this short-term investigation, the study found no significant effect of tillage on grain yield across the crop rotation. While RT tended to exhibit higher yields in 2018 and 2019, the differences were not statistically significant. This aligns with previous studies (Botha, 2013; Khorami et al., 2018) suggesting that, in rain-fed conditions with low water supply during growing seasons, factors such as water and nutrient availability play a more prominent role in influencing crop productivity than short-term variations in soil physical properties.

Conclusively, the short-term effects observed in our study contribute valuable insights into the dynamic relationship between reduced tillage practices and soil properties, emphasizing the need for a nuanced understanding of these impacts in optimizing sustainable agricultural practices. This refined discussion integrates specific short-term outcomes with relevant studies in the field, highlighting the necessity for further investigations into the long-term effects of tillage practices.

## 4.5 | CRT as a suitable alternative to CT and RT

Our investigation regarding the effects of CRT on crop yield and soil properties reveals intriguing results. There was no clear trend toward a lower yield effect over time by using CRT. So, our findings suggest that CRT presents a viable option with moderate yet positive effects on soil physical properties. We observed that CRT has the potential to stabilize crop yields, offering a comparable performance to RT.

The study aligns with Zikeli & Gruber (2017), who proposed that a reduction in deep soil inversion, as implemented in CRT, can occur without detrimental effects on yield and may even contribute to improved soil quality. Similarly, Cooper et al. (2016) demonstrated that double-layer ploughing, a component of CRT, resulted in yields similar to RT, indicating no inherent disadvantage to this tillage approach. This outcome holds practical significance for farmers, emphasizing that CRT can provide benefits without compromising yields, which are often a prime concern for practitioners.

Our findings support the notion that CRT offers advantages such as enhanced water infiltration, reduced evaporation, and improved soil structure, as highlighted

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by Salem et al. (2015). These benefits gain particular importance in the context of changing climate conditions, where altered rainfall patterns and increased drought occurrences necessitate adaptive agricultural practices.

In light of our study results, we recommend that farmers in the study region consider the adoption of CRT as a potential tillage method. Particularly during the early years of transition, use, and application, our findings do not indicate significant yield losses associated with CRT.

## 5 | CONCLUSIONS

We conducted a comprehensive analysis of the short-term effects of different tillage practices on soil physical and mechanical properties and crop yields. Our findings highlight several critical aspects of tillage short-term impact, including the following: (1) RT tends to increase BD compared to CT in the short term, with the most significant differences observed in the second year. CRT offers a viable alternative to CT, maintaining similar BD values over the same period. (2) CT and CRT consistently exhibit higher $K_s$ values compared with RT, especially in 2019. The loosening of the soil in CT and CRT leads to increased $K_s$, although these effects may diminish over time because of natural settlement and field traffic. (3) RT displays distinct pore structure characteristics with lower macroporosity and pore connectivity, beginning in the second year. In contrast, CT maintains higher macroporosity and pore connectivity. (4) The combination of classical soil physical methods with X-ray computed tomography offers a more comprehensive understanding of soil structure changes resulting from tillage practices. (5) Despite variations in soil physical properties between tillage variants, crop yields remain similar in our trial. This suggests that factors other than soil properties play a more significant role in crop productivity under the prevailing water-limited conditions. (6) RT equipment's shallow working depth contributes to the formation of a stable pore system, enhancing soil stability against machine load. (7) Short-term fluctuations in soil properties because of tillage practices are evident, emphasizing the importance of assessing initial responses. (8) CRT emerges as a sustainable compromise between CT and RT, offering moderate improvements in soil physical properties while maintaining stable crop yields. CRT provides an opportunity for farmers to transition to reduced tillage without immediate yield losses.

In conclusion, our study underscores the significance of assessing short-term tillage effects on soil management and crop production. It highlights the potential of CRT as a practical alternative for practitioners seeking to balance soil health and crop yield stability. As we face evolving climate patterns, optimizing tillage practices remains essential for sustainable agriculture.

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## DATA AVAILABILITY STATEMENT

When the manuscript is published, the data will be freely available through our university library.

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