Timeliness and traffic intensity in spring fieldwork in Norway: Importance of soil physical properties, persistence of soil degradation, and consequences for cereal yield

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Future increase in precipitation in Scandinavia may exacerbate the dilemma of spring fieldwork that farmers have, concerning topsoil compaction versus delayed sowing on autumn ploughed soil. The former may lead to soil physical degradation, while the latter may lead to a shorter growing season, both with consequential loss of cereal yield potential. In order to enable farmers to adapt their spring fieldwork to climate change, research needs to include seedbed preparation at higher soil moisture conditions. A split-plot experiment in southeastern Norway in 2014–2017 explored the effects of timing (early, medium, late) and traffic intensity (zero, one, two or three additional wheelings) of spring fieldwork on soil physics and yield. Early spring fieldwork in the unfavourably wet conditions of 2016 gave rise to larger and stronger aggregates, higher penetration resistance, changed pore characteristics and reduced yields. Increased penetration resistance persisted until autumn. The small effect of traffic intensity was explained by location, soil type and intensity range involved. In this context of spring fieldwork timeliness, the proportion of 2–6 mm aggregates and penetration resistance were the properties most strongly correlated with other soil physical properties and cereal yield.

Key words: seedbed preparation, soil cultivation, timing, soil compaction, yield losses

Introduction

In cold-temperate regions with high soil water content in spring, timing and intensity of field traffic during seