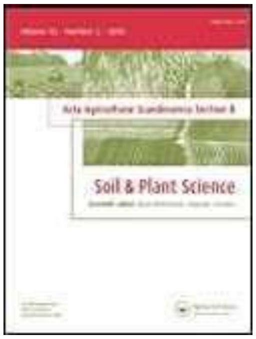

Soil compaction and stress propagation after different wheeling intensities on a silt soil in South-East Norway

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Keywords:	soil compaction, precompression stress, stress propagation, saturated hydraulic conductivity, wheeling intensity, yield

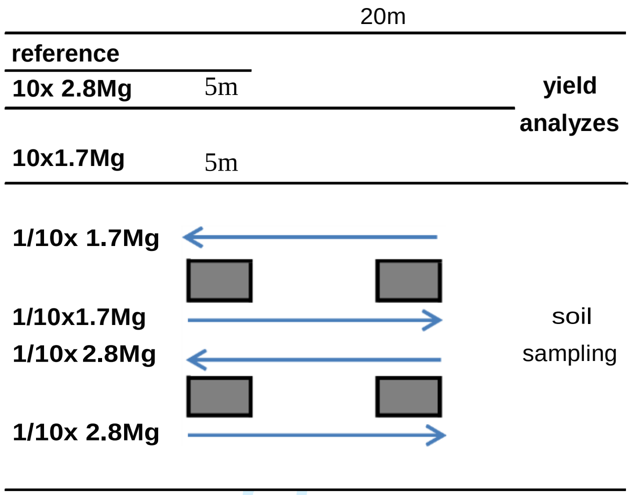

Figure l: Field layout: Upper part compacted wheel by wheel for yield monitoring in 2015 and 2016, lower part for soil sampling as described in the text.

Figure 2: The tractor/trailer combination used in the compaction trial.

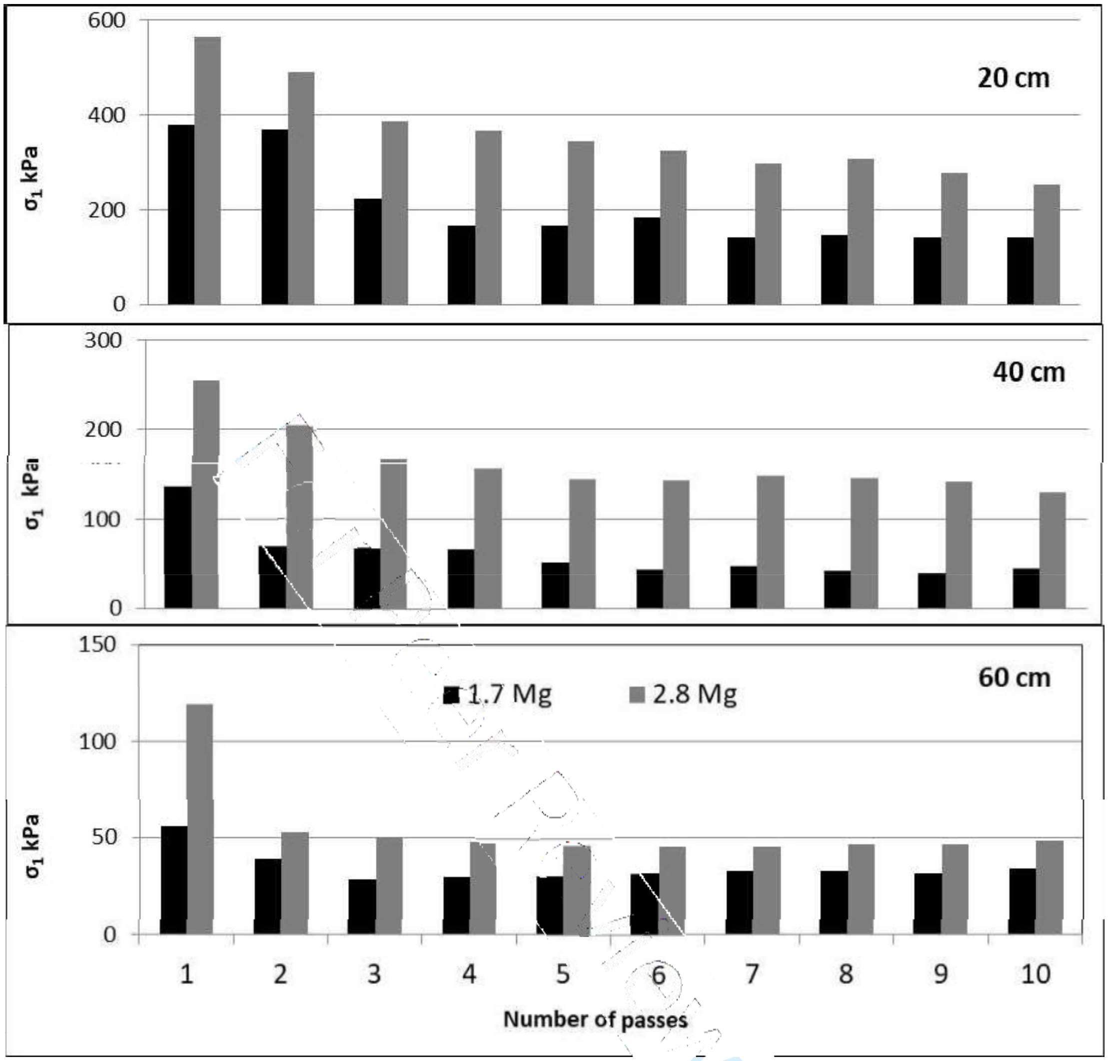

Figure 3: Major principal stress (crl) for wheeling **1-10 in** top- and subsoil as registrered with the SST system. Average l. 7Mg: 20cm 206kPa, 40cm 6lkPa, 60cm 56 kPa. 2.8Mg: 20cm 361 kPa, 40cm 164 kPa, 60cm 55kpa, n=2

