Seasonal dynamics in wheel load-carrying capacity of a loam soil in the Swiss Plateau

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Abstract

Subsoil compaction is a major problem in modern agriculture caused by the intensification of agricultural production and the increase in weight of agricultural machinery. Compaction in the subsoil is highly persistent and leads to deterioration of soil functions. Wheel load-carrying capacity (WLCC) is defined as the maximum wheel load for a specific tyre and inflation pressure that does not result in soil stress in excess of soil strength. The soil strength and hence WLCC is strongly influenced by soil matric potential (h). The aim of this study was to estimate the seasonal dynamics in WLCC based on in situ measurements of h, measurements of precompression stress at various h and simulations of soil stress. In this work, we concentrated on prevention of subsoil compaction. Calculations were made for different tyres (standard and low-pressure top tyres) and for soil under different tillage and cropping systems (mouldboard ploughing, direct drilling, permanent grassland), and the computed WLCC was compared with real wheel loads to obtain the number of trafficable days (NTD) for various agricultural machines. Wheel load-carrying capacity was higher for the top than the standard tyres, demonstrating the potential of tyre equipment in reducing compaction risks. The NTD varied between years and generally decreased with increasing wheel load of the machinery. The WLCC simulations presented here provide a useful and easily interpreted tool to guide the avoidance of soil compaction.

Keywords: Soil compaction, precompression stress, trafficability, soil matric potential, tillage systems

Introduction

Subsoil compaction is a major problem in modern agriculture, resulting from the intensification of agricultural production and the increase in weight and traffic intensity of agricultural machinery. Compaction in the subsoil is highly persistent (Berisso et al., 2012; Schjønning et al., 2013) and leads to deterioration of soil functions and ecological services, reduced root and plant growth and therefore lower crop yields (Soane & van Ouwerkerk, 1994). For a sustainable soil management, the most effective action is to avoid soil compaction completely by ensuring that soil stress does not exceed soil strength.

Precompression stress, σpc, is typically used as the parameter to indicate the mechanical strength of soil against compaction (Horn & Fleige, 2003). Deformation is assumed to be elastic and recoverable if the applied stress, σ, is smaller than σpc. In contrast, if the applied load induces a soil stress that is greater than σpc, plastic deformation occurs, which leads to permanent soil compaction. Hence, soil compaction could be avoided by restricting soil stress, so that σ < σpc.

Soil stress is primarily a function of the applied surface load, which for wheeled vehicles is determined by tyre dimension and properties, tyre inflation pressure and wheel load, and for tracked vehicles by the track properties and undercarriage load. Furthermore, soil properties and conditions influence the transmission of stress in soil.
Dynamic wheel load-carrying capacity

Precompression stress is affected by soil texture and soil structure, and for a given soil a function of soil matric potential, \( h \). Hence, soil compaction risk is a function of soil moisture. For example, Vero et al. (2014) proposed a threshold for trafficability for slurry spreading based on the soil moisture deficit that relates actual soil moisture to soil moisture at field capacity.

Aridorsson et al. (2003) calculated the seasonal risk of soil compaction of a sugar beet harvester (8 Mg wheel load) by combining simulations of soil water content, laboratory measurements of \( \sigma_{pc} \) at various \( h \) and simulations of soil stress using SOCOMO (Van den Akker, 2004). Van den Akker (2004) created a wheel load-carrying capacity (WLCC) map of the Netherlands for one-specific tyre width and inflation pressure and one-specific \( h \) (\(-300\) hPa). Wheel load-carrying capacity is defined here as the maximum (allowable) wheel load for a specific tyre and inflation pressure that does not result in soil stress in excess of soil load-carrying capacity.

The objective of this study was to combine certain features of the approaches used by Aridorsson et al. (2003) and Van den Akker (2004) to calculate the seasonal dynamics in WLCC based on \textit{in situ} measurements of \( h \), laboratory measurements of \( \sigma_{pc} \) at various \( h \) and simulations of soil stress. Calculations were made for different tyres for an Eutric Cambisol on the Swiss Plateau under three different tillage and cropping systems (mouldboard ploughing, direct drilling and permanent grassland). The computed WLCC was compared with typical (real) wheel loads to obtain the number of trafficable days (NTD) for various agricultural machines, which we define as the number of days where WLCC > real wheel load.

