Vulnerability of Bavarian silty loam soil to compaction under heavy wheel traffic: impacts of tillage method and soil water content

H. Güçlü Yavuzcan\textsuperscript{a,*}, Dietmar Matthies\textsuperscript{b}, Hermann Auernhammer\textsuperscript{c}

\textsuperscript{a}Gazi University, Department of Industrial Technology Education, Besevler, 06500 Ankara, Turkey
\textsuperscript{b}Technical University of Munich, Department of Forest Labor Science and Applied Informatics, Am Hochanger 13, D-85354 Freising, Germany
\textsuperscript{c}Technical University of Munich, Department of Crop Production Engineering, D-85354 Freising, Germany

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Abstract

Soil compaction caused by traffic of heavy vehicles and machinery has become a problem of world-wide concern. The aims of this study were to evaluate and compare the changes in bulk density, soil strength, porosity, saturated hydraulic conductivity and air permeability during sugar beet (\textit{Beta vulgaris} L.) harvesting on a typical Bavarian soil (Regosol) as well as to assess the most appropriate variable factors that fit with the effective controlling of subsequent compaction. The field experiments, measurements and laboratory testing were carried out in Freising, Germany. Two tillage systems (conventional plough tillage and reduced chisel tillage) were used in the experiments. The soil water contents were adjusted to 0.17 g g\textsuperscript{-1} (\(w_1\)), 0.27 g g\textsuperscript{-1} (\(w_2\)) and 0.35 g g\textsuperscript{-1} (\(w_3\)).

Taking the increase in bulk density, the decrease in air permeability and reduction of wide coarse pore size porosity (\(-6\) kPa) into account, it seems that CT (ploughing to a depth of 0.25 m followed by two passes of rotary harrow to a depth 0.05 m) of plots were compacted to a depth of at least 0.25 m and at most 0.40 m in high soil water (\(w_3\)) conditions. The trends were similar for “CT \(w_1\)” (low soil water content) plots. However, it seems that “CT \(w_1\)” plots were less affected than “CT \(w_3\)” plots with regard to bulk density increases under partial load. In contrast, diminishments of wide coarse pores (\(-6\) kPa) and narrow (tight) coarse pores (\(-30\) kPa) were significantly higher in “CT \(w_1\)” plots down to 0.4 m. Among CT plots, the best physical properties were obtained at medium soil water (\(w_2\)) content. No significant increase in bulk density and no significant decrease in coarse pore size porosity and total porosity below 0.2 m were observed at medium soil water content. The soil water content seemed to be the most decisive factor.

It is likely that, CS (chiselling to a depth of 0.13 m followed by two passes of rotary harrow to a depth 0.05 m) plots were less affected by traffic treatments than CT plots. Considering the proportion of coarse pore size porosity (structural porosity) and total porosity, no compaction effects below 0.3 m were found. Medium soil water content (\(w_2\)) provides better soil conditions after traffic with regard to wide coarse pore size porosity (\(-6\) kPa), air permeability (at 6 and 30 kPa water suction), total porosity and...
Problems of soil degradation resulting from compaction during crop production are now recognised as having a much wider impact than merely on the growth and yield of the crop in question. Some effects in the soil are likely to be cumulative and long lasting and may cause serious decline in the quality of the environment through a number of mechanisms.

Evidence for the widespread occurrence of soil compaction during the production of a wide range crops have been extensively searched and reviewed (Raghavan et al., 1990; Soane and van Quwerkerk, 1995; Yavuzcan et al., 2002).

Soils are three-phase systems that undergo changes as soon as the external stresses exceed the internal soil strength defined by the pre-compaction stress value. Soil compaction can result either in a higher bulk density or, when soil loading is attended with retarded water fluxes and high dynamic forces, in a completely homogenised soil characterised by a lower bulk density and a predominance of fine pores (Horn et al., 1995).

Soil compaction caused by traffic of heavy vehicles and machinery results in soil structure deterioration, both in the topsoil and in the subsoil. In soil compaction, not only pure static stress, but also dynamic forces play a role, caused by vibration of the engine and the attached implements and by wheel slip. Owing to dynamic loading, soil physical properties such as pore size distribution and pore continuity are negatively affected, which entails decreases in air and water permeability and results in increased soil strength or, in the presence of excess soil water, decreased soil strength due to kneading (Horn et al., 1995).

Changes in agricultural production techniques have been dramatic over the past few decades. Tillage intensity has increased or decreased depending on local circumstances, but in all cases there has been a steady upward trend in tractor power and machinery axle load. Increased loads are causing damage to the structure of the soil. This damage has increased the risk of soil erosion and raised the energy demand for cultivation (Chamen and Audsley, 1993). Modern agricultural machines help to reduce labor cost and to perform field operations in a precise timeframe. To counter the increasing weight of large machines, low-pressure tires have been developed. This helped to keep constant contact pressure on the soil surface and the topsoil stress. Calculations and measurements show, however, that subsoil stress depends more on axle loads than on contact pressure (Landefeld and Brandhuber, 1999). Several studies confirmed a compaction effect of heavy agricultural equipment on the subsoil, the detrimental effects of which might last for years (Alakukku and Elonen, 1995; Hakansson and Reeder, 1994).

Trafficability and load bearing capacity of bare and arable land are mainly governed by soil structure and soil strength, being primarily associated with moisture content and density. In addition, plant roots may reinforce field soils. However, the vegetation component will not be further considered here. Weather conditions such as rainfall events, drought periods, frost actions etc. cause temporal and special changes in soil moisture and pore volume. Moreover, agricultural soils are subject to loosening processes by tillage and load bearing processes by traffic during the seasonal production cycle. As a result of the above natural and man-induced changes in soil structure and strength, trafficability, in turn, follows a dynamic pattern during a year (Perdok and Kroesbergen, 1999).

The farmer’s aim during primary tillage in Germany is to produce and maintain a loosened soil by ploughing once or sometimes twice a year to the full depth of the arable layer (20–35 cm). This practice has resulted in a special soil compaction problem. It is recognised that many arable soils have a severely compacted layer below the plough depth created by the standard practice of ploughing with two tractor wheels running in the furrow. Farmers try to remove
these layers by periodic deep loosening. Tillage improves the poor macro-soil structure but seldom improves the micro-soil structure; while traffic following tillage quickly re-compacts the soil (Sommer and Zach, 1992). A cycle of tillage–traffic–tillage–traffic has developed, but the deeper the tillage the deeper the next wheel traffic compacts the weakened soil structure (Taylor, 1986).

During the passage of wheeled machines, existing voids are reduced in size and changed in shape and may become deformed, disrupted, closed or disappear completely. During compaction, at first large voids are reduced in size. A reduction in macroporosity (diameter of the voids >100 μm) by 3% (v/v) or more of total porosity is common (Kooistra and Tovey, 1994).