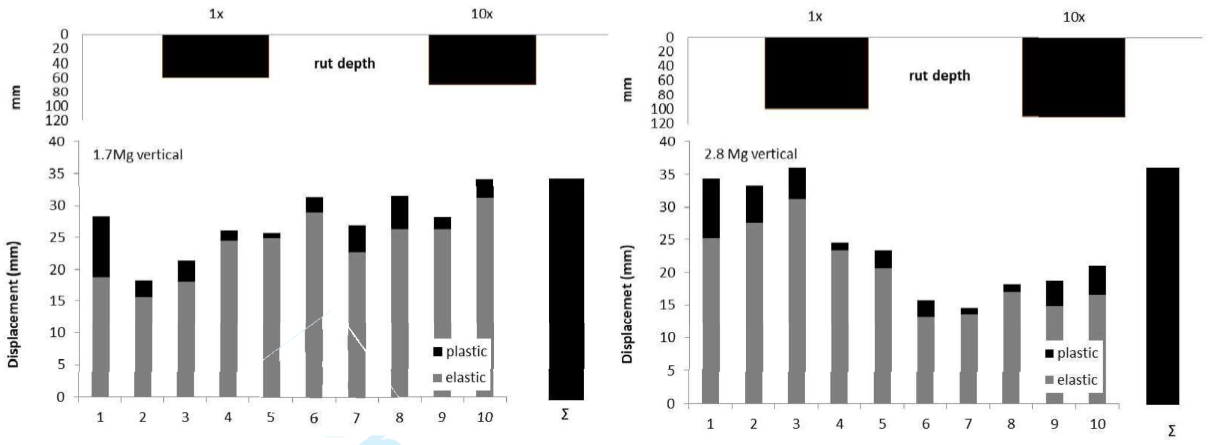

Figure 4. Elastic and plastic vertical displacement (mm) in the upper soil layer for all ten passes n=2 . Rut depth (mm) measured with a ruler after the first and tenth wheeling , n= 4

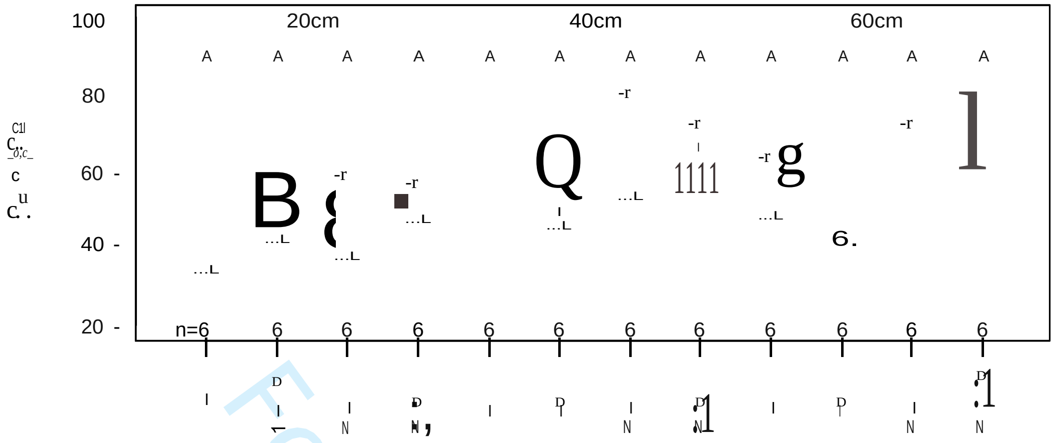

Figure 5: Box plots (n=6) of Pc in soils after wheeling with different intensities and wheel loads. 1.7_01= single wheeling with 1.7Mg whee lload, 1.7_10= multiple wheeling with l.7Mg wheelload, 2.8_01= single wheeling with 2.8Mg wheelload, 2.8_10= multiple wheeling with 2.8Mg wheelload. Figures with a different letter are significantly different from each other. Median - and average valne o

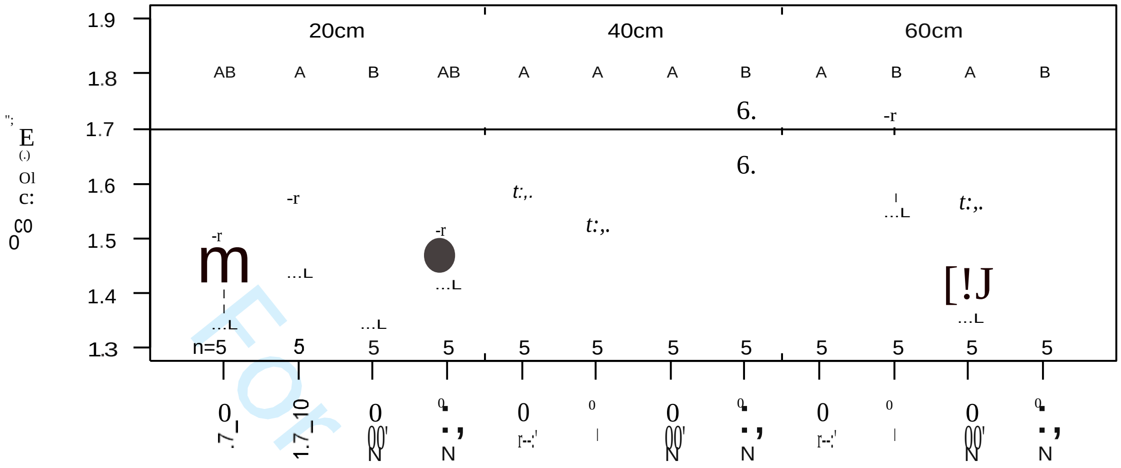

Figure 6: Box plots (n=8) of bulk density in soils after wheeling with the different intensities and wheel loads. See Figure 5 for details. Figures with a different letter are significantly different from each other. Median - and average value o

