Impact on soil compaction of driving agricultural machinery over ground frozen near the surface

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1. Introduction

Compaction of arable soils caused by agricultural machinery is a significant problem on arable land subject to intensive cultivation, particularly in the temperate climate area of Central and Eastern Europe (e.g. Fulajtár, 2000). Compaction severely restricts a number of important ecological soil functions. Air capacity decreases and gas exchange is restricted (Ball and Robertson, 1994; Horn and Rostek, 2000). Another likely consequence of soil compaction and the establishment of platy and coherent soil structure is reduced water infiltration with water run-off and erosion (Horn et al., 1995). In some cases even yield decrease has been observed (Voorhees, 2000). In early spring and late autumn, the water content of arable soils is in most cases near the field capacity and there is therefore a high risk of compaction if driven over (Arvidsson et al., 2003). In addition to numerous preventive measures, such as reducing the wheel load and internal tyre pressure or using specialised chassis, a recommended practice in Central European agriculture involves driving over soil which is frozen near the surface. This option is available for several agronomical measures, such as the timely spreading of mineral fertiliser early on in the year or the tillage of unused arable land during the winter, particularly in agricultural areas of Central Europe’s temperate climate zone. During years with particularly wet spells of autumn weather, part of the grain maize harvest also occurs on ground which is slightly frozen, in order to guarantee the ability to drive over it. All of the measures named here make use of weather situations where a light frost (usually ≥2 °C) occurs at night and by day temperatures above freezing (usually >5 °C). Hence this does not concern prolonged periods of frost, rather solely ground frozen near the surface for only a few hours. From an agricultural point of view this is necessary to ensure, for example, the solubility of mineral fertilisers in the soil, which by day is not frozen.

It is already known from other scientific disciplines that the strength of frozen soils overall can be very high (Yang et al., 2010), up to the point where crushing occurs. There are, however, no findings concerning the depth of frost penetration required to effectively prevent compaction when the soil is driven over by agricultural machines. The results of a field trial carried out in March 2010 to answer this question are set out below.

2. Materials and methods

The test site was located in Central Germany on the north-eastern edge of the federal state of Thuringia. The soil type (FAO soil classification) was an Albic Luvisol of the soil textural class silt loam (90 g kg⁻¹ sand, 130 g kg⁻¹ clay) and located in the topsoil. The organic carbon content in the topsoil was equal to 12 g kg⁻¹. The soil water contents in the topsoil at the time of the test were 0.31–0.33 m³/m³. This corresponds to ~95% of soil field capacity. In autumn 2009 before the tests were carried out, a cultivator was used to prepare the entire test area...
at a depth of 25 cm. At the time of the experiment, there were still no cultivated plants growing on the test area. The precompression stress (Rücknagel et al., 2007; Rücknagel et al., 2010) of the loosened soil at a depth of 20 cm was 21 kPa (logarithm 1.32).

A tractor with a seedbed combination with drill served as a test device. Each variant was driven over once with the tractor. The wheel load of the rear wheels (tyre size 680/75 R 32) was 4100 kg with an inflation pressure of 80 kPa. Apart from the control (1) that was not driven over, the test variants comprised a variant with no frost (2), a variant with 2–3 cm depth of frost penetration (3) and a variant with 5–7 cm depth of frost penetration (4). The frost depths were determined by breaking open the frozen layers for each variation at various points and then measuring the respective strength (Picture 1). Each variant was replicated four times. The variant with no frost was created by covering the tracts of land to uncover. Dry bulk density, air capacity and saturated hydraulic conductivity were determined from soil cores (n=12) taken at uncovered. Dry bulk density, air capacity and saturated hydraulic conductivity were determined from soil cores (n=12) taken at uncovered points and then measuring the respective strength of Darcy’s law applied to saturated water movement within the soil as a measure of the hydraulic permeability of water-saturated soil (unit cm/d). Apart from size and shape, soil permeability for water is influenced heavily by pore continuity. Determination takes place in a stationary facility according to the principle described by Kolute and Dircsen (1986).

The physical soil parameters were determined using soil core samplers. The precompression stress in formula (1) was calculated with a linear regression model with logarithm of precompression stress (log $\sigma_p$, Logarithm of unit kPa) and water content in percent of field capacity (FC):

$$k = -2.0 \log \sigma_p + 0.03 \times FC + 3.2$$  \hfill (2)

Furthermore, the depth of the rut driven in was identified for the individual variants. In addition, the depth of tyre sinkage across the tyre width was measured at intervals of 5 cm and using a level staff with 4 replications per variant. The control variant that was not driven over was also included as a reference level, in order to rule out any natural unevenness in the ground. The statistical analysis of the data was carried out with an ANOVA and a subsequent comparison of mean values (Tukey-Test).

The concentration factor ($k$, no unit) in formula (1) was calculated with a linear regression model with logarithm of precompression stress (log $\sigma_p$, Logarithm of unit kPa) and water content in percent of field capacity (FC):

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Furthermore, the depth of the rut driven in was identified for the individual variants. In addition, the depth of tyre sinkage across the tyre width was measured at intervals of 5 cm and using a level staff with 4 replications per variant. The control variant that was not driven over was also included as a reference level, in order to rule out any natural unevenness in the ground. The statistical analysis of the data was carried out with an ANOVA and a subsequent comparison of mean values (Tukey-Test). Significance with an error probability of $p<0.05$ are shown in different lower case letters. The variation coefficient ($s\%$) was also calculated for the depth of tyre sinkage. In addition to this, the standard deviation ($s$) and the mean value ($\bar{\sigma}$) of the respective tyre sinkage are needed.

$$s\% = s/\bar{\sigma} \times 100$$  \hfill (3)

High coefficients indicate an increasing variability of the characteristic recorded. The standard deviation is calculated here from the sum of squares (SQ) and the number of all replicated measurements ($n$) using the equation:

$$s = \sqrt{(SQ/(n-1))}$$  \hfill (4)
precompression stress. In their investigations, precompression stress lasting consolidation at ground pressure levels which correspond to approximately 6. In some cases, Keller and Lamandé (2010) observe capacity on clay soil at 30 cm depth. Overall, ground pressure exceeds corresponds approximately to Arvidsson and Keller’s (2007) measurement variant. The height of the ground pressure calculated here corre-

A depth of frost penetration of 5 cm is therefore sufficient to reduce the risk of compac-
tion with a wheel load of 4000 kg and appropriately adjusted inflation pressure (80 kPa).