Short crop rotations with 60–70% cereals and 30% root crops are common on German arable soils. Those soils are tilled very intensively and therefore their ability to support traffic is poor (Sommer and Zach, 1992).

Compaction can influence crop production by changing important soil properties, particularly bulk density, soil strength, aggregate size distribution and continuity of pores. In turn, these changes affect infiltration, drainage, water availability, aeration, root exploration and nutrient uptake, all of which can have a direct bearing on crop production. To describe adequately the effect of soil compaction on crop production, it will be necessary to understand and describe changes in soil conditions caused by machinery traffic.

The introduction of six-row sugar beet harvesters with total loads of approximately 35 Mg on two axles caused a major concern among Swedish sugar beet rowers regarding the risk of subsoil compaction (Arvidsson, 2001). Due to high loads on the wheels of sugar beet harvesters, soil compaction may occur which reduces air permeability, capacity of water retention and water movement. This is primarily dependent on the machine load and therefore can be influenced by tire sizes only to a small degree (Gruber and Brokjans, 1991).

Gysi (2001) investigated the impact of a single pass with sugar beet harvester on the soil properties of an unploughed Eutric Cambisol and observed that the compaction caused by a single pass with a load of 107 and 108 kN was restricted to the upper 25 cm of the soil. Arvidsson (2001), observed that heavy axle loads during sugar beet harvest in southern Sweden could often cause subsoil compaction, including increased penetration resistance and reduced hydraulic conductivity, which can be seen as a long-term threat to soil productivity. He also concluded that, the data concerning saturated hydraulic conductivity may be useful for modelling the effects of subsoil compaction, for example on erosion and denitrification, since little such data was available in the literature.

The main objectives of this study were:

1. to evaluate and compare the changes in bulk density, soil strength, coarse pore size porosity, total porosity, saturated hydraulic conductivity and air permeability during sugar beet (Beta vulgaris L.) harvesting on a typical Bavarian soil;
2. to compare the impacts of compaction parameters due to variable factors namely; three different soil water content, two different types of soil preparation and two different harvester loadings;
3. to assess the most appropriate variable factors that fit with the effective controlling of subsequent compaction in sugar beet (B. vulgaris L.) production.

2. Materials and method
2.1. Site, soil and experimental design

Experiments were carried out at the Dürnast Research Farm of Technical University of Munich, 40 km north of Munich. The climate of the region is characterised by a 30-year mean annual temperature of 7.4 °C and a 30-year annual precipitation of 803 mm (Sommer et al., 2003). The soil in the field was classified as perfectly drained medium textured silty loam of the Bavarian series (Regosol) with 130, 580 and 290 g kg\(^{-1}\) of clay, silt and sand, respectively. The plastic and liquid limits of the experimental area were assessed as 0.19 and 0.37 g g\(^{-1}\), respectively. The effects of two different tillage practices, two wheel loads and three soil water contents were examined. The treatments were arranged in a randomised split plot design with tillage method as the main factor and soil water content and wheel load as the secondary factors. Four replicates were carried...
The field was under conventional tillage for some time. During the last 4 years conventional cultivation method with ploughing were practiced in the field. There was no stubble on plots. Climatic data were obtained from the official weather station regularly. Average monthly climatic data during the field operation and vegetation period are given in Table 1.

2.2. Field operations

Four wheel drive MB Trac. Turbo 900/90 PS tractor weighing 46 kN was used for field operations including tillage, seedbed preparation, drilling, fertilising and spraying. Both front and rear axle were fitted with 11.2.R.32 (12.5 A8***PR 1L) tires, inflated to 340 kPa.

Two tillage systems were performed in the experimental plots as mentioned below:

1. CT (ploughing to a depth of 0.25 m followed by two passes of a rotary harrow to a depth of 0.05 m);
2. CS (chiselling to a depth of 0.13 m followed by two passes of a rotary harrow to a depth of 0.05 m).

Above mentioned practices were fulfilled in the late April. In the early May, monogerm sugar beet seeds calibrated to 3.5–4.75 mm were sowed with a 12 row pneumatic drill. In the mid of May, fertilising (with fertiliser weighing 0.75 Mg), late May, first spraying (with a sprayer weighing 1.4 Mg) and early June, second spraying were accomplished, respectively. During fertilising, with a total load of approximately 39.8 kN on the rear axle, a weight distribution of 29% front and 71% rear was achieved. For spraying operation, rear axle load was 3.8 kN providing a weight distribution of 37% front and 63% rear loads.

As, working widths of both fertiliser and sprayer were 15 m, controlled traffic was applicable. Thus, the traffic lanes during fertilising was performed in the mid of each row and subsequent passes were made exactly over the established traffic lanes. Spraying rate was 400 l ha⁻¹.

The low soil water content was achieved by covering the soil surface with a plastic sheet for 6 weeks to prevent the infiltration of rain (Gysi et al., 1999). Thus, on late August 1999, approximately 6 weeks prior to harvesting, two successive covers of 12 m² (3 m × 4 m) on each plot were covered with plastic sheets. The remained test area was exposed to natural precipitation.

Two days before harvesting, in mid-October 1999, soil water contents in the test area were checked. The average water content of the soil under plastic covers was found to be approximate to the plastic limit (0.17 g g⁻¹). One of the successive covers on each plot remained without any procedure whilst the other was detached and watered until reaching approximately 0.27 g g⁻¹. Since, high amount of rainfall was occurred in the first week of October, the soil water content of the area exposed to natural precipitation was close to liquid limit (0.35 g g⁻¹). Consequently, three different soil water contents were achieved in each plot (w₁ = 0.17 g g⁻¹, w₂ = 0.27 g g⁻¹, w₃ = 0.35 g g⁻¹). Soil water content was measured gravimetrically before traffic treatments.