Materials and methods

\textbf{Methodology}

We calculated seasonal dynamics of WLCC by combining \textit{in situ} measurements of \( h \), laboratory measurements of \( \sigma_{pc} \) at various \( h \) and simulations of vertical soil stress. In our work here, WLCC was calculated for the 0.35 m soil depth, aiming at protecting the subsoil. This is further considered in the Discussion. Several steps are needed for the WLCC simulations, as follows:

1. Soil stress (here: vertical soil stress at 0.35 m depth, \( \sigma_v \)) as a function of wheel load, \( F_{wheel} \) was calculated. For this, we used SoilFlex (Keller et al., 2007) that simulates soil stress using the semi-analytical equations based on the work of Boussinesq (1885), Fröhlich (1934) and Söhne (1953). The stress distribution at the tyre-soil contact area was calculated from tyre and loading characteristics according to Keller (2005). We used a concentration factor (Fröhlich, 1934) of five (Keller & Aridorsson, 2004). For a given tyre, we made simulations at a range of wheel loads, always using the rated tyre inflation pressure (given for a driving speed of 10 km/h). This yielded a relationship between wheel load and vertical soil stress at 0.35 m depth, that is \( F_{wheel} = WLCC(\sigma_v) \).

2. For the maximal (allowable) wheel load, that is for WLCC, we have \( \sigma_v = \sigma_{pc} \) and \( F_{wheel} = WLCC \). Combining with Step 1 above, we obtain a relationship between WLCC and precompression stress, that is WLCC(\( \sigma_{pc} \)).

3. Precompression stress as a function of soil water tension, \( \sigma_{pc}(h) \), was derived from measurements (see section ‘Soil core sampling and uniaxial compression tests’ below). Alternatively, \( \sigma_{pc}(h) \) relationship could be derived from pedo-transfer functions.

4. Soil matric potential was measured \textit{in situ} over time, \( t \) (see section ‘experimental site’ below), yielding a time course of \( h(t) \). Alternatively, \( h(t) \) could be simulated using a soil water balance model.

5. The WLCC over time, WLCC(\( t \)), is obtained by combining steps 1–4.

We simulated WLCC(\( t \)) for one experimental site with different tillage and cropping treatments and for a range of different tyres. The computed WLCC was further compared with real wheel loads to obtain NTD for various machines, that is the number of days where WLCC > real wheel load.

\textbf{Experimental site}

Measurements and simulations were made in the long-term field experiment ‘Oberacker’ in Zollikofen near Berne, Switzerland, that was established in 1994 and compares two tillage systems: mouldboard ploughing (MP; ‘in-furrow’ ploughing before 2002, since 2003 ‘on-land’ ploughing; ploughing depth: 0.2 m) and direct drilling (DD), each with six experimental plots (9 x 80 m). Between the experimental plots are permanent grass (PG) strips of 3 m width. The soil is classified as a Eutric Cambisol with a loam texture (Table 1).

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|c|}
\hline
\textbf{Soil characteristics} & \textbf{Topsoil, 0.1–0.16 m} & \textbf{Subsoil, 0.35–0.41 m} \\
\hline
\textbf{Clay (% by weight)} & 17.7 & 18.5 & 16.9 & 15.7 & 15.0 & 15.2 \\
\textbf{Silt (% by weight)} & 22.1 & 22.2 & 22.8 & 21.4 & 19.1 & 20.2 \\
\textbf{Sand (% by weight)} & 57.5 & 57.0 & 57.8 & 61.9 & 64.8 & 63.6 \\
\textbf{OM (% by weight)} & 2.7 & 2.3 & 2.6 & 1.0 & 1.0 & 1.0 \\
\textbf{Dry bulk density (Mg/m$^3$)} & 1.37 & 1.47 & 1.46 & 1.55 & 1.50 & 1.49 \\
\hline
\end{tabular}
\caption{Soil characteristics of the site ‘Oberacker’ for the topsoil (0.1–0.16 m) and subsoil (0.35–0.41 m) for mouldboard ploughing (MP), direct drilling (DD) and permanent grass (PG)}
\end{table}

\( \text{Clay < 0.002 mm; Silt 0.002–0.05 mm; Sand 0.05–0.2 mm; OM: organic matter content.} \)
Tensiometers, permanently installed in all three treatments (MP, DD and PG) at 0.35 m depth since 2001, yield quasi-continuous in situ measurements of \( h \) (readings are taken three times a week from March to October and once a week during the winter (November–February)). Five tensiometers were installed in each treatment. Here, we present median values per treatment and analyse data from the years 2001 to 2011 inclusive.