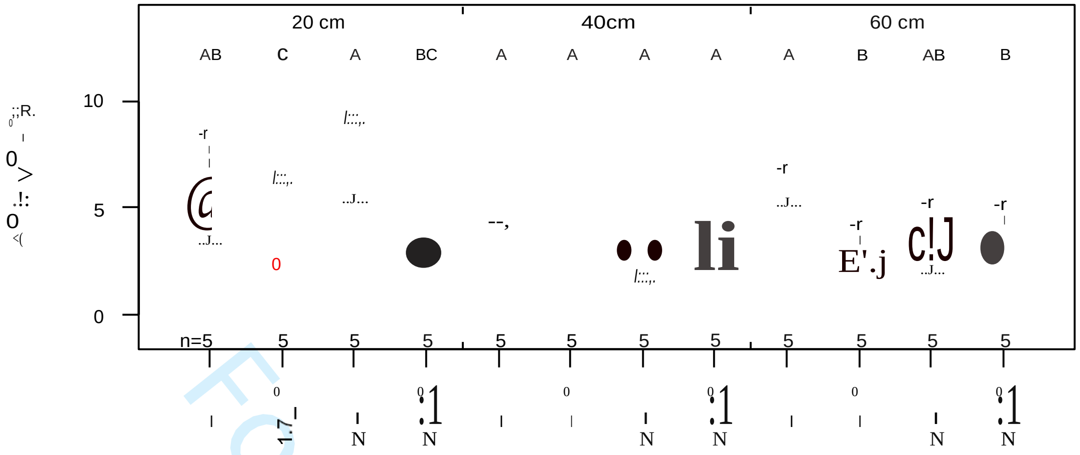

Figure 7: Box plots of Air capacity. Figures with a different letter are significantly different from each other. See figure 5 for details. Median - and average value o

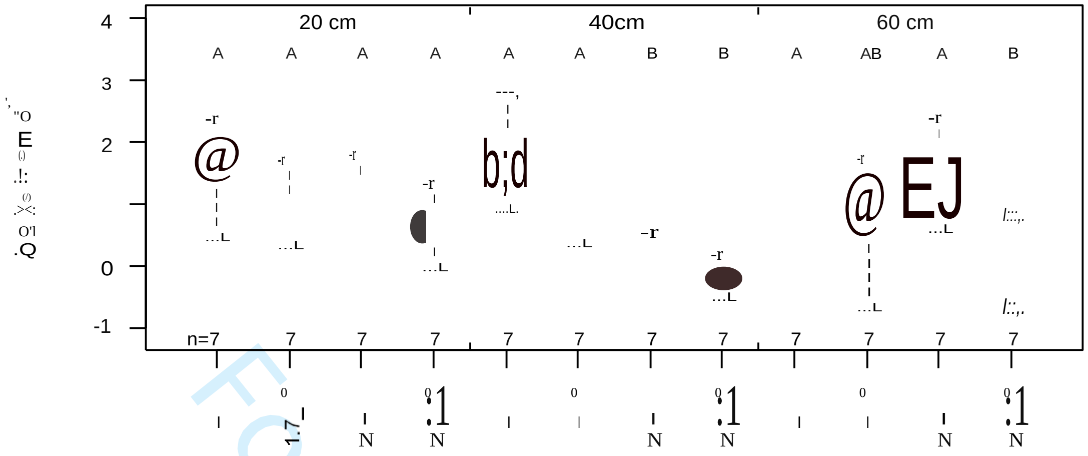

Figure 8: Box plots of saturated hydraulic conductivity (Ksat) log scale. Figures with a different letter are significantly different from each other. See Figure 5 for details. Median - and average value o

Table 1. Particle size distribution and organic carbon content of the soil (Haplic Stagnosol)

Depth	**Horizon**[1]	**Sand**	**Silt**	**Clay**	**Texture**[1]	**Corg**
cm		-------	%	-------		
20	Ap	8	83	9	Si	2.4
40	Cg1	6	84	10	Si	
60	Cg2	5	84	11	Si	

[1] Soil horizons and texture according FAO (2006)

Temperature	**Average**	**2015**	**2016**
April	3,1	+2.2	+1.1
May	9,5	-1,9	+1.5
June	14,2	-1,6	+0.9
July	15,3	-0,4	+0.7
August	13,9	+0.8	0
September	9,5	+1.2	+4.2
Precipitation	**Average**		
April	36	-19,2	+30
May	52	+61	-11.2
June	68	-7,4	-54
July	77	-9,4	-18.6
August	80	-14,8	+34.2
September	79	+56	-57.2

Tab. 2: Average (1961-1990) air temperature (*C) and precipitation (mm) in the growing season at the field location and the deviations from these values during the trial years.

tractor		tyre dimension	wheel load (kg)	Inflation pressure (kPa)	Contact area (cm^2)	Average ground pressure (kPa)
front	light	42070R28	1500	200	1109	133
	heavy				2400	61
back	light	520/70R38	1555	200	1269	131
	heavy		1700		2799	60
trailer	light	500/50-17	1700	290	956	164
	heavy		2800		1471	178

Table 3: Contact area and average ground pressure for the tractor and the trailer. Light= 12 Mg total weight, heavy= 17 Mg total weight

	2015		2016	
	yield - average t/ha	s.e.	yield - average t/ha	s.e.
reference	3.4	*0.30*	5.9	*0.35*
lOx 1.7 Mg	2.4	*0.18*	6.7	*0.21*
lOx 2.8 Mg	2.7	*0.06*	6.3	*0.66*

Table 4: Spring barley yields (Mg/ha) in 2015 and 2016 after wheeling with different intensity. n=2, Average barley yield on the trial farm was 5.4 t/ha both years