A six-row (3 m working width) self-propelled sugar beet harvester weighing 243.1 kN (69.95 kN rear axle load and 168.54 kN front axle load) was used for the harvesting process. The rear and front axle was fitted with 800/65 R 32-172 A8 tires inflated to 230 kPa. The track width was 2.20 m for each tire. Partial (50%) loading of the harvester corresponded

### Table 1

Average monthly climatic data during the field operation and vegetation period (http://www.stmelf.bayern.de/lbp/agm/station/agm_start.html)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>March</th>
<th>April</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>August</th>
<th>September</th>
<th>October</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temperature, 2 m (°C)</td>
<td>5.05</td>
<td>8.42</td>
<td>14.11</td>
<td>14.95</td>
<td>18.04</td>
<td>16.94</td>
<td>15.69</td>
<td>8.35</td>
</tr>
<tr>
<td>Air temperature, 20 cm (°C)</td>
<td>4.65</td>
<td>8.22</td>
<td>14.11</td>
<td>15.08</td>
<td>18.00</td>
<td>16.81</td>
<td>15.36</td>
<td>8.15</td>
</tr>
<tr>
<td>Soil temperature, 5 cm (°C)</td>
<td>4.79</td>
<td>9.36</td>
<td>16.24</td>
<td>19.14</td>
<td>21.65</td>
<td>20.11</td>
<td>17.46</td>
<td>9.49</td>
</tr>
<tr>
<td>Soil temperature, 20 cm (°C)</td>
<td>4.26</td>
<td>8.41</td>
<td>14.67</td>
<td>18.11</td>
<td>20.42</td>
<td>19.35</td>
<td>16.36</td>
<td>10.60</td>
</tr>
<tr>
<td>Soil temperature, 50 cm (°C)</td>
<td>3.90</td>
<td>7.47</td>
<td>12.74</td>
<td>16.70</td>
<td>18.77</td>
<td>18.55</td>
<td>16.69</td>
<td>11.99</td>
</tr>
<tr>
<td>Relative humidity, 2 m (% v/v)</td>
<td>85.30</td>
<td>82.74</td>
<td>81.38</td>
<td>80.78</td>
<td>80.22</td>
<td>80.82</td>
<td>83.52</td>
<td>88.25</td>
</tr>
<tr>
<td>Wind velocity, 2.5 m (m s⁻¹)</td>
<td>1.47</td>
<td>1.44</td>
<td>1.51</td>
<td>1.10</td>
<td>1.20</td>
<td>0.78</td>
<td>0.90</td>
<td>1.08</td>
</tr>
<tr>
<td>Cumulative rain (mm)</td>
<td>50.3</td>
<td>77.6</td>
<td>116.1</td>
<td>84.2</td>
<td>80.0</td>
<td>62.3</td>
<td>70.6</td>
<td>39.3</td>
</tr>
</tbody>
</table>
with the rear axle load of 109.58 kN and front axle
load of 208.17 kN. In case of full (100%) loading, axle
loads were 159.03 and 228.07 kN, respectively.
Harvester was operated as to different row positions
rather than successive row positions to accomplish at
least one pass with partial (50%) and full load on each
different soil water content range each differently
tilled plot. Adjustment of the loading was done by
removing the excessive load into a container. An
adjacent plot without wheel traffic was used as control
plot.

2.3. Field measurements

At the beginning of the field experiments, soil
samples down to 40 cm were taken from four locations
of the field to conduct soil texture, sedimentation and
plastic limit analysis.

Soil bulk density, soil water content and penetration
resistance were measured periodically on each plot till
harvesting. Measurement of controlled traffic rows
took place at the centre of wheel tracks. All
measurements related with these properties were
performed with regard to row position rather than
randomly within each plot in order to reduce sampling
error.

After harvesting the samplings were performed at
each differently tilled plot, soil water content and
harvester loading chosen. Undisturbed soil cores
from 0.2 m down to 0.4 m in 0.05 m were taken
(five samples in each depth range in each treatment)
for the laboratory analysis of saturated hydraulic
conductivity, coarse pore size porosity (structural
porosity) and air permeability. The soil cores were
stored at 4°C until laboratory measurements were
performed.

Soil bulk density and soil water content were
measured using CPN Stratagauge (twin probe gamma
day density meter) from 0 to 0.5 m in 0.05 m
increments (Model MC-S-24, Campbell Pacific
Nuclear Corp., Martinez, CA) at three locations per
plot. The calibration of Stratagauge was done by the
manual core method taken in each plot down to 0.5 m.
Before stratagauge process, a cylinder was driven into
the soil with a hammer attachment in order to bore a
same size hole.

Penetration resistance was measured with a hand
operated recording type electronic penetrometer
(penetrologger) having a 30° steel cone of 1 cm²
base area, and values were recorded at each 0.05 m
interval down to 0.4 m (Model P1.52, Eijkelkamp
Agrisearch Equipment, The Netherlands). Ten inser-
tions were made in each plot.

To calculate mean ground pressure, a plywood
sheet was placed on a concrete surface and the
combine was driven onto it. Spray paint was then
applied and the combine removed. To estimate the
actual contact area, total length and width of the
unpainted area were measured and the area was
approximated as an ellipse. The wheel load, contact
area and average estimated ground pressure of the
front and rear wheels of sugar beet harvester for
empty, partial and full loading conditions are given in
Table 2.

2.4. Laboratory analysis

Saturated hydraulic conductivity was measured
with a closed system soil water permeameter having a
capacity of 20 samples (Model 09.02, Eijkelkamp
Agrisearch Equipment, The Netherlands). Before the
measurements, undisturbed soil samples taken in soil

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Empty</th>
<th>Partial</th>
<th>Full</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheel load (kN)</td>
<td>Front 84.27</td>
<td>Rear 34.98</td>
<td>Front 104.09</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>54.79</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Rear 114.06</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>79.52</td>
</tr>
<tr>
<td>Contact area (m²)</td>
<td>Front 0.49</td>
<td>Rear 0.457</td>
<td>Front 0.543</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.572</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Rear 0.659</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.726</td>
</tr>
<tr>
<td>Tyre inflation pressure (kPa)</td>
<td>Front 230</td>
<td>Rear 230</td>
<td>Front 230</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>230</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Rear 230</td>
</tr>
<tr>
<td>Average contact pressure (kPa)</td>
<td>Front 171.63</td>
<td>Rear 76.53</td>
<td>Front 191.69</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>95.79</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Rear 173.04</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>109.53</td>
</tr>
</tbody>
</table>
sample rings were settled down into water basin for 24 h and afterwards attached to the sample ring cartridge. The obtained permeability factors were classified as to Kuntze et al. (1994).

After saturation, the samples in the laboratory were drained by a ceramic pressure plate outflow method with pressures of 6 and 30 kPa. Proportion of pore size classes were estimated basing on the water desorption characteristics (Tebrügge and Düring, 1999). Accordingly, difference of soil water contents between 0 and 6 kPa water suction was determined as wide coarse pore size porosity, between 6 and 30 kPa water suction as narrow (tight) coarse pore size porosity and remained from the total porosity as medium and fine pore size porosity (Hartge, 1978). Total pore volume was obtained by gravimetric method.

Air permeability was measured by a air permeameter working on a principle of passing a controlled flow of air (under constant pressure) through the soil sample (Gysi et al., 1999). Air permeability factors were classified as to Kuntze et al. (1994).