Soil core sampling and uniaxial compression tests

Soil core sampling was carried out in spring at field water content close to field capacity. Intact cylindrical soil cores (100 mm in diameter, 60 mm in height) were sampled in the upper subsoil (0.35–0.41 m depth) in three plots of MP and DD, respectively, and two plots of PG. Samples were also taken in the topsoil, but these are not subject of this article. We collected 15 soil cores per plot and depth. In the laboratory, the soil samples were slowly saturated from below, drained to five different \( h \) of \(-30, -60, -100, -200\) and \(-500\) hPa (three samples per plot, depth and \( h \)), and subjected to uniaxial compression tests. Fifteen vertical normal stresses (20, 30, 40, 50, 60, 80, 100, 125, 150, 200, 250, 400, 600, 800 and 970 kPa) were applied sequentially for 30 min, and the displacement was read at the end of each loading interval.

Soil precompression stress was obtained for each soil sample from soil strain as a function of the logarithm of applied vertical normal stress and determined at the intersection of the virgin compression line with the \( x \)-axis at zero strain (Dias Junior & Pierce, 1995; McBride & Joosse, 1996). Next, we established empirical relationships between \( \sigma_{pc} \) and \( h \) for each treatment. Precompression stress as a function of time was then obtained by combining the \( \sigma_{pc}(h) \) functions with the tensiometer measurements.

Risk assessment

We considered machinery used for common field operations in the study region and assigned the machinery with typical (real) wheel loads (Table 2). Each machine was equipped with either typically used standard (ST) tyres or low-pressure top (TOP) tyres (Table 3). We calculated WLCC(\( t \)) as described in the methodology section for all tyres, and compared WLCC(\( t \)) with the real wheel loads (Table 2), which yielded NTD for each machine.

Results

Precompression stress

Precompression stress was similar for DD and PG (varying between 80 and 130 kPa) and slightly higher (especially at

<table>
<thead>
<tr>
<th>Case</th>
<th>Machinery</th>
<th>Wheel load(^a) (Mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 a</td>
<td>Tractor(^b) (100 kW)</td>
<td>2.25</td>
</tr>
<tr>
<td></td>
<td>b Tractor (100 kW) with on-land plough</td>
<td>3.5</td>
</tr>
<tr>
<td>2 a</td>
<td>Tractor(^b) (170 kW)</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>b Tractor (170 kW) with chisel plough or sowing machine</td>
<td>4.5</td>
</tr>
<tr>
<td>3 a</td>
<td>Slurry tanker 12 m(^3) with tandem-axle or 6 m(^3) single-axle</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td>b Slurry tanker 8 m(^3) single-axle</td>
<td>5.0</td>
</tr>
<tr>
<td>4 a</td>
<td>Combine harvester (4–5 m)</td>
<td>5.0</td>
</tr>
<tr>
<td></td>
<td>b Combine harvester (5–7 m)</td>
<td>7.0</td>
</tr>
<tr>
<td>5 a</td>
<td>Self-propelled forage harvester</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td>b Self-propelled sugar beet harvester</td>
<td>11.0</td>
</tr>
</tbody>
</table>

\(^a\)Refers to the largest wheel load of the machine (i.e. rear wheel of the tractor, front wheel of the harvesters) at operation (i.e. considering load transfer due to drawbar pull). \(^b\)Mechanical front wheel drive.

Table 3 Characteristics of the standard and top tyres for the machinery given in Table 2

<table>
<thead>
<tr>
<th>Tyre</th>
<th>Case</th>
<th>Size</th>
<th>Section width (mm)</th>
<th>Overall diameter (mm)</th>
<th>Rim diameter (mm)</th>
<th>Slope ( m^a )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard (ST)</td>
<td>1</td>
<td>460/85R38</td>
<td>495</td>
<td>1750</td>
<td>965</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>520/85R42</td>
<td>539</td>
<td>1945</td>
<td>1067</td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>600/60R30.5</td>
<td>639</td>
<td>1496</td>
<td>775</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>520/85R42</td>
<td>539</td>
<td>1945</td>
<td>1067</td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>800/65R32</td>
<td>799</td>
<td>1840</td>
<td>813</td>
<td>2.2</td>
</tr>
<tr>
<td>Top (TOP)</td>
<td>1</td>
<td>650/60R38</td>
<td>677</td>
<td>1735</td>
<td>965</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>900/50R42</td>
<td>853</td>
<td>1947</td>
<td>1067</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>750/60R30.5</td>
<td>760</td>
<td>1680</td>
<td>775</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>900/60R32</td>
<td>863</td>
<td>1894</td>
<td>813</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>1050/50R32</td>
<td>1055</td>
<td>1858</td>
<td>813</td>
<td>1.9</td>
</tr>
</tbody>
</table>