Soil compaction and stress propagation after different wheeling intensities on a silt soil in South-East Norway

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Abstract

The objective of this study was to evaluate the effect of wheeling with two different wheel loads (1.7 Mg, 2.8 Mg) and contrasting wheeling intensities (1x, 10x) on the hearing capacity of a Stagnosol derived from silty alluvial deposits. Soil strength was assessed by laboratory measurements of the precompression stress in topsoil (20 cm) and subsoil (40 and 60 cm) samples. Stress propagation, as well as elastic and plastic deformation during wheeling were measured in the field with combined stress state (SST) and displacement transducers (DTS). We also present results from soil physical analyses (bulk density, air capacity, saturated hydraulic conductivity) and barley yields from the first two years after the compaction. Although the wheel loads used were comparatively small, typical for the machinery used in Norway, the results show that both increased wheel load and wheeling intensity had negative effects on soil physical parameters especially in the topsoil but with similar tendencies also in the subsoil. Stress propagation was detected down to 60 cm depth (SST). The first wheeling was most harmful, but all wheelings led to accumulative plastic soil deformation (DTS). Under the workable conditions in this trial, increased wheeling with a small machine was more harmful to soil structure than a single wheeling with a heavier machine. However, the yields in the first two years after the compaction did not show any negative effect of the compaction.

Keywords

Soil compaction, precompression stress, stress propagation, saturated hydraulic conductivity, wheeling intensity, yield

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Introduction

Increasing production costs lead to growing economic pressure on Norwegian farms. In the attempt to enhance productivity and achieve more economical crop production, there is a growing demand for tractive- and machine power (Lebert, Boken et al. 2007) even on smaller farms (Soane, Dickson et al. 1982, Flowers and Lal 1998). In Norway this is of special concern because climate change with higher rainfall during the season and at harvesting (Hanssen-Bauer , Førland et al. 2015), leads to an increasing risk for soil compaction if heavy machinery is used under unfavourable conditions. Especially harvesting is a problem, as farmers are often confronted with the decision whether to harvest cereals at the earliest possible date , when the soil may be still wet and at risk for severe soil compaction, or to postpone harvest until the soil has dried enough to reduce the risk of compaction but incurring the risk of reduced cereal quality (Sogn and Hauge 1976) and protein content (Sander, Allaway et al. 1987).

Harvesting and associated transport lead to high wheeling intensity and high risk of severe soil compaction. Efficient management of field traffic has a huge potential to reduce the number of passes and thereby the risk of soil degradation (Duttmann, Brunotte et al. 2013). In Norway, there is a national aim toraise cereal production by 20% by 2030 (Vagstad, Abrahamsen et al. 2013, Matdepartement 2016) and there is increasing focus on improving cereal yields. Soil compaction impairs root growth and reduces water and nutrient uptake, which causes yield and quality decline and can even induce increased denitrification, erosion and nutrient leaching (Unger and Kaspar 1994, Lipiec 2012), even several years after compaction (Håkansson and Reeder 1994). Soil compaction due to traffic on agricultural land is therefore assumed to be one of the main causes of soil physical degradation (Flowers and Lal 1998, Pagliai, Marsili et al. 2003) and yield stagnation also in the Scandinavian countries (Petersen, Haastrup et al. 20l0). Avoiding additional soil compaction is therefore of high priority. Special attention should be paid to subsoil compaction due to the use of heavy machinery under high soil moisture conditions. While damage by compaction in the upper soil horizon may be alleviated after four to five years (Håkansson, Voorhees et al. 1987), due to biological, climatic and anthropogenic influences (Gysi, Ott et al. 1999), these effects may be limited in the subsoil and techniques to remediate compacted subsoil are scarce (Lebert, Boken et al. 2007). Subsoil compaction is therefore be assumed to be permanent, persisting over a long period even in northern climates with significant freeze and thaw (Saini 1978, Wolkowski 1990, Håkansson and Reeder 1994, Lipiec 2012, Riggert, Seehusen et al. 2017) and shrinking and swelling cycles (Lamande, Berisso et al. 2012).

The main object of this paper is to describe how typical Norwegian farm machinery (used for instance for harvesting) with different wheel loads (1.7 and 2.8 Mg) and contrasting wheeling frequency (l and lO passes) influences stress propagation and consequently induces further soil deformation. The use of such heavy machinery has rarely been investigated on silt soil under the conditions in southeastern Norway, where the climate is characterized by long, cold winters and relatively short growing seasons with variable rainfall. The methods used to determine the effects of compaction include (l) measurement of the precompression stress to determine soil strength, (2) a combined stress-state and displacement-stress transducer system to determine the major principal stresses and soil deformation in top- and subsoil that occur during wheeling.

In addition, we present results of soil physical parameters (BD, AC, Ksat) to verify soil compaction. These findings are discussed in relation to the yields monitored for two years following the compaction treatment.

Material and methods

Field site

The trial was located on a silt soil in Solør (Stagnosol, medium erosion risk, poor natural drainage) near Kongsvinger (60.25°N, 12.08°E) in South East Norway (WRB 2006) (see Table 1).

The compaction treatments were performed in early summer 2015. The field was divided into two parts (Figure 1). One part of the field was used for the compaction treatment (stress measurements and soil sampling) while the second part was compacted wheel by wheel (10x) with different axle loads (1.7 Mg, 2.8 Mg) and was used for yield analyses in 2015 and 2016. Two strips 1.5 m wide and 15 m long (22.5 m^2) on each treatment plot were harvested. The previous crop was spring barley (2014) Cultural practices were relatively consistent during the study period. All plots were ploughed the autumn before the compaction (2014). The plots were also spring ploughed (25cm) in both 2015 (after the compaction) and 2016. Timing of seeding, fertilizing and soil tillage depended on local climate conditions and the field was treated (e.g. seeding, plant protection) in the same way as the surrounding fields. Seeding (barley, *hordeum vulgare L.)* was done the 16th of June (2015) and 15th of May (2016). Herbicides and fungicides were used both years. Harvesting was done 22th October (2015) and 4th of September (2016).