As mentioned before, soil samples taken from four locations within the experimental site were exposed to wet sieving for the assessment of soil texture (with metal sieves having 6.3, 2.0, 0.63, 0.2 and 0.063 mesh sizes). To obtain the accurate determination of the particle size distribution of the smallest fractions, hydrometer method was applied (Kuntze et al., 1994).

2.5. Statistical analysis

The effects of tillage system, wheel traffic and moisture content on bulk density, penetration resistance, porosity, air permeability, water permeability and pore size distribution were evaluated by the analysis of variance with tillage as the main effect, soil water content as the first split plot and depth as the second split plot. Comparisons of mean values were accomplished using least significant differences (LSD) at $\alpha \leq 0.05$.

3. Results

3.1. Penetration resistance

Cone penetrometer readings performed during the vegetation period are shown in Table 3. The first readings were done 1 week after fertiliser application and second readings were done 3 days after second spraying. There were no field operations between the

<table>
<thead>
<tr>
<th>Time</th>
<th>Tillage method</th>
<th>Plot</th>
<th>Penetration resistance (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>0–0.1 m</td>
</tr>
<tr>
<td>18.05&lt;sup&gt;d&lt;/sup&gt;</td>
<td>CS</td>
<td>NWT</td>
<td>1097 b</td>
</tr>
<tr>
<td></td>
<td></td>
<td>WT</td>
<td>1760 a</td>
</tr>
<tr>
<td></td>
<td>CT</td>
<td>NWT</td>
<td>763 c</td>
</tr>
<tr>
<td></td>
<td></td>
<td>WT</td>
<td>1726 a</td>
</tr>
<tr>
<td>06.06&lt;sup&gt;e&lt;/sup&gt;</td>
<td>CS</td>
<td>NWT</td>
<td>1092 b</td>
</tr>
<tr>
<td></td>
<td></td>
<td>WT</td>
<td>1680 a</td>
</tr>
<tr>
<td></td>
<td>CT</td>
<td>NWT</td>
<td>1054 b</td>
</tr>
<tr>
<td></td>
<td></td>
<td>WT</td>
<td>1772 a</td>
</tr>
<tr>
<td>01.07&lt;sup&gt;f&lt;/sup&gt;</td>
<td>CS</td>
<td>NWT</td>
<td>1584 b</td>
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<tr>
<td></td>
<td></td>
<td>WT</td>
<td>2460 a</td>
</tr>
<tr>
<td></td>
<td>CT</td>
<td>NWT</td>
<td>1430 b</td>
</tr>
<tr>
<td></td>
<td></td>
<td>WT</td>
<td>2378 a</td>
</tr>
</tbody>
</table>

<sup>a</sup> CS: chisel tilled plot, CT: ploughed plot.
<sup>b</sup> NWT refers to the non-wheel track zone and WT refers to tracked zone.
<sup>c</sup> Numbers within each column followed by the same letter are not significantly different at 0.05 confidence level.
<sup>d</sup> LSD<sub>0.05</sub> = 179 kPa.
<sup>e</sup> LSD<sub>0.05</sub> = 220 kPa.
<sup>f</sup> LSD<sub>0.05</sub> = 346 kPa.
second and third readings. Due to high precipitation in June, the process of drying tended to alleviate compaction. Thus, the third readings were significantly higher than those of second readings at all depths and tillage methods concerned. Another important note is that, the penetration resistance of non-wheel tracks in CT plots significantly increased at 0–0.1 and 0.1–0.2 m depth in the second reading.

### Table 4
Penetration resistance (kPa) of different treatments after harvesting at partial harvester load

<table>
<thead>
<tr>
<th>Soil water content&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Treatment&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Tillage&lt;sup&gt;c&lt;/sup&gt; method</th>
<th>Penetration resistance (kPa)&lt;sup&gt;d&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>0–0.1 m</td>
</tr>
<tr>
<td>w&lt;sub&gt;3&lt;/sub&gt;</td>
<td>WT</td>
<td>CS</td>
<td>926 ef</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CT</td>
<td>835 f</td>
</tr>
<tr>
<td></td>
<td>NWT</td>
<td>CS</td>
<td>933 ef</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CT</td>
<td>812 f</td>
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<td>1681 b</td>
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<td></td>
<td>CT</td>
<td>1375 c</td>
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<td>NWT</td>
<td>CS</td>
<td>1110 de</td>
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<td>1156 d</td>
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<td>WT</td>
<td>CS</td>
<td>2162 a</td>
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<td></td>
<td></td>
<td>CT</td>
<td>2126 a</td>
</tr>
<tr>
<td></td>
<td>NWT</td>
<td>CS</td>
<td>1677 b</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CT</td>
<td>1680 b</td>
</tr>
</tbody>
</table>

<sup>a</sup> w<sub>3</sub>: high soil water content close to liquid limit, w<sub>2</sub>: medium soil water content between liquid and plastic limit, w<sub>1</sub>: low soil water content close to plastic limit.

<sup>b</sup> WT: wheel track zone, NWT: non-wheel track zone.

<sup>c</sup> CS: chisel tilled plot, CT: ploughed plot.

<sup>d</sup> Numbers within each column followed by the same letter are not significantly different at 0.05 confidence level (LSD<sub>0.05</sub> = 205 kPa).

<sup>e</sup> Could not be determined due to high soil strength.

### Table 5
Penetration resistance (kPa) of different treatments after harvesting at full harvester load

<table>
<thead>
<tr>
<th>Soil water content&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Treatment&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Tillage&lt;sup&gt;c&lt;/sup&gt; method</th>
<th>Penetration resistance (kPa)&lt;sup&gt;d&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>0–0.1 m</td>
</tr>
<tr>
<td>w&lt;sub&gt;3&lt;/sub&gt;</td>
<td>WT</td>
<td>CS</td>
<td>820 efg</td>
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<tr>
<td></td>
<td></td>
<td>CT</td>
<td>932 ef</td>
</tr>
<tr>
<td></td>
<td>NWT</td>
<td>CS</td>
<td>729 fg</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CT</td>
<td>687 g</td>
</tr>
<tr>
<td>w&lt;sub&gt;2&lt;/sub&gt;</td>
<td>WT</td>
<td>CS</td>
<td>1449 c</td>
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<tr>
<td></td>
<td></td>
<td>CT</td>
<td>1613 c</td>
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<tr>
<td></td>
<td>NWT</td>
<td>CS</td>
<td>1210 d</td>
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<tr>
<td></td>
<td></td>
<td>CT</td>
<td>962 e</td>
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<tr>
<td>w&lt;sub&gt;1&lt;/sub&gt;</td>
<td>WT</td>
<td>CS</td>
<td>2533 a</td>
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<td></td>
<td></td>
<td>CT</td>
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<td>CS</td>
<td>1887 b</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CT</td>
<td>2050 b</td>
</tr>
</tbody>
</table>

<sup>a</sup> w<sub>3</sub>: high soil water content close to liquid limit, w<sub>2</sub>: medium soil water content between liquid and plastic limit, w<sub>1</sub>: low soil water content close to plastic limit.

