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Computed tomography and soil physical measurements of compaction behaviour under strip tillage, mulch tillage and no tillage

Julia Pöhlitz[a,*], Jan Rücknagel[a], Barbara Koblenz[a], Steffen Schlüter[b], Hans-Jörg Vogel[b], Olaf Christen[a]

[a] Martin Luther University Halle-Wittenberg, Department of Agronomy and Organic Farming, Betty-Heimann-Str. 5, 06120 Halle/Saale, Germany
[b] Helmholtz Centre for Environmental Research GmbH – UFZ, Department of Soil Physics, Theodor-Lieser-Str. 4, 06120 Halle/Saale, Germany

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ABSTRACT

In recent years, there has been an increased application of conservation-oriented tillage techniques, where instead of being turned the soil is only loosened or not tilled at all. Strip tillage, a special form of conservation tillage, results in small-scale structural differences, since tillage is performed only within the seed row, while the soil between seed rows is not tilled. However, tillage always impacts upon physical soil properties and processes.

A combined application of conventional soil mechanical methods and X-ray computed tomography (X-ray CT) is employed here in order to investigate small-scale structural differences in a chernozem (texture 0–30 cm: silt loam) located in central Germany under strip tillage (within and between seed rows) compared to no tillage and mulch tillage. Apart from recording changes over time (years: 2012, 2014, 2015) to dry bulk density and saturated conductivity at soil depths 2–8 and 12–18 cm, stress-strain tests were conducted to map mechanical behaviour for a load range of 5–550 kPa at a soil depth of 12–18 cm (year 2015). Mechanical precompression stress was determined from the stress-dry bulk density curves. In addition, computed tomography scans were created followed by quantitative image analysis of the morphometric parameters mean macropore diameter, macroporosity, connectivity and anisotropy of the same soil samples.

For strip tillage between seed rows and no tillage, a significant increase in dry bulk density was observed over time compared to strip tillage within the seed row and mulch tillage. This was more pronounced at a soil depth of 2–8 cm than at 12–18 cm. Despite higher dry bulk density, strip tillage between the seed row displayed also an increasing saturated conductivity compared to strip tillage within the seed row and mulch tillage. The computed tomography scans showed that the macropores became more compressed and soil aggregates were pushed together as mechanical stress increased, with the aggregate arrangement being transformed down into a coherent soil mass. The soil mechanical and morphometric parameters supported each other in terms of what they revealed about the mechanical properties of the soil structures. For instance, in the strip tillage between seed rows and no tillage treatments, the lack of soil tillage not only resulted in higher dry bulk densities, but also higher aggregate densities, mechanical precompression stress values, mean macropore diameters as well as lower macroporosity and connectivity values compared to mulch tillage and strip tillage within the seed row. The computed tomography parameters are therefore highly suitable for providing Supplementary information about the compaction process. Overall, this study showed that strip tillage combines the advantages of no tillage and a deeper, soil conservation-oriented primary tillage because, on a small scale, it creates two distinct soil structures which are beneficial in terms of optimal plant growth as well as mechanical resistance by driving over the soil.

1. Introduction

Soil tillage aims to increase crop yields and at the same time preserve ecological soil functions, like habitat functions and regulatory functions for water and nutrients. In recent decades, an increasing number of practitioners have abandoned traditional tillage methods which turn the soil using a plough (conventional) in favour of conservation-oriented soil tillage (see e.g. Licht and Al-Kaisi, 2005; Nowatzki et al., 2009). The latter does not involve turning the soil with a plough, but instead only loosening it or leaving it completely untilled. Conservation tillage thus covers the soil surface with dead plant material (Gajri et al., 1999). This has both ecological and economic

* Corresponding author.
E-mail address: julia.poehlitz@landw.uni-halle.de (J. Pöhlitz).

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benefits for the soil, such as for example conserving water, preventing soil erosion, preserving economic productivity, reduced investments in machinery and less time spent on seedbed preparation (Carter, 2004; FAO, 1993). There are a variety of conservation tillage systems, which can be roughly divided into no tillage, mulch tillage, strip tillage, ridge tillage and minimum tillage (FAO, 1993). Strip tillage is special in that the soil is divided into a sowing zone and a soil management zone. The sowing zone, which is 5–15 cm wide, is worked mechanically down to a depth of 25 cm in order to optimise the soil and microclimate conditions for crop germination and growth, while the soil management zone is left untilled (Lal, 1983). Strip tillage therefore combines the conventional advantages of no tillage and those of deeper, non-turning primary tillage. It also allows farmers to combine individual working steps, thus reducing the number of times the field is driven over (Nowatzki et al., 2009).

However, any type of tillage affects the physical properties of the soil (Carter, 2004). In particular, there is a higher risk of compaction damage if the machinery used has not been adapted to the site and local conditions (Rücknagel et al., 2012; Koch et al., 2008). Compaction processes mainly affect parameters such as dry bulk density, aggregate stability, pore size distribution, infiltration rate and water conservation (FAO, 1993). This causes a deterioration in nutrient uptake and plant growth, while surface run-off increases (e.g. Paglai and Jones, 2002; Voorhees, 1986).