Climate and soil water content at sampling

The climatic conditions during the trial period were recorded by a nearby weather station and the mean monthly air temperature and precipitation are compared in table 3 to the average values for the period 1961-1990. In 2015 it was slightly colder than average. The month (May) before our compaction treatment was wetter than average but both June and July were drier than average. There was little precipitation the days before the compaction treatment and none during it, resulting in workable conditions, with higher soil moisture tension (upper soil layer -25kPa; subsoil -63kPa) than assumed field capacity (-10kPa) while wheeling.

The growing season in 2016 was both warmer and drier than in 2015 and average (Tab. 2).

Machinery

In both cases single (lx) and multiple (l0x) passes were performed with the same tractor and trailer combination but with different payloads on the trailer. The equipment is typical for small and medium-sized farms in Norway and is commonly used for potato (Solanum tuberosum) transport at harvest.

The lighter tractor/trailer combination had a total weight of 13 Mg, resulting in a wheel load of 1.7 Mg for the trailer. The heavier tractor/trailer combination had a total weight of 17 Mg, resulting in a wheel load of 2.8 Mg for the trailer (tandem axles) (Figure 2). The chosen machinery weight may also be representative for a combine harvester.

Tire inflation pressure (Table 3) was chosen according to factory recommendations. The machinery was weighed prior to the wheeling experiment on a portable scale and the contact area of the wheels was determined by marking the tyre-print with flour. The latter was photographed from above and the image was processed digitally (Gysi, Ott et al. 1999, Zink, Fleige et al. 2010). To determine the average ground pressure, the total load was divided by the surface contact area (Table 3).

Due to the trailer's construction, with tandem axles located towards the end of the trailer (Figure 2), some of the trailer's weight was supported by the back axle of the tractor. Higher trailer weight therefore also increased wheel load on the back axle of the tractor. Higher wheel load led to a higher contact area on the tractor than the trailer, which led to reduced average ground pressure but increased ground pressure on the trailer (Table 3).

Soil measurements

Stress-state and displacement stress transducer systems

In order to determine the influence of various wheel loads and wheeling intensities on soil structure , stress propagation was measured with a stress-state-transducer system (SST) consisting of three sensor heads able to register six normal pressures at one point under the traffic tane. The arrangement of strain gauges on the aluminium sensor head of the SST (Kiel2) is based on the theory of six-directional stress measurements , which was developed by (Harris 1960) and advanced by Grasle (1999). With this arrangement, the vertical stress impact is described by the major principal stress (cr_{1}) and calculated using the SSTKIEL.exe program developed by Johnson (1994). Further details about stress theory and the mathematics behind the development and function of the transducer can be found in Nichols et al. (1987) and (Horn, Johnson et al. 1992). In addition the SST was connected to a displacement transducer system (DTS) (Wiermann, Werner et al. 2000) which was located at 20 cm depth, thus measuring the amount of elastic and plastic displacement in vertical direction in the soil layer directly below

20 cm. The measuring system was installed in 1 x 1 m trenches with the sensors located at 20, 40 and 60 cm depth parallel to the driving direction beneath the centre of the wheel rut. The distance between sensor head and profile wall was about 50 cm (Zink, Fleige et al. 2010). There were done two replications of the SST and DTS measurements. Rut depth was measured with a ruler after every wheeling.

Soil sampling and laboratory measurements

Undisturbed soil samples were taken in order to analyse the stress strain behaviour and to derive the precompression stress (Pc), saturated hydraulic conductivity (Ksat), pore size distribution (total pore volume, TPV; air capacity, AC) and bulk density (DB) in known depths. Soil samples were obtained after first and tenth pass of the light and the heavy tractor-trailer combination.

Soil precompression stress was derived from stress strain measurements carried out under confined conditions (undisturbed soil samples 236 cm3; n=8 per horizon) at field soil moisture content, using a pneumatic multistep oedometer (uniaxial confined compression test) and eight load steps (20, 40, 60, 80, 100, 150, 300 and 400 kPa) (Peth, Rostek et al. 2009). Bach step lasted for two hours to allow drainage of excess pore water. Pc values were determined graphically following the method of Casagrande (1936). Saturated soil samples (100 cm^3; n=10 per horizon) were used to determine saturated hydraulic conductivity based on the hood permeameter method described by Hartge (1993). Undisturbed soil samples (100 cm^3; n=5 per horizon) obtained for analysis of pore size distribution were saturated, drained, using a suction table at-3 kPa to -50 kPa matric potential and pressure plate at 1.5 MPa (identical to -1500 kPa matric potential) and weighed at each step. Finally, the dry bulk density (BD) and air capacity at-3 kPa (AC) were derived. Disturbed samples (- 250 g) were taken for grain size distribution analysis at each depth using the combined sieve and pipette method (Hartge and Horn 2009) with texture following FAO (2006).

Statistical analyses

Values of cr$_1$, Pc, Ksat, AC and DB were analysed using the R statistical software package (2014); cr$_1$, Pc, DB and AC were assumed to be normally distributed and homoscedastic, based on graphical residual analysis. In contrast, Ksat values were not assumed to be normally distributed (skewed to the right), with nonparametric multiple contrast tests according to (Konietschke, Hothorn et al. 2012) thus applied instead. The data were also tested by applying analyses of variance (ANOVA), followed by a corresponding cell means model (Schaarschmidt and Vaas

2009). The significance of the different tests was set at a a-leve) of 5 % and is indicated by upper case letters in the figures.