<sup>b</sup> WT: wheel track zone, NWT: non-wheel track zone.

<sup>c</sup> CS: chisel tilled plot, CT: ploughed plot.

<sup>d</sup> Numbers within each column followed by the same letter are not significantly different at 0.05 confidence level (LSD<sub>0.05</sub> = 214 kPa).

<sup>e</sup> Could not be determined due to high soil strength.
compared to the first reading. This implies the susceptibility of CT plots to compaction. At the third readings, it can be clearly seen that, there were no considerable difference between CT and CS plots. There was more compaction after sowing than after seedbed preparation, probably because of the relatively high wheel loading.

Cone penetrometer readings at partial (50%) and full (100%) harvester loadings due to soil water content and tillage methods are shown in Tables 4 and 5, respectively. As seen from the tables, the penetrometer data are inherently very variable. Due to its high strength and hard structure, readings could not be performed at low soil water contents (w₁) between 0.1 and 0.4 m. At 0–0.1 m, the highest penetration resistances were obtained in low soil water conditions of which were significantly higher than those of medium (w₂) and high (w₃) soil water conditions. Apart from this, penetrometer readings in “w₂” plots were also significantly higher than those of “w₃” plots. It is surprising that, there were no significant differences between the wheel track and non-wheel track zones in the topsoil (0.1 m) of “w₃” plots, under partial load. However, in case of full load on high soil water contents (w₃), CT plots exhibited significant changes in the top 0.1 m.

The impacts of wheel load were not visible for CS plots at high soil water content (w₃) and partial loading in 0.1–0.2 m depth. In contrast, considerable differences can be seen in CT plots (NWT and WT). Impacts of wheel loads are also visible in medium soil water conditions both at CS and CT treatments under partial load. The increments were higher in CT plots (30%) plots than in CS plots (13%). On the other side, considerable differences can be visible at 100% loading between non-tracked and tracked zones at 0.1–0.2 m depth. Generally, in comparison to partial load, full load led to more strict differences between tracked and non-tracked zones. During full loading, wheel tracks led to an increase of 44 and 41% in CT plots at 0.1–0.2 m, respectively for high and medium soil water contents. The increments were rather low for CS treatments at the same depth (17 and 12%, respectively, for high and medium soil water contents). Wheel track induced penetration resistance increases were 35 and 17%, respectively, at 0.2–0.3 m in CT plots. In particular, traffic induced increments were lower under partial loading.

Significantly higher penetration resistance of the NWT plots having low soil water content (w₁) can be attributable to the drying/shrinking process. However, wheel traffic impacts are also visible in w₁ plots as indicated by significant differences relative to control plots at 0–0.1 m. There was no tillage induced differences in w₁ plots at 0–0.1 m.

3.2. Bulk density

Figs. 1 and 2 illustrate typical dry bulk density profiles measured before and after wheeling for both tillage systems corresponding to different soil water content profiles. Field data present a variability that reflects soil structure heterogeneity of a plough layer. Traffic significantly affected the bulk density to a depth of maximum 0.3 m. At both loading conditions, the greatest significant differences with the control plots occurred at the topsoil (0–0.1 m). The partial loading caused an increase in topsoil dry bulk density of about 0.18–0.39 Mg m⁻³ in CT and 0.11–0.26 Mg m⁻³ in CS plots. Under full loading, these rates were 0.27–0.28 and 0.09–0.23 Mg m⁻³, respectively.

In medium (w₂) soil water content, compaction was restricted in the top 0.1 m except full load in CT plots. Full load in CT plots caused a significant increase in bulk density down to 0.15 m. There was no significant difference between “w₁” and “w₃” plots under full load in both tillage systems. However, under partial load, significant differences between these soil water contents can be observed down to 20 cm particularly in CT plots.

Only in “w₃” (high soil water content) plots under partial loading did wheel load cause significant bulk density with regard to control at a depth of 0.3 m. In other cases of high soil water conditions, compaction effects were restricted at 0.25 m depth. The impacts of high soil water content can be visible especially in CT plots with significantly higher differences compared to control plots down to 25–30 cm. The results imply the impact of soil water content on compaction, induced by wheeling especially in CT plots.

Due to the smaller contact area, the ground pressure was approximately 18 kPa higher at 50% loading than 100% loading in the front wheels of the harvester. However, this difference is balanced by the rear wheels, which are approximately 14 kPa higher in
100% loading. With regard to this observation, it is not surprising that bulk density was higher in the topsoil of partial load experiments than in full load experiments particularly in “w3” plots.

The risk for compaction is more visible for “CT w3” plots down to 25–30 cm depth. In this respect, medium soil water (w2) conditions have the lowest risk. There were only slight differences between the bulk densities under partial and full load. For CS plots, significant increases were limited to 0.10 m at medium soil water conditions and 0.15 m at low soil water conditions. For wet conditions the risk was extended approximately to 20 cm.

3.3. Porosity

Variation of wide coarse pore size porosity (w3) (−6 kPa), narrow (tight) coarse pore size porosity (w1) (−30 kPa) and total porosity at the subsoil (0.2–0.4 m) under partial load is given in Table 6. The impacts of soil water content and tillage system on wide coarse pore size porosity (w3) were found to be significant (P < 0.01). Accordingly, the significant changes can be seen at 0.2–0.3 m depth in “w3” and “w1” plots. Although, the control plots of CT treatments have 40% (v/v) higher wide coarse pore size porosity than CS plots, after traffic treatments the proportion was decreased by 93% (v/v) in high soil water conditions and 110% (v/v) in low soil water conditions at 0.2–0.3 m depth. These reductions were 52 and 19% (v/v), respectively, in CS plots. At 0.3–0.4 m depth, the differences were relatively small but still measurable and significant for “CT w1” and “CT w3” plots. For CS plots, significant differences relative to control plot were observed only in high soil water (w3) conditions at 0.2–0.3 m depth. In other
cases of CS treatments, the differences were insignificant. The highest reductions at this depth were found in “CT w3” plots (30%, v/v decrease) and in “CT w1” plots (43%, v/v decrease). Generally, decrease in the proportion of wide coarse pores has increased the proportion of medium and fine sized pores of the total pore volume (results not shown).