When investigating compaction effects in agricultural soils, conventional soil mechanical methods such as soil compression tests make it possible to map the compaction process and identify volumetric soil deformation for different initial soil structures. This yields indirect information about functional properties of the internal structure, such as the stress-strain relationship and aggregate density/bulk density ratio (Rücknagel et al., 2007). Typically, there is a lack of direct information about changes to geometric properties and morphologies of the void system. With this in mind, in recent decades non-destructive imaging methods, such as X-ray computed tomography (X-ray CT), have been increasingly used to successfully answer questions about soil physical properties (e.g. Keller et al., 2013; Schlüter et al., 2011, 2016). Computed tomography not only detects the spatial distribution of pore geometries and maps their positions precisely, but also enables quantitative image analysis.

Only a few studies have dealt with the combined analysis of structural differences between individual conservation soil tillage systems and compaction effects in those soil tillage systems with the aid of computed tomography scans (e.g. Dal Ferro et al., 2014; Jarvis et al., 2017; Luo et al., 2010). None of these studies considered the strip tillage method. In addition, no links have been established between conventional soil mechanical methods and those involving computed tomography. Using a combination of soil mechanical and computed tomography methods, this study therefore focuses on the influence of the special, two-part soil structure present under strip tillage compared to mulch tillage and no tillage. Specifically, it aims to answer the following questions: (i) Does the strip tillage method create small-scale structural differences within and between the seed rows? (ii) Under strip tillage, how do dry bulk density and aggregate density change as stress increases compared to mulch tillage and no tillage? (iii) To what extent can morphometric parameters, based on X-ray CT, map soil compaction behaviour in strip tillage compared to mulch tillage and no tillage? (iv) Are there correlations between the parameters measured using conventional methods and those measured with X-ray CT? (v) And what implications do the results have for agricultural land use? Overall, this study aims to explore to evaluating the role of the different soil tillage methods in the compaction process.

2. Materials and methods

2.1. Trial site

Soil sampling was performed at the strip tillage experiment set up by the International Crop Production Centre in Bernburg-Strenzfeld (Germany, federal state Saxony-Anhalt, 11° 41′ E, 51° 50′ N; 80 m above sea level) in 2012. The average annual temperature is 9.7 °C and average annual precipitation is 511 mm. The soil type is a chernozem (FAO, 1998). The texture of the top soil (0–30 cm) contains 60 g kg^{-1} sand, 740 g kg^{-1} silt and 200 g kg^{-1} clay, constituting a silt loam (USDA, 1997). The total organic carbon content in the top soil is equal to 1.65 g kg^{-1} and the pH value is 6.8.

2.2. Experimental procedure

The field experiment is organized as a completely randomised block design including four blocks each with the treatments strip tillage, mulch tillage and no tillage. Each individual trial plot measures 18 × 50 m. Row spacing in the strip tillage treatment is 50 cm; the tilled strips measure 15–20 cm across and are ploughed to a depth of 20–25 cm. For strip tillage, there was no soil tillage between seed rows. Because of this differentiation in the strip tillage treatment, spatially separate samples were taken from within (strip tillage WS) and between (strip tillage BS) seed rows. These were considered as independent treatments for the rest of the experimental procedure and during evaluation. In the mulch tillage treatment, soil was tilled with cultivator to a depth of 15–20 cm, while the no tillage treatment was not tilled.

For the soil physical investigations, undisturbed soil samples (250 cm^3, height = 6 cm) were taken in the years 2014 and 2015 in three replications per tillage treatment and field block from soil depths 2–8 cm (n = 48) and 12–18 cm (n = 48). In addition, 12 soil core samples (n = 48) were taken from the same blocks used in the tillage treatments depths in the year 2012 before the trial was set up, in order to determine the initial physical conditions. The soil conditions at sampling time were always the same for all three sampling years (close to field capacity corresponding to a matric potential of −6 kPa) and always took place in the crop winter wheat.

Two types of soil compression test were conducted in the study. Only one load step was applied to those soil samples which were used to determine aggregate density (AD) after the soil compression tests (one load step application). With respect to the soil mechanical investigations, for each of 8 different load steps (5, 10, 25, 50, 100, 200, 350 and 550 kPa) undisturbed soil samples (220 cm^3, height = 2.8 cm) were taken at soil depth 12–18 cm from each tillage treatment per field block (5 × 4 × 8 = 160 samples). The soil samples used in the computed tomography investigations after the soil compression tests were subjected to 8 successive load steps (classical load application) (Bradford and Gupta, 1986). For the computed tomography investigations, an undisturbed soil sample (220 cm^3) were taken at soil depth 12–18 cm from each tillage treatment per field block (5 × 4 = 20). These samples were also subject to the same loads steps, which were however applied successively with CT scans in between.

2.3. Soil compression test

The soil samples (220 cm^3) were first slowly saturated by capillary action before being drained for at least seven days in a sandbox with a hanging water column at a matric potential of −6 kPa (Klute, 1986) and then weighed.

The stress-strain relationship was determined in drained conditions with the aid of fully automated oedometers and software (WINBOD32, Wille Geotechnik, APS Antriebs-, Prüf- und Steuertechnik GmbH, Göttingen-Rosdorf, Germany). Loads were applied uniaxially. Compaction was performed parallel (one load step application) or successively (classical load application) for the load steps 5, 10, 25, 50,