Results:

Stress- state- transducer measurement (SST)

All wheeling caused noticeable major principal stress (cr$_{1}$) down to 60 cm depth. Differences were found with respect to soil depth, the number of wheeling events and wheel load. Stresses were highest in the upper soil layer. The first wheeling caused the highest stress at all depths but the decline with increasing number of wheelings was more marked in deeper soil depth than at 20 cm, where especially the 2.8 Mg treatment showed reactions even after the 10th wheeling. Higher wheel load (2.8Mg) led to higher stress than the smaller one (1.7 Mg) (Figure 3).

DTS

Most of the measured soil deformation was found to be elastic , but especially the initial wheeling caused more pronounced plastic deformation in the vertical direction, diminishing with increasing number of wheel passes. (Figure 4). Each wheeling event led to additional plastic soil displacement. There were only small differences between the different wheel loads. Higher wheel load led to slightly increased cumulative plastic displacement , approximately 35 mm at 1.7 Mg wheel load and 36 mm at 2.8 Mg wheel load. Vertical soil displacement was seen as ruts on the soil surface. Higher wheel load caused deeper ruts. It was the first wheeling that caused the majority of rut depth in both cases.

Precompression stress (PC):

Differences in Pc values, measured at field moisture content, were not significant but there was a tendency that the Pc in the upper soil layer increased with wheeling intensity and wheel load (Figure 5). Multiple wheeling (l0x) with 1.7 Mg wheel load led to an increase in Pc compared to single wheeling (lx). In the case of 2.8 Mg wheel load, l0x wheeling caused an increase in Pc compared to single wheeling. Higher wheel load led to an increase compared to smaller wheel load (1.7 Mg) for single wheeling with the 1.7 Mg trailer. In the case of multiple wheeling , higher wheel load did not result in any increase in Pc. Pc can be classified as low (30-60 kPa), medium (60-90 kPa) and high (90-120 kPa) (Horn and Fleige 2003). According to this classification, all Pc values in the upper soil layer can be classified as low.

There was a tendency that the differences were less pronounced in 40 cm depth. Multiple wheeling with 1.7 Mg led to a reduction compared to lx wheeling. l0x wheeling with 2.8 Mg led to a slight increase compared to single wheeling. Single wheeling with 2.8 Mg increased the Pc at this depth compared to multiple wheeling with 1.7 Mg.

At 60 cm depth , multiple wheeling caused a (both 1.7Mg and 2.8Mg) increase compared to single wheeling. Higher wheel load (2.8 Mg) led to an increase compared to smaller wheel load. Single wheeling with 2.8 Mg led to a slight increase compared to multiple wheeling with 1.7 Mg. With the exception of multiple wheeling with l. 7 Mg (classified as low), all Pc values in 40 cm and 60 cm depth could be classified as medium (Figure 5).

Effects on physical soil properties and functions

Bulk density (BD)

The effect of wheeling on bulk density (BD) varied (Figure 6). In the upper soil layer both an increase in wheeling intensity and in weight increased BD. Multiple wheeling with 1.7 Mg increased BD more than the single wheeling with 2.8 Mg. At 40 cm depth both increasing wheel load (single wheeling 12%, multiple wheeling 29 %) and increasing wheeling intensity (1.7Mg +10 %, 2.8Mg + 27 %) led to an increase in BD (Figure 6). At 60 cm soil depth multiple wheeling led to a significant increase in BD compared to single wheeling. Also in this layer multiple wheeling with 1.7 Mg did increase DB more than single wheeling with 2.8 Mg.

Air capacity (AC):

Air capacity (AC), expressed as the amount of pores >50 µm, was influenced by both wheeling intensity and wheel load but few effects were significant (Figure 7). In the upper soil layer (20 cm), multiple wheeling significantly decreased AC compared to single wheeling with the same wheelload. Multiple wheeling with 1.7Mg caused a significantly greater reduction in AC than single wheeling with 2.8Mg. At 40 cm depth no significant effects between treatments were found. In the subsoil (60 cm), multiple wheeling with 1.7 Mg led a higher decrease in AC than single wheeling with this wheelload.

Saturated hydraulic conductivity (Ksat)

Results for the K_{sat} values for the upper soil layer (20 cm) showed no significant effects (Figure 8). At 40 cm depth wheeling with 2.8 Mg led to a significant decrease in K_{sat} compared to wheeling with 1.7Mg In the subsoil (60 cm) multiple wheeling with 2.8 Mg significantly decreased K_{sat} compared to the other treatments.

Yields:

In 2015, yields on reference plot (Figure l) were 37 % lower than average barley yields on this farm (about 5.4 Mg/ ha), mostly due to late seeding (Table 4). That was a trend towards reduced yields on the compacted plots compared to the unloaded reference plot. Multiple wheeling with 1.7 Mg wheel load caused approximately 31 % yield loss white multiple wheeling with 2.8 Mg caused 22 % yield loss. In 2016 the yields on the reference plot were slightly higher (+11 %) than on the surrounding area. Yields after multiple wheeling were 11 % (1.7 Mg) respective 5 % (2.8 Mg) higher than on the reference plot.

Discussion:

The main aim of this study was to determine effect of wheeling with two different wheel loads of machinery representing typical Norwegian farm machinery on soil stability , stress propagation, as well as the soil parameters needed to verify soil compaction.

Machinery:

The machinery used in this trial was used on equal terms (e.g. tire equipment, inflation pressure) as done by farmers under practical conditions (Table 3). Although wheel loads used in this trial were not considered to be especially heavy, compared to machinery which may exceed 6.6 Mg wheel load also on Norwegian farms (Seehusen, Børresen et al. 2014, Seehusen, Riley et al. 2014), the trailer had comparatively small tires and high inflation pressure which led to a high average ground pressure (Figure 2, Table 3). It may be expected, that the use of wider tires and/ or reduced inflation pressure would have increased contact area and thereby reduced compaction of the upper soil layer (Raper 2005, Lamande and Schjønning 2011).