The impacts of tillage system and soil water content on the proportion of narrow (tight) coarse pore size porosity (−30 kPa) and total porosity were found to be significant ($P < 0.01$). The proportion of narrow coarse pores in CT control plots was twice as high as CS control plots at 0.2–0.3 m depth. This is probably due to the deep loosening of the soil in CT treatments. For CT plots, significant differences with regard to narrow coarse pore size porosity occurred only in low soil water conditions at 0.2–0.4 m depth. This could be attributable to the shrinking of the soil during drying process. In CS plots there was no significant difference. Below 0.3 m depth, except “CT w1” plots, no significant changes were observed.

The variation in the total porosity was rather low corresponding to the changes in bulk density at 0.2–0.4 m depth. At 0.2–0.3 m depth, the significant decreases were occurred in “CT w3” plots by 8% (v/v) and “CT w1” plots by 7% (v/v). In CS plots, there was no significant difference relative to control at all soil water contents. For 0.3–0.4 m depth, no significant decrease in total porosity was measured.

3.4. Saturated hydraulic conductivity and air permeability

Variation of saturated hydraulic conductivity and air permeability (at 6 and 30 kPa water suction) under partial load is shown in Table 7. Tillage method, soil water content and traffic did not have significant effect on saturated hydraulic conductivity at 0.3–0.4 m
depth. At 0.2–0.3 m depth, saturated hydraulic conductivity of control CT plots were considerably higher than control CS plots, confirming the measurements of coarse pore size porosity. Nevertheless, after wheeling, no statistical significance was achieved between CT and CS treatments and among soil water contents. The saturated hydraulic conductivities of CS plots were reduced permanently to 10% or even lower of the original conductivity of control plots in high and low soil water conditions. These reductions were to

| Table 6 | Proportion of wide coarse pores (−6 kPa), narrow (tight) coarse pores (−30 kPa) and total porosity (% v/v) measured on undisturbed soil cores after partial harvester load |
|---------|---------------------------------|---------------------------------|---------------------------------|
| Treatmenta | Tillageb method | Wide coarse pores (−6 kPa)c | Narrow coarse pores (−30 kPa)c | Total porosityc |
|          |                   | 0.2–0.3 m | 0.3–0.4 m | 0.2–0.3 m | 0.3–0.4 m | 0.2–0.3 m | 0.3–0.4 m |
| WT (w3)  | CS                | 5.27 c    | 9.223 b   | 1.21 b    | 2.00 b    | 40.70 bc  | 37.33 d   |
|          | CT                | 5.84 bc   | 7.678 c   | 2.33 a    | 2.88 a    | 42.28 bc  | 42.74 ab  |
| WT (w2)  | CS                | 7.08 b    | 8.792 bc  | 1.38 b    | 2.18 b    | 41.23 bc  | 43.32 ab  |
|          | CT                | 10.69 a   | 8.127 bc  | 2.35 a    | 1.89 bc   | 43.82 ab  | 44.62 a   |
| WT (w1)  | CS                | 6.77 b    | 9.608 ab  | 1.64 b    | 2.25 ab   | 41.91 bc  | 39.75 bc  |
|          | CT                | 5.37 bc   | 4.397 d   | 1.68 b    | 1.32 c    | 42.80 b   | 40.16 bc  |
| Controld | CS                | 8.03 b    | 11.18 a   | 1.41 b    | 1.89 bc   | 40.29 c   | 38.87 cd  |
|          | CT                | 11.29 a   | 10.02 ab  | 2.81 a    | 2.34 ab   | 45.85 a   | 41.74 b   |
| LSD0.05  |                   | 1.49      | 0.64      | 2.17      |           |           |           |

a WT: wheel track, w3: high soil water content close to liquid limit, w2: medium soil water content between liquid and plastic limit, w1: low soil water content close to plastic limit.
b CS: chisel tilled plot, CT: ploughed plot.
c Numbers within each column followed by the same letter are not significantly different at 0.05 confidence level.
d Control group refers to the non-wheel track zone exposed to natural precipitation.

Table 7
Saturated hydraulic conductivity and air permeability (at 6 and 30 kPa air pressure) measured on undisturbed soil cores after partial harvester load

| Table 7 | Saturated hydraulic conductivity (m day−1) and air permeability (×10−8 cm s−1) measured on undisturbed soil cores after partial harvester load |
|---------|-------------------------------------------------|---------------------------------|---------------------------------|
| Treatmenta | Tillageb method | Saturated hydraulic conductivityc | Air permeability (×10−8 cm s−1)c |
|          |                   | 0.2–0.3 m | 0.3–0.4 m | 0.2–0.3 m | 0.3–0.4 m | 0.2–0.3 m | 0.3–0.4 m |
| WT (w3)  | CS                | 0.33 c    | 1.10 a    | 3.6 b     | 27.6 bc   | 20.5 c    | 35.3 d    |
|          | CT                | 0.84 c    | 0.62 a    | 8.0 b     | 23.2 bc   | 48.5 c    | 39.8 d    |
| WT (w2)  | CS                | 0.83 c    | 1.69 a    | 13.0 b    | 76.0 ab   | 30.8 c    | 129.0 bc  |
|          | CT                | 1.26 c    | 1.43 a    | 43.4 ab   | 46.6 bc   | 56.0 c    | 49.0 d    |
| WT (w1)  | CS                | 0.39 c    | 1.61 a    | 9.0 b     | 60.0 abc  | 16.5 c    | 72.5 cd   |
|          | CT                | 0.73 c    | 0.90 a    | 7.4 b     | 28.0 bc   | 50.5 c    | 22.3 d    |
| Controld | CS                | 3.63 b    | 1.05 a    | 70.0 a    | 97.0 a    | 206.5 b   | 196.3 b   |
|          | CT                | 4.91 a    | 1.46 a    | 84.0 a    | 95.3 a    | 282.2 a   | 274.5 a   |
| LSD0.05  |                   | 1.21      | 44        | 75        |           |           |           |

a WT: wheel track zone, w3: high soil water content close to liquid limit, w2: medium soil water content between liquid and plastic limit, w1: low soil water content close to plastic limit.
b CS: chisel tilled plot, CT: ploughed plot.
c Numbers within each column followed by the same letter are not significantly different at 0.05 confidence level.
d Control group refers to the non-wheel track zone exposed to natural precipitation.
the 17 and 15% of the control plot, respectively, for CT plots. The poorer hydraulic conductivities were obtained in CS \(w_1\) and CS \(w_3\) plots classified as average according to Kuntze et al. (1994). The saturated hydraulic conductivity in any of the treatments was lower than the critical limit of \(1.0 \times 10^{-6} \text{ m s}^{-1}\) as indicated by Lipiec and Hatano (2003).

