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Uniaxial compression behaviour and soil physical quality of topsoils under conventional and conservation tillage

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ABSTRACT

Considering conventional tillage with a mouldboard plough and conservation tillage with a cultivator or disc harrow, this study analysed whether structural differences in the soil of the lower topsoil led to any difference in this layer's susceptibility to compaction, and also how density changed – in the whole soil and also in the individual aggregates – during the compaction process in both tillage variants. To this end, soil samples were taken from the lower topsoil of seven medium-term and long-term soil tillage trials conducted in Central Europe. Compression tests were performed on these samples and they were also used to determine dry bulk density, aggregate density, air capacity and saturated hydraulic conductivity. The stress/bulk density functions as well as the stress/strain functions from the compression tests were analysed and the precompression stress determined. At two test sites, compaction behaviour was analysed for whole soil and for aggregates separately. In the case of conservation tillage, the soil structure demonstrated higher dry bulk density as well as lower air capacity and saturated hydraulic conductivity. Aggregate density was mostly similar. It increased relatively slowly during compaction, and often not before high loading steps. This is why higher precompression stress values in the variants under conservation tillage were mostly the result of a dense compaction of aggregates, and indicated higher stability against mechanical loads. However, for both variants the virgin compression section of the stress/bulk density functions displayed similar compression behaviour; and generally higher settlement for conventional tillage in the compression test did not result in higher dry bulk densities than with conservation tillage. Stability against mechanical loads in the conservation tillage variants should therefore not be overestimated.

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1. Introduction

Traditional primary tillage using a plough, also called “conventional tillage”, usually involves turning the whole of the topsoil. This fully works any crop residues into the soil. Besides this system, around the world tillage methods have become established which refrain from turning the soil in this way, and often also from loosening the whole of the topsoil. Crop residues are only worked into the soil close to the surface (e.g. mulch tillage and reduced tillage). It is also possible to dispense with loosening the soil altogether (no-tillage). These methods are known collectively as “conservation tillage” systems (FAO, 1993).

One important reason for using conservation tillage systems is that they cost less (Ndaeyo, 2010), but usually result in comparable yield levels under temperate climate conditions like those of Western or Central Europe (Rücknagel et al., 2004; Brennan et al., 2014). Apart from this, environmental aspects also play a role. Factors associated with conservation tillage include a higher energy output/input ratio (Borin et al., 1997), the enrichment of soil organic carbon near the soil surface in particular (Six et al., 1999; Tebrügge and Düring, 1999), and reductions in sediment loss and nutrient loss through erosion (Chichester and Richardson, 1992).

Conservation tillage is also seen as a preventive way to protect the soil against compaction damage (Brunotte et al., 2013). Among other reasons, this is because conventional tillage with a plough commonly involves the tractor wheel driving in the furrow. On-land ploughing, which involves all wheels of the tractor driving on top of the soil, is recommended but not common practice. In the case of conventional tillage with driving in the furrow, the wheel induced stress is transferred directly into the subsoil (Weisskopf et al., 2000). By contrast, conservation tillage involves driving on the surface of the soil. By shifting the tyre-soil contact area to the surface, there is a greater reduction in stress down to the subsoil, in turn decreasing the risk of plough sole compaction. In addition, differences in physical soil properties as a result of conservation tillage mean that, when driving over the land with agricultural machinery, the soil stress in the topsoil and subsoil can be reduced (Zink et al., 2010).

As regards soil physical properties, there are particularly striking differences between conventional and conservation tillage in the lower topsoil, an area which is no longer tilled regularly and thus often more

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densely layered (Rasmussen, 1999; Deubel et al., 2011). Particularly where conservation tillage is practised in the long term, a continuous, vertically oriented pore system with higher saturated hydraulic conductivity may form (Azooz and Arshad, 1996). These vertically oriented pores are comparatively less susceptible to compaction (Hartge and Bohne, 1983). However, there are indications that, in conservation tillage soils, the layers below the reduced tillage depth display air-filled porosity, air diffusivity and permeability levels which lie below the critical ranges for favourable plant growth (Schjonning, 1989; Götze et al., 2013). Compacted and displaying high dry bulk density and low porosity, these soil layers are described as the "no-till pan" (Reichert et al., 2009).

For the lower topsoil in particular, the question thus arises as to whether different physical soil conditions in the tillage variants lead to different sensitivity to compaction in this layer. The uniaxial compression test is well suited to this analysis, because it allows the application of defined increasing soil pressures and comparable matric potentials to soil samples taken directly from this layer. Using the stress/strain or stress/bulk density function derived from this, it is possible to identify not only the compression index but also the precompression stress. Soil precompression stress is a key criterion for the soil's stability when subjected to mechanical loads (Horn and Rostek, 2000). Once it is exceeded, this leads to irreversible changes in soil functions. As yet, however, it remains unclear to what extent precompression stress levels of the whole soil and of aggregates are dependent on various textural and structural conditions. Therefore a further aim was to investigate how density changed – in the whole soil and also in the individual aggregates – during the compaction process in the conventional and conservation tillage variants. Based on this, it is possible to determine the maximum pressure load which will not cause aggregate compaction, and consequently the highest load under which the soil is able to regenerate a sufficient macropore or inter-aggregate pore system. In order to answer these questions, this article analysed compression tests from the lower topsoil of seven medium-term and long-term soil tillage trials in Central Europe.