\(^a\)The slope \( m \) relates soil stress to wheel load (soil stress at 0.35 m depth (in kPa) = \( m \times \) wheel load (in Mg)) and can be regarded as an indicator of the ‘damage potential of a tyre’ (see text and Figure 2 for details).

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more negative $h$) in MP (80–180 kPa) (Figure 1). Precompression stress was similar for DD, PG and MP at $h = -30$ hPa, but $\sigma_{pc}$ increased stronger with decreasing (more negative) $h$ for MP. The relationship between $\sigma_{pc}$ and $h$ could be well described as $\sigma_{pc}(h) = a + b \log (|h|)$ ($R^2$ between 0.73 and 0.98), cf. Figure 1.

Soil stress as a function of wheel load

Simulated soil stress at 0.35 m depth was linearly related with wheel load, as shown exemplarily for two tyres in Figure 2. We propose the slope, $m$, of the $\sigma_v$ versus $F_{wheel}$ relationship as an index for the ‘soil damage potential’ of a tyre. The larger $m$, the higher $\sigma_v$ for a given $F_{wheel}$. The slope $m$ is listed for all tyres included in this study in Table 3. The slope $m$ was always smaller for the TOP tyres compared with the ST tyres, which implies that the TOP tyres yielded lower $\sigma_v$ than the ST tyres for a given $F_{wheel}$.

Impact of weather conditions and soil matric potential on WLCC

The average in situ $h$ at the 0.35 m depth over the years 2001–2011 showed a high similarity between DD and MP, while PG was less dry from May to July (when water use by crops is high in DD and MP), but drier in August (after crop harvest in DD and MP) (Figure 3). The seasonal dynamics of $h$ is reflected in the seasonal dynamics of WLCC. In Figure 4, we plot WLCC of the wettest year (2001; total precipitation = 1329 mm) and the driest year (2003; total precipitation = 745 mm) of the period 2001–2011, and the average WLCC of the period 2001–2011. The WLCC shown in Figure 4 was calculated for DD and a 750/60R30.5 tyre (TOP tyre of case 3; Table 3). The WLCC for 2001 was highly dynamic, while the 2003 and the average WLCC was smoother. The WLCC ≥5 Mg was hardly reached in 2001, whereas in 2003 the soil was trafficable with high wheel loads from May to the end of September. It is clear from Figure 4 that the amount and distribution of precipitation during a year have a high influence on WLCC.

Impact of tillage and cropping system on WLCC

Differences in WLCC between the different management systems may be due to differences in $h$ or differences in $\sigma_{pc}(h)$. On average, there were hardly any differences in $h$ between DD and MP, while PG showed a different evolution of $h$ between May and September (Figure 3). The precompression stress was similar in DD and PG, but higher (especially at more negative $h$) in MP. Hence, differences in WLCC (Figure 5) between DD and MP were primarily due to differences in $\sigma_{pc}(h)$, differences between DD and PG were mainly due to differences in $h$, and differences between MP and PG were due to both differences in $\sigma_{pc}(h)$ and $h$. MP showed higher $\sigma_{pc}$ at more negative $h$, which resulted in higher WLCC (up to 2 Mg difference to DD) especially during the dry summer months.

WLCC difference between TOP and ST tyres

An example of the difference in WLCC between TOP and ST tyres is shown in Figure 6. For this specific case (case 3, Tables 2 and 3), WLCC of the 600/60R30.5 ST tyre was always ≤5 Mg indicating that a single-axled 8 m$^3$ slurry tanker equipped with ST tyres could not be used at any time without a risk of soil compaction. In contrast, WLCC of the 750/60R30.5 TOP tyre was >5 Mg from May to July,
suggesting that the single-axled 8 m³ slurry tanker equipped with TOP tyres could be used during that period. However, when using the recommended tyre inflation pressure at a driving speed of 40 km/h (as used for transport on roads), WLCC is significantly reduced (Figure 6). Figure 6 demonstrates that (i) lower wheel loads (cf. slurry tanker with 3.5 and 5.0 Mg wheel load, respectively) and (ii) good tyre equipment (cf. TOP vs. ST tyre) increase the number of trafficable days and thus the timeliness of machinery. The advantage of low wheel loads and good tyres is underpinned by the fact that in years with more precipitation WLCC was seldom larger than \( F_{\text{wheel}} \) for machines with high wheel loads (Figure 4) and that WLCC for the 600/60R30.5 ST tyre was <5 Mg even for the driest year 2003 (not shown).