Soil water content and traffic had considerable impacts on air permeability \((P < 0.01)\). At 6 kPa water suction, there was no significant difference between the control groups. Thus, tillage induced effects at 6 kPa water suction was insignificant. After wheeling, except “CT \(w_2\)” plots, considerable changes were occurred relative to control plots. However, differences within each group were insignificant. Due to the deep loosening of the soil down to 0.25 m, CT plots have higher air permeability in overall evaluation at 0.2–0.3 m depth except low soil water conditions. After wheeling, the air permeability of CT treatments was diminished by 85% in “\(w_3\)” plot, 48.33% in “\(w_2\)” plot and 91.19% in “\(w_1\)” plot relative to the control group at a depth of 0.2–0.3 m. These reductions were 94.8, 81.42 and 87.14%, respectively, in CS treatments. In both CT and CS treatments medium soil water conditions provided better air permeability. Irrespective of the tillage system used, air permeability in high and low soil water content did not differ from each other significantly, most of which are classified as poor according to Kuntze et al. (1994). Tillage induced effects can be visible at 30 kPa water suction as shown by significantly higher air permeability of CT control plots than CS control plots down to 0.4 m depth. In particular, traffic caused significant reduction in air permeability. However, differences within each compaction group were insignificant. Only the CS plots having medium soil water content were not affected by traffic significantly at 0.3–0.4 m depth. The air permeability in none of the treatments was lower than \(1.0 \times 10^{-12} \text{ m}^2\) suggested as the critical lower limit (Lipiec and Hatano, 2003) for agronomic performance of poorly drained soils.

3.5. Rut depth

Rut depth, which can be taken as a measure of soil surface damage, showed distinctly lower values in “\(w_1\)” plots compared to “\(w_3\)” plots (Fig. 3). Tillage system and soil water content had considerable effects on rut dept. The highest rut depths were obtained in “\(w_3\)” plots under full loading. Soil surface damage was significantly higher in “CT \(w_3\)” plots under partial and full load.

4. Discussions

Considering the clay content and the packing density of the experimental area (medium prior to
traffic treatment), the susceptibility of our soil to compaction can be classified as “high” according to Jones et al. (2003). With regard to this observation, in case of minimal subsoil protection, soils having high water content become extremely vulnerable and low water content become moderately vulnerable to compaction. The recommended average contact pressure in very vulnerable and moderately vulnerable soils ranges between 100 and 150 kPa (Jones et al., 2003). These recommended values have been exceeded both in partial and full load treatments.

A very negative trend is the fact that wheel loads are still increasing. The International Working Group on Soil Compaction by Vehicles with high axle load considered wheel loads of 50 kN as “high”. Nowadays, wheel loads up to 100–120 kN are used in agriculture on wet and moist soils during sugar beet harvesting. With these high wheel loads and low tire inflation pressures are not an option anymore to prevent subsoil compaction because even if largest tires available are used tire inflation pressures of more than 160 kPa are needed to bear these wheel loads (Van den Akker et al., 2003).

The load was unevenly distributed onto the four wheels and due to rising of the lifting units as well as to the laterally extended unloading elevator. For this reason, the highest load was applied to the right front wheel. The ground pressure was approximately 18 kPa higher at partial loading than full loading in the front wheels of the harvester. This confirms the results of Gysi et al. (1999). Thus, the increasing wheel loads from partial to full did not lead to a significant increase in most cases as mentioned by Röhring et al. (1997).

The axle load and tillage treatments had significant effects on soil bulk density and penetration resistance. This does not fit in well with the results of Lal and Ahmadi (2000) indicating that axle load treatments did not have any significant effect on bulk density and penetration resistance. Considering only the increases in bulk density, the compaction caused by a single pass with a wheel load of 10.61 and 11.62 Mg was restricted maximum to the upper 0.3 m of “CT w3” plots and 0.2 m of “CS w3” plots. Below this depth, no compaction effects with regard to bulk density increase were measured. This confirms the observations of Gysi (2001). Arvidsson (2001) found no statistically significant differences between one pass with a six-row sugar beet harvester and the control treatment for any of the soil physical parameters investigated. Our findings do not comply with this result. Since most of the results were obtained in the field during harvest, they clearly demonstrate that subsoil compaction may occur under normal field conditions. The soil water content seemed to be the most decisive factor as mentioned by Arvidsson et al. (2001) and Defossez et al. (2003). With regard to the results of other researchers these findings are quite surprising. Alakkuku et al. (2003) and Hakansson and Reeder (1994) reported considerable compaction with comparable or smaller loads down to deeper soil layers using lower wheel loads. Model simulations by Arvidsson et al. (2003) showed that for sandy clay loam subsoil the risk is more than 60% that the subsoil is compacted in early autumn by a wheel load of 80 kN. Arvidsson et al. (2001) measured compaction to more than 0.5 m depth under heavy sugar beet harvesters during normal field conditions in autumn. Particularly, “CT w3” plots have approximately 0.3 Mg m\(^{-3}\) increase in bulk density after traffic in the 0.1 m layer. Defossez et al. (2003) mentioned that, a compaction about 0.3 Mg m\(^{-3}\) may induce a decrease of 50% oxygen diffusion rate.

Nevertheless, wide coarse pore size porosity and air permeability measurements may indicate a susceptibility to compaction down to a maximum depth of 0.4 m after traffic with six-row sugar beet harvester under “CT w3” and “CT w1” plots. This observation to a limited extent can be valid for “CS w3” and “CS w1” plots as indicated by the air permeability decreases down to 0.4 m. Apparently, soil pore system was substantially affected by traffic. The results were also consistent with most previous reports on subsoil compaction. For example, the trafficking of a moist Vertisol by a laden (wheat) harvester gave a significantly poorer structural state to a maximum depth of 0.4 m (Radford et al., 2000). Arvidsson et al. (2001) applied 35 Mg harvester load under wet conditions and this caused compaction to a depth of 0.5 m. Arvidsson (2001) declared that, high axle load traffic (10 Mg axle load, 300 kPa inflation pressure) most often caused detectable differences in soil physical properties to around 0.50 m depth on soils with clay content ranging from 2 to 65%. Alakkuku et al. (2003) indicated that the risk of subsoil compaction is high when the exerted stresses are higher than the bearing capacity of soil and soil water content decreases the bearing capacity of soil water.
This result can be visible especially at bulk density, saturated hydraulic conductivity, air permeability and coarse pore size porosity measurements. Since compaction mainly affects the largest pores, which govern the saturated hydraulic conductivity, the latter parameter may be a more sensitive indicator of compaction than bulk density as indicated by Arvidsson (2001).

Decreasing tillage intensity from the conventional system to CS generally resulted in an increase in bulk density of the upper soil (control plots). This observation is in agreement with Tebrügge and Düring (1999). As well as that, decreased tillage intensity led to a significant decrease in coarse pore size porosity (structural porosity), total porosity, saturated hydraulic conductivity and air permeability (at 30 kPa water suction) of the CS control plots. However, field managed with CT, without consideration to which depth or which soil water content it is practiced, are more sensitive to compaction and the correlated change in structure than are those managed with CS. This complies with the results of Röhring et al. (1997) and Yavuzcan (2000).