(l) Precompression stress (Pc)

Precompression stress is a measure for internal soil strength and is regarded as the stress limit (threshold value) at which the soil deformation changes from elastic to plastic (Peth, Rostek et al. 2009). Data from this study show that increase in both wheel load and wheeling intensity may lead to increase in the Pc values at both 20 and 60cm depth. According to the PC theory, with stresses that exceed Pc, plastic, irreversible soil deformation may be expected (Wiermann, Werner et al. 2000, Horn and Fleige 2009). This may effect important parameters such as air permeability and saturated hydraulic conductivity (Horn and Fleige 2003). Such stresses should therefore be avoided.

(2) Stress propagation and soil deformation in top- and subsoil during wheeling

Our results from the SST measurements show that all wheeling led to stresses in both topsoil and subsoil (Figure 3). The leve! of average major principal stress after wheeling with 2.8mg (55-361 kPa) measured in our trial (Table 4) is in agreement with findings by Zink, Fleige et al. (2010) who tested wheel loads of 3.3 Mg on a Luvisol (83 % silt). Their results show that the first pass caused highest stress in the soil but that every wheeling caused additional stress, which is also in agreement with earlier Norwegian studies on a clay soil (Seehusen , Riley et al. 2014). A dependency of the stress entries (cr_1) on the soil type is not yet clearly proven. Thus, Zink et al.(20 **l** 0) found no differences in the distribution of cr_1 for different initial rates (boulder clay and loess) in their study. By comparing these locations, they determine a 40 % decrease in the stress entries from 20 cm to 40 cm soil depth and by 75 % from 20 cm to 60 cm analogously for both substrates. However , the variations of the stress entries at the boulder grave! locations is greater, which may be attributed to its highertextural heterogeneity. Similar conclusions were made by Ktihner (1997) and Pytka (2005), who conducted wheeling on sandy-loam. They did not find any significant differences in the stress propagation or the total stress input depending on soil type. Only an increased proportion of coarse fragments (> 0.2 cm) contributes to different propagation of stress entries in the subsoil. Horn (1986) attributes the difference in stress in his investigations in southern Germany to the high amount of coarse fragments (> 35 %) more than to the composition of the soil texture. In any case, Pytka et al. (2006) and Pytka (2010) showed a trend towards higher stress leveis on the loess soil <luring further stress measurements with machines than on sandy and loess soils.

Results from the associated DTS measurement show that wheeling led to both elastic and plastic displacement in all cases (Figure 4). Plastic dis placement, caused by stresses that exceed the elastic displacement , is visible as ruts on the soil surface, and has important influences on pore structure and function (Peth, Rostek et al. 2009). It creates not only a new soil structure but also changes soil properties and mechanical stability (Peth and Horn 2006). It is therefore expected to cause irreversible and harmful and soil compaction (Peth, Rostek et al. 2009). Our results show that the first wheeling caused the highest amount of plastic deformation but that every wheeling caused plastic displacement with a cumulative effect (Figure 4). This reduction of soil displacement with increasing number of wheeling events, due to a more stable soil structure created by the progressive compaction of soil part icles, has been shown by other authors earlier (Zink 2009, Seehusen , Riley et al. 2014).

Ruts

The results show that the trailer had, due to its smaller tyres and high inflation pressure, a higher average ground pressure than the tractor. Tyre deflection increases with wheel load (Holtkemeyer 2005, Noltin g, Brunotte et al. 2011) and in our study higher wheel load led to a higher contact area and thereby a reduced contact pressure for both tractor and trailer wheels (Table 3). Despite the partly higher contact area, the higher wheel load caused deeper ruts, as is known from other studies (Botta, Tolon Becerra et al. 2009). The results presented in Figure 4 show that the main rut formation happened after the first wheeling but that additional wheeling contributed to rut formation. The extent of rut formation may be explained by the comparatively high average ground pressure (Table 3) and the loose soil structure in the upper soil layer of the research field due to ploughing the previous autumn. This loose structure , which can also be found after harvest of e.g. potato , is not optimal for wheeling and is prone to rut formation. Ruts are formed though the vertical and horizontal displacement of a soil associated with both soil compression and shearing (Horn, Vossbrink et al. 2007), which destroys the soil structure in the upper part of the soil and increases roIling resistance and fuel consumption, thereby decreasing the efficiency of fieldwork (Bygden, Eliasson et al. 2004, Volk , Denker et al. 2011). Besides, ruts lead to an uneven soil surface which may lead to problems under fieldwork (e.g. seed ing and harvesting), increasing the need for intensive soil loosening (McGarry 2003) and limiting possibilities for fieldwork (Chamen, Alakukku et al. 2003). Rut formation should therefore be limited as much as possible by reducing wheeling on soft ground (e.g. new tilled soil) and by choosing wide tyres and low inflation pressure.

Wheeling intensity

Although not significant in all cases, the findings from this study high light the fact that multiple wheeling with a comparatively small wheel load may be more harmful than single wheeling with a higher wheel load, especially in the upper soil layer. This has also been shown in earlier studies (Bakker and Davis 1995, Hamza and Anderson 2005, Seehusen 2014), where differences in wheel load between machinery were greater than in this study. Different studies show that increasing wheeling intensity leads to smaller vertical stresses in the upper soil layer due to an increase in bulk density, elasticity and shear strength, but it may result in further deformation of deeper soil horizons (Horn, Domzal et al. 1995) also when using light machinery (Botta, Tolon Becerra et al. 2009). This is of great practical interest since, depending on the size and form the field and working width of the machinery, the wheeled area (tracks) may cover up to more than 60 % of the field area which may be wheeled up to four times (soil tillage, fertilizing, spraying, harvesting) during one season. Some parts of the field (headlands) may even be wheeled up to 40 times (Stahl, Schmidt et al. 2001, Duttmann, Brunotte et al. 2013).