**Number of trafficable days**

The number of trafficable days (NTD) as presented in Table 4 were calculated for the months March to November (a total of 275 days in this period) averaged over the years 2001–2011. The highest NTD were obtained for the single tractors with NTD > 200 in all management systems and for both TOP and ST tyres. The NTD decreased with increasing wheel load, and NTD decreased rapidly for wheel loads ≥5 Mg. The NTD was small for the forage harvester with 6 Mg wheel load and the combine harvester with 7 Mg wheel load, especially in PG and DD. The NTD was zero in all tillage and cropping systems for the sugar beet harvester with 11 Mg wheel load. The TOP tyres always obtained a higher NTD compared with ST tyres, indicating the potential for good tyre equipment to reduce soil compaction risks and increase timeliness for machinery use.

Generally, NTD decreased from MP to DD to PG. We are aware that most field operations listed in Tables 2 and 4 are not realistic for PG and that many field operations are relevant under certain periods of the year only; nevertheless, we calculated NTD for the whole year and all machinery in all management systems for the purpose of comparison. As mentioned elsewhere, WLCC for MP was higher than WLCC in DD or PG during drier periods due to the higher \( \sigma_{pc} \) under dry conditions, which resulted in higher NTD for...
wheel loads $\geq 5$ Mg. The NTD was zero for wheel loads $\geq 5$ Mg for the ST tyres in DD and PG.

**Discussion**

**Methodology**

We calculated soil stress with Fröhlich’s (1934) model that includes the ‘concentration factor’, $v$. The concentration factor alters the pattern of the stress decay with depth. Here, we used a constant value of $v = 5$ for all simulations, that is for all soil moisture conditions and for all tillage and cropping treatments. A value of $v = 5$ was found by Keller & Arvidsson (2004) to result in good predictions when compared with measurements. Measurements presented by Wiermann et al. (2000) suggest that stress decays more rapidly with depth in reduced tillage systems, and hence that a smaller $v$ should be used for soil under reduced tillage. However, Trautner (2003) found a larger stress attenuation in recently tilled soils, which would suggest a smaller $v$ in ploughed systems. Lamandé & Schjønning (2011) observed no significant difference in stress propagation between a recently tilled soil and soil that was not tilled for about 1.5 yr. The contradictory results show that there is no general agreement as to how soil structure impacts stress transmission (see also Keller et al., 2014).

The impact of soil moisture and soil structure on the stress at the tyre–soil interface was not considered in our study. Although an impact is expected, currently only few data exist, which however do not permit the derivation of general rules on the evolution of the tyre–soil contact properties with changing soil conditions (see Keller & Lamandé, 2010). We
suggest that more research is needed on the effects of soil structure (tillage systems) on stress transmission.

We determined \( \sigma_{pc} \) from the intersection of the virgin compression line with the \( x \)-axis at zero strain. This method yields lower values for \( \sigma_{pc} \) than the Casagrande (1936) method, as demonstrated by Arvidsson & Keller (2004). Keller et al. (2012) obtained \( \sigma_{pc} \) with the Casagrande method and observed from wheeling experiments that permanent strain was measured in the field when the ratio \( \sigma_v/\sigma_{pc} \) exceeded roughly 0.5. Hence, the method used here reflects best field conditions.

Precompression stress was measured at \( h \) between \(-30 \) and \(-500 \) hPa. Hence, we do not know \( \sigma_{pc} \) at very wet (\( >-30 \) hPa) and dry (\( <-500 \) hPa) conditions. The \( \sigma_{pc} \) versus \( h \) relationship, and therefore WLCC(\( h \)), is unclear, especially at the wet end, because saturated soil is theoretically incompressible, which would result in infinite WLCC. However, field soil is seldom completely saturated. We implemented WLCC(\( h \)) = WLCC(-30 hPa) for \( h > -30 \) hPa.