The drier the soil, the lower its deformability, the better it transmits stress to depth. The considerably higher strength of the NWT (non-wheel track zone) dry soil is attributable to the drying/shrinking process under plastic covers prior to harvesting. In the experiments presented by Arvidsson (2001), it is possible that an increase in strength only developed after one or more drying cycles. However, direct penetrometer measurements indicated that the dry soil was not strong enough to resist compaction in the topsoil. The results show one of the difficulties in using penetration resistance to measure the effects of soil compaction particularly in dry soils since no data could be obtained due to high soil strength at 0.1–0.5 m depth.

Our results demonstrate the impact of soil water content on soil compaction induced by wheeling. The changes in soil water content were clearly reflected in the bulk density, structural porosity, soil strength and rut depth. The wet soil was too weak to resist compaction. The contradictory effects to explain the relationships between soil water content and structural porosity (Richard et al., 1999) can be valid between the soils having medium \( w_2 \) and high \( w_3 \) soil water conditions. However, considering the low \( w_1 \) and medium \( w_2 \) soil water contents, structural porosity increases as soil water content increases. Soil water content also affected the rut depth directly.

The measured penetration resistance measurements were not consistent with other research results. The data obtained in high and medium soil water conditions does not meet the general expectation that a decreasing coarse pore size porosity increases penetration resistance. In general changes were opposite to this expectation. Such conflicting evidence has already been noted in the results of Gysi et al. (1999). Probably, excess soil water decreased soil strength due to kneading as mentioned by Horn et al. (1995). Thus, penetrometer resistance does not appear to be a suitable parameter for assessing soil compaction under these conditions.

Saturated hydraulic conductivity data in the subsoil were not statistically significant at 0.3–0.4 m depth. This result is consistent with the results of bulk density obtained at 0.3–0.4 m depth in different treatments. In contrary, the differences were significant compared to control values at 0.2–0.3 m. However, the differences between the treatments were insignificant. The results at this depth may indicate a subsoiling demand for the further seasons at “CS \( w_3 \)” and “CS \( w_1 \)” plots, classified as average according to Kuntze et al. (1994). In field traffic experiments of Arvidsson (2001) with wheel loads of 80 kN on sandy loams and loams, hydraulic conductivities of several subsoils were reduced permanently to 10% of the original conductivities. Our results confirm this, partially at 0.2–0.3 m depth. The results of our experiments confirm that moderate changes in bulk density may decrease the saturated hydraulic conductivity dramatically at 0.2–0.3 m depth. However, a restrictive condition with regard to soil drainage was not observed.

In all cases, except the medium soil water conditions of CS treatment, changes in air permeability in the subsoil were statistically significant and the soil pore system was apparently affected with the changes in air permeability. In particular, significant differences were obtained only with control groups and within the treatments no significant differences were observed at 6 kPa water suction. Unlike saturated hydraulic conductivity, considerable changes were still visible at 0.3–0.4 m depth. The results were consistent with the coarse pore size measurements. Accordingly, susceptibility towards compaction may be indicated for “CT \( w_3 \)” and “CT \( w_1 \)” plots.
Structural porosity in most cases 10% or higher compared to the control samples as complying with the results of Arvidsson (2001).

Structural porosity (coarse pore size porosity) lower than 0.10 m$^3$ m$^{-3}$ is usually considered to be limiting for crop growth (Richard et al., 1999). We found that structural porosity was below the threshold 0.10 m$^3$ m$^{-3}$ in low ($w_1$) and high ($w_3$) soil water contents irrespective of the tillage treatment. Total porosity is also reduced after wheel track, but often less than the wide coarse pore size porosity, due to increased portion of medium and fine sized pores conforming the results of Kooistra and Tovey (1994). Lipiec and Hatano (2003) revealed that compaction of loamy soil by tractor mainly reduced wide coarse pores (>50 μm) and to lesser extent pores <50 μm. Our study confirms this result by means of the water desorption evaluation.

In particular medium soil water conditions provided the better structure and resistance to traffic induced compaction. Adekalu and Osunbitan (2001) indicated that, generally the optimum soil water contents of the soils fall between the plastic limit and liquid limit (but closer to the liquid limits). It is likely that, 0.27 g g$^{-1}$ soil water content is very close to the optimum soil water content of the soil to resist further compaction.

Taking the increase in bulk density, the decrease of air permeability, the reduction of coarse pore size porosity into account, it seems that CT plots were compacted to a depth of at least 0.25 m and at most 0.40 m in high soil water conditions. The trends were almost similar for “CT $w_1$” plots. However, it seems that “CT $w_1$” plots were less affected than “CT $w_3$” plots with regard to bulk density increases under partial load. In contrast, diminishment of coarse pore size porosity was significantly higher in “CT $w_1$” plots down to 0.4 m. Among CT plots, the best physical properties were obtained at medium soil water content. No significant increase in bulk density and no significant decrease in structural porosity and total porosity below 0.2 m were observed at medium soil water content.

It is likely that, CS plots were less affected by traffic treatments than CT plots. Considering structural porosity and total porosity no compaction effects below 0.3 m were found. Medium water content provide better soil conditions after traffic with regard to structural porosity, air permeability (at 6 and 30 kPa water suction), total porosity and bulk density.

5. Conclusions

The results clearly demonstrate that for conditions in southern Germany, heavy sugar beet harvesters may cause compaction down to 0.3–0.4 m depth during normal field conditions in the autumn. The risk for compaction is higher for high and low soil water contents as well as CT treatments. Farmers can reduce the risk by harvesting earlier in the autumn, when the soil water content of the subsoil is normally lower. The soil water content seemed to be the most decisive factor. Our results demonstrate the impact of soil water content on soil compaction induced by wheeling. Structural porosity and air permeability and bulk density seems to be suitable parameters to detect soil compaction under the conditions tested.

The compactive forces were negatively correlated with optimum soil water contents. In particular medium soil water conditions provided the better structure and resistance to traffic induced compaction.

The results show that, to avoid subsoil compaction under high soil water conditions, the maximum wheel load or ground contact pressure of these machines (sugar beet harvesters) must be substantially reduced, by reducing the total load and/or equipping the machinery with more wheels or tracks. Besides, to prevent subsoil compaction, the stresses induced by field traffic must be less than the subsoil’s bearing capacity. Soil wetness decreases the bearing capacity of the soil. The machines and equipment used on fields in critical conditions should be adjusted to the actual strength of the subsoil by controlling wheel/track loads.

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References