2. Materials and methods

2.1. Test sites and variants

The trials were located at seven different sites in Germany (Table 1) which are characterised by a moderate continental climate with mean annual temperatures of between 8.5 and 9.5 °C as well as mean annual precipitation of between 460 and 640 mm. Each test site included a medium-term or long-term tillage experiment with the variants "conventional tillage" with a mouldboard plough (tillage depth 25 cm) and "conservation tillage" with a cultivator or disc harrow (tillage depth 8–15 cm). In the tillage trials, the clay content in the topsoil varied between 40 and 310 g kg^{-1}, while the sand content ranged between 40 and 750 g kg^{-1}, thus covering a very broad range of soil textures. The total organic carbon content varied between 7 and 20 g kg^{-1}. On all sites, the gravel content was below 20 g kg^{-1}.

2.2. Soil compression tests

For each site and tillage variant, horizontally oriented soil core samples ($n = 4$–8) were extracted from the topsoil (soil depth 15 … 22 cm) at four different places; these samples were taken for subsequent soil compression tests. With the exception of the Warin site, all samples were taken in the spring (March until May). Ploughing and seedbed preparation already occurred in the autumn of the previous year. At the Warin site, sampling took place during autumn approximately two months after ploughing and seedbed preparation. The soil cores used in the compression tests had a diameter of 100 mm and a height of 28 mm. After collecting the soil, the samples were saturated and then adjusted to a matric potential of −6 kPa in a sand box. This matric potential corresponds to field capacity. The loading steps 5, 10, 25, 50, 100, 200, 350 and 550 kPa were applied in succession to the soil core samples. The tests took place in drained conditions with a loading time of 180 min per loading step and relaxation phases lasting 15 min. In previous tests on soils of similar textural classes, for loading times of up to 540 min only very slight increases in settlement were measured in comparison to 180 min. Therefore, settlement can be regarded as largely finished after 180 min. However, just how matric potential changed during the soil compression tests was not measured. The oedometer applied (Bradford and Gupta, 1986) was fully automatic, and the settlement (S) was recorded to an accuracy of 0.01 mm. After drying the sample cores at 105 °C until the sample mass remained constant, the dry bulk density at the beginning of the experiment (BD_t) was determined after treatment in the oedometer. Using the settlement (S) of the sample after each loading step compared to its initial height (H) as well as the density of the whole soil at the beginning of the experiment (BD_t), it was possible to calculate the resulting density of the whole soil for each loading step ($BD_{t\ xi}$):

$$BD_{t\,xi} = ((H-S)/H)^{-1} * BD_t \qquad (1)$$

The stress/bulk density functions as well as the stress/strain functions from the compression tests were analysed separately. Taking the last three loading steps of the compression tests, these were used to identify the respective slopes of the virgin compression lines (m_{VCL}). This involved calculating the change in settlement and dry bulk density from 200 kPa ($S_{200\ kPa}$ or $BD_{200\ kPa}$) to 550 kPa ($S_{550\ kPa}$ or $BD_{550\ kPa}$) in

Table 1
Experimental sites with texture and total organic carbon (TOC) in the topsoil layer.

Site name	Federal state	Trial duration (years)	Taxonomy[a]	Texture (g kg^{-1})		Texture class[b]	TOC (g kg^{-1})	
				Clay	Sand		Conv.[c]	Cons.[d]
Bad Kreuznach	Rhineland-Palatinate	6	Haplic Luvisol	240	230	Silt Loam	14	13
Bernburg	Saxony-Anhalt	7	Chernozem	190	110	Silt Loam	16	15
Buttelstedt	Thuringia	3	Chernozem	310	40	Silty Clay Loam	19	20
Görzig	Saxony-Anhalt	8	Chernozem	240	220	Silt Loam	15 [e]	
Lückstedt	Saxony-Anhalt	4	Gleyic Cambisol	40	750	Loamy Sand	7	8
Warin	Mecklenburg-Western Pomerania	6	Cambisol	100	590	Sandy Loam	–	
Zschortau	Saxony	17	Haplic Planosol	130	560	Sandy Loam	7	10

[a] FAO soil classification.
[b] USDA classification scheme (Gee and Bauder, 1986).
[c] Conventional tillage.
[d] Conservation tillage.
[e] Content not differentiated between the tillage variants.

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