This is a conflict in Norway, where the short growing season is one of the most yield-limiting factors (Seehusen, Waalen et al. 2016). The return to field capacity is comparatively early and soils are often moist during harvesting in autumn. On the one hand, larger machinery may offer greater efficiency, which gives the opportunity to take advantage of workable conditions and to make the most of the short growing season (Riley 2016, Seehusen, Waalen et al. 2016). On the other hand, lighter machinery may be of advantage to avoid soil compaction if wheeling under moist conditions is unavoidable (Alakukku, Weisskopf et al. 2003, Holtkemeyer 2005). Reducing machinery weight on existing machinery, as done in this trial, could therefore be an option to adapt machinery to different conditions.

(3) Soil parameters to verify soil compaction

Compaction implies an increase in bulk density (Whalley, Dumitru et al. 1995). Although not significant in all cases, multiple wheeling increased BD in 20cm and 60cm depth. At 40 cm depth both higher wheel load and greater wheeling intensity increased BD. Since this field was ploughed for years before our trial, these comparatively high values in this layer may be a consequence of an earlier compaction of the plough layer, as earlier studies on this field indicate (Seehusen, Hofgaard et al. 2016). Studies show that all compaction leads to a change of pore functions (Horn and Fleige 2009). Compaction could be classified according to the total macroporosity (or air capacity, AC, pores > 50µm) as extremely porous (macroporosity >40 %), porous (25-40 %), moderately porous (10-25 %), compact (5-10 %) and very compact (<5 %) (Pagliai and Vignozzi 2002, Pagliai, Vignozzi et al. 2004). Our results (Figure 7), indicate that AC was negatively affected by all wheel passes. In the upper layer the soil may be classified as "compact" after single wheeling (1x) and "very compact" after multiple wheeling (10x) irrespective of wheel load. In the deeper soil layers all wheeling (irrespective of number and weight) led to a reduction in macroporosity, classified as "very compact" with the exception of single wheeling with 1.7 mg at 60 cm depth (classified as "compact" 6 %). The suggested threshold value of 10 vol.% macroporosity in the upper soil layer (Riley 1988b, Lipiec 2012) as a limit for good plant growth, was not found with any of the treatments.

Saturated hydraulic conductivity (Ksat) depends on pore size and pore continuity (Zink, Fleige et al.2011) and is considered to be of high indication value to describe damage to soil structure. Changes to this parameter may not only affect crop production directly but they may have a negative impact on the ecosystem itself (Horn and Fleige 2009). Results from this study show that all values after multiple wheeling were lower than the threshold value <10 cm d^{-1}) (Lebert, Boken et al. 2007, Horn and Fleige 2009). This may reduce water infiltration, cause water ponding and increased erosion (Fleige and Horn 2000). Although rainfall intensity seldom exceeds 1 cm h^{-1} (Manen, Benestad et al. 2011) these values could be limiting if it rains for several hours with high intensity. Climate change in Norway is predicted to cause both higher total precipitation but also more events of strong rain (Hanssen-Bauer, Førland et al. 2015), so the values we found may be even more problematic in the future.

(4) Yield

Several studies show that soil compaction may cause yield reduction (Czyz 2004) and result in severe yield loss (Lebert, Brunotte et al. 2004). Our data for the stress registered underneath the tractor tyres was up to 565 kPa (Figure 3). Swedish studies (Lofkvist 2005) showed that pressures above 200 kPa in the upper soil layer led to a reduction in barley rooting depth, reduced shoot and root dry weight and reduced leaf length. We would, according our findings, have expected severe yield loss due to soil compaction. However, the yield results of the first two years after the compaction did not fit these assumptions. Although the yields for the year of the compaction (2015) were lower than on the nearby fields, this was mostly caused by delayed seeding due to compaction treatment and soil sampling. Despite ploughing after compaction, before seeding, the yield results show an effect of compaction (Table 4). Yields in 2016 were generally higher, mostly due to favourable weather conditions throughout the growing season (Table 1). Yields on the compacted treatments showed no yield loss compared to the uncompacted treatment. There may be different reasons for this finding. All plots were spring ploughed (25cm) in both 2015 and 2016 which is commonly assumed being effective to loosen the (top-) soil (Appel 2012). Since it is mostly the topsoil compaction that is associated with yield loss (Håkansson and Reeder 1994), repeated ploughing may have been effective to alleviate a possible negative effect oftopsoil compaction on plant growth. Studies described by Håkansson et al. (1987) showed that crop responses to compaction vary widely between years, but are on average negative. Subsoil compaction is expected to be persistent, lead to permanent yield loss and its effects are therefore of great interest (Håkansson and Reeder 1994). But since it is cause off "only" 3-4 % of the yield loss (Petersen, Haastrup et al. 2010), it may be difficult to detect in short term studies. Anyhow, yield, although economically important, is therefore not a precise indicator of the state of soil structure (Lebert, Brunotte et al. 2004, Lofkvist 2005)

Conclusion:

Results from this study show that also comparatively small wheel loads, especially in combination with a high average ground pressure, can cause recognizable compaction, also below the ploughed layer. It is not only the wheel load that is causal but also the number of wheelings. Under workable conditions , as in our experiment, the use of a smaller machinery for soil conservation is only meaningful if this does not lead to an increased wheeling frequency.

The reported yield data the first two years after the compaction show no yield decline. Studies over a longer period of time are necessary to reveal the influence of (sub-) soil compaction on yields. However, compaction may deteriorate important soil parameters (e.g. saturated hydraulic conductivity) which may have negative environmental impact and cause secondary effects such as tater drying , increased risk for soil compaction and shortened growth period. Soil compaction may therefore still be of ecological and economical concern. These effects are expected to be even more problematic in the light of climate change with more severe precipitation. New soil samples on this field will help to determine long time effect of soil compaction on soil structure.

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