In this study, we only considered the 0.35 m soil depth for calculation of WLCC. This depth was chosen because it represents the upper subsoil where subsoil stresses are the greatest. It has been shown that compaction is persistent for \( >10 \) yr even in the upper subsoil (Berioso et al., 2012; Schjønning et al., 2013). The 0.35 m depth represents a reference depth in Swiss soil protection regulations (BAFU & BLW, 2013) that aims at protecting subsoil. Networks of permanently installed tensiometers measuring \( h \) at 0.35 m depth have been established in Switzerland (FaBo, 2013; LANAT BE, 2013), and these and similar measurements could be used in the assessment of soil compaction risks as demonstrated with our approach. We are fully aware that an evaluation at the 0.35 m depth does not necessarily imply zero compaction risk at deeper subsoil layers, as \( \sigma_v \) could be larger than \( \sigma_{pc} \) at another depth. Especially machinery with high wheel loads transmits high stresses also to greater depths (Schjønning et al., 2012). Although having a higher regeneration potential, compaction of the topsoil should not be neglected either. Recovery from topsoil compaction takes several years even in ploughed systems (Arvidsson & Håkansson, 1996; Weisskopf et al., 2010), and topsoil compaction in reduced tillage systems may be a serious problem (Schjønning & Thomsen, 2013). It will be easy to refine our approach in the future by considering several soil depths.

**Precompression stress**

Precompression stress of the subsoil was higher in MP than in DD and PG (Figure 1). This disagrees with the results presented by Horn (2004), who observed higher \( \sigma_{pc} \) at 0.35 m depth under reduced tillage compared with ploughed soil, which was associated with a better soil structure in reduced tillage. We measured a stronger increase in \( \sigma_{pc} \) with decreasing \( h \) (i.e. upon drying) in MP than in DD or PG. We conjecture that the higher \( \sigma_{pc} \) and the stronger impact of \( h \) on \( \sigma_{pc} \) in MP are due to a poor soil structure. This is supported by the higher subsoil bulk density in MP (Table 1) and the fact that poor soil structure is associated with hard setting (i.e. strong increase in strength upon drying) (Daniells, 2012). It is interesting that \( \sigma_{pc} \) of DD and PG were very similar, suggesting that the soil structure was similar in both systems.

**Wheel load-carrying capacity and number of trafficable days**

It is apparent from Figures 3 and 4 that the soil matric potential has a high influence upon the dynamics of WLCC. The WLCC(\( t \)) followed a similar time course as the

### Table 4 Average number of trafficable days per year for the years 2001–2011 in the months March to November (total number of days: 275) for all analysed cases and for top (TOP) and standard (ST) tyres (see Tables 2 and 3 for details), and tillage and cropping systems (mouldboard ploughing, MP, direct drilling, DD and permanent grass, PG)

<table>
<thead>
<tr>
<th>Case</th>
<th>Machinery</th>
<th>TOP</th>
<th>ST</th>
<th>TOP</th>
<th>ST</th>
<th>TOP</th>
<th>ST</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 a</td>
<td>Tractor (100 kW)</td>
<td>275</td>
<td>252</td>
<td>275</td>
<td>271</td>
<td>266</td>
<td>261</td>
</tr>
<tr>
<td>1 b</td>
<td>Tractor (100 kW) with on-land plough</td>
<td>196</td>
<td>152</td>
<td>219</td>
<td>192</td>
<td>240</td>
<td>210</td>
</tr>
<tr>
<td>2 a</td>
<td>Tractor (170 kW)</td>
<td>260</td>
<td>212</td>
<td>275</td>
<td>232</td>
<td>262</td>
<td>248</td>
</tr>
<tr>
<td>2 b</td>
<td>Tractor (170 kW) with chisel plough</td>
<td>181</td>
<td>0</td>
<td>205</td>
<td>58</td>
<td>224</td>
<td>198</td>
</tr>
<tr>
<td>3 a</td>
<td>Slurry tanker 12 m³ with tandem-axle</td>
<td>216</td>
<td>176</td>
<td>236</td>
<td>201</td>
<td>248</td>
<td>218</td>
</tr>
<tr>
<td>3 b</td>
<td>Slurry tanker 8 m³ single-axle</td>
<td>12</td>
<td>0</td>
<td>133</td>
<td>0</td>
<td>203</td>
<td>173</td>
</tr>
<tr>
<td>4 a</td>
<td>Combine harvester (4–5 m)</td>
<td>94</td>
<td>0</td>
<td>182</td>
<td>0</td>
<td>208</td>
<td>188</td>
</tr>
<tr>
<td>4 b</td>
<td>Combine harvester (5–7 m)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>148</td>
<td>0</td>
</tr>
<tr>
<td>5 a</td>
<td>Self-propelled forage harvester</td>
<td>12</td>
<td>0</td>
<td>128</td>
<td>0</td>
<td>203</td>
<td>191</td>
</tr>
<tr>
<td>5 b</td>
<td>Self-propelled sugar beet harvester</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