In agricultural practice, tractors and other agricultural machines with high wheel loads and internal tyre pressure are often employed (see for example Schäfer-Landefeld et al., 2004). However, it remains doubtful whether ground frozen near the surface can also buffer the ground pressures which occur when subject to such machinery, which sometimes amount to 400 kPa at a depth of 30 cm (Trautner and A. Arvidsson, 2003).

The low depths of frost penetration of no more than 7 cm also ensure favourable conditions for shallow soil tillage. A greater depth of frost penetration would presumably increase the necessary tractive force and decrease the quality of work.

3. Results and discussion

A low depth of tyre sinkage is primarily to be regarded as a horti-
cultural quality criterion. It also provides initial indications of changes in the soil structure. The mean tyre sinkages amounted to 3.2 cm (no frost), 1.4 cm (depth of frost penetration 2–3 cm) and 1.1 cm (depth of frost penetration 5–7 cm). (Fig. 1). However, the different depths of frost penetrations do not differ significantly from each other. The tyre sinkage was distributed increasingly unevenly over the track width with a decreasing depth of frost penetration, especially in the variant without frost. This can also be seen in the variation coeffi-
cients calculated amounting to 51% (no frost), 49% (depth of frost penetration 2–3 cm) and 43% (depth of frost penetration 5–7 cm). The reason for this is the sinking of the lugs which characterised the appearance of the track especially in the variant with no frost. In a light frost the lug impressions were clearly less pronounced and at a depth of frost penetration of 5–7 cm the tyre sinkage was relatively evenly distributed over the width of the track. In the latter case the sinking of the wheel was associated with a fracture of the entire frozen surface, with the load being transmitted via the spaces between the lugs. There are analogies here with the fracture of strong plough pans in the subsoil where the strength of the plough pans is exceeded (Peth et al., 2006).

Because of the intensive tillage in the autumn before the test was carried out, the soil structure before being passed over was very porous with high air capacities and a very high saturated hydraulic conductivity (Table 1). Driving over the soil that was not frozen led to a significant compaction of the entire topsoil which was reflected in the increase in dry bulk density and conversely in the decrease of air capacity and saturated hydraulic conductivity. This is also to be expected with the vertical principal stress of 135 kPa, calculated for a depth of 20 cm, which is present when driving over the unfrozen variant. The height of the ground pressure calculated here corre-
sponds approximately to Arvidsson and Keller’s (2007) measurement results for similar agricultural technology (70 kPa inflation pressure and 3300 kg wheel load) and water content equivalent to field capacity on clay soil at 30 cm depth. Overall, ground pressure exceeds precompression stress in the experiment presented here by a factor of approximately 6. In some cases, Keller and Lamandé (2010) observe lasting consolidation at ground pressure levels which correspond to precompression stress. In their investigations, precompression stress was exceeded by factor 3 at most. Very pronounced soil consolidation was recorded here. At a depth of 7–13 cm the minimum requirements of an intact soil structure required by Lebert et al. (2004) and Paul (2004) (0.08 m³/m³ air capacity and 10 cm/d saturated hydraulic conductivity) were not met in some cases. While the frozen variants were able to sig-
ificantly buffer the compressive stress when passed over, they could not completely prevent changes in soil structure. At both depths, however, the minimum requirements of a functional soil structure were definitely maintained. No appreciable differences were detected between the depths of frost penetrations. A depth of frost penetration of as little as 2–3 cm is therefore sufficient to reduce the risk of compac-
tion with a wheel load of 4000 kg and appropriately adjusted inflation pressure (80 kPa).

Table 1

<table>
<thead>
<tr>
<th>Depth 7–13 cm</th>
<th>No wheeled (control plot)</th>
<th>No frost</th>
<th>Depth of frost penetration 2–3 cm</th>
<th>Depth of frost penetration 5–7 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry bulk density (kg/m³)</td>
<td>1130 a</td>
<td>1320 b</td>
<td>1260 c</td>
<td>1250 c</td>
</tr>
<tr>
<td>Air capacity (m³/m³)</td>
<td>0.121 a</td>
<td>0.081 b</td>
<td>0.131 c</td>
<td>0.148 c</td>
</tr>
<tr>
<td>Saturated hydraulic conductivity (cm/d)</td>
<td>222 a</td>
<td>4 b</td>
<td>36 c</td>
<td>91 ac</td>
</tr>
<tr>
<td>Depth 7–23 cm</td>
<td>1260 a</td>
<td>1390 b</td>
<td>1340 c</td>
<td>1320 c</td>
</tr>
<tr>
<td>Saturated hydraulic conductivity (cm/d)</td>
<td>0.175 a</td>
<td>0.100 b</td>
<td>0.138 c</td>
<td>0.134 c</td>
</tr>
</tbody>
</table>

**References**


Horn, R., Domzal, H., Slowinska-Jurkiewicz, A., Ouwkerk van, C., 1995. Soil compac-