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measured in situ \( h \) (Figure 3), and WLCC was low during wet conditions (e.g. November to March) and high in dry periods (e.g. June to August). Consequently, WLCC was generally much smaller in a wet than in a dry year. This is also reflected in the NTD that were generally fewer in the wet than in the dry year (not shown). The high dynamics of WLCC is not captured in soil compaction risk maps, for example. As mentioned above, WLCC at \( h > 30 \) hPa is uncertain. Under very dry conditions, it occasionally happened that WLCC was larger than the maximal tyre load capacity (as given from the tyre manufacturer).

Soil stress was calculated by considering the rated inflation pressures at 10 km/h. The WLCC was smaller when using the recommended inflation pressures at higher speed (e.g. 40 km/h, as used during transport on roads), see Figure 6. Similarly, over-inflation reduced WLCC (not shown). Hence, it is important to adjust the tyre inflation pressure to field use, for example using central tyre inflation systems.

We were able to show the importance of using good tyre equipment towards reducing soil compaction risks: the TOP tyres performed better than the ST tyres (cf. Figures 2 and 6, Tables 3 and 4). Nevertheless, soil matric potential had a larger influence on WLCC than tyre dimension. The differences between TOP and ST tyres were small under wet soil conditions. Moreover, at high wheel load (\( > 5 \) Mg), the compaction risk was considerable even with a TOP tyre.

The NTD is presented in Table 4 for the main working season, which does not consider the actual operating time. Therefore, it is possible that NTD is reasonably large within the considered period, but WLCC < real wheel load at the very specific moment when the soil would be trafficked. For example, Arvidsson et al. (2003) pointed out that sugar beet harvest occurs mainly during wet conditions in October or November where WLCC is generally small. Under our conditions, NTD for machinery with \( \geq 5 \) Mg wheel load (see Table 2) was very small until April inclusive (NTD \( \leq 6 \)) and zero in November (Figure 7). The NTD was also small in August and October, while NTD was large from May to July (Figure 7). Note that NTD = 0 for wheel load \( \geq 7 \) Mg under DD and PG. The real wheel loads (Table 2) were assumed to be constant for our simulations; however, the wheel load can either increase (e.g. harvester) or decrease (e.g. slurry tanker) during field operation.

We believe that the dynamic WLCC and the comparison with real wheel loads and computation of NTD, either in graphical (cf. Figures 4–7) or tabulated form (Table 4) is a useful tool that is more easily interpreted in practice than soil strength (precompression stress) values or risk maps that do not consider the dynamic impact of soil matric potential. The dynamic WLCC approach combined with real wheel loads not only displays the compaction risk but also yields information on the timeliness of various agricultural machines.

**Conclusion**

We introduce an approach to calculate seasonal dynamics of wheel load-carrying capacity, WLCC, by combining in situ measurements of \( h \), laboratory measurements of \( \sigma_{pc} \) at various \( h \) and simulations of vertical soil stress. The WLCC varied greatly during a year due to dynamics in \( h \), and WLCC was low during wet periods and higher under dry soil conditions. In situ \( h \) is easy and cheap to measure with a tensiometer. Furthermore, WLCC is influenced by the \( \sigma_{pc} \) versus \( h \) relationship, which was found to be different.
between the two tillage systems MP and DD but similar for DD and PG. In comparing various tyres, we demonstrated that the potential for good tyre equipment to reduce compaction risk and increase timeliness for machinery use. Machinery with high wheel loads (>5 Mg) result in small NTD, even with good tyre equipment, suggesting that such machinery is not compatible with sustainable soil management. Hence, use of small wheel loads and good tyre equipment is recommended to reduce compaction risks and increase NTD. The WLCC simulations presented here may be a useful and easily interpreted tool, for example for guidelines to avoid soil compaction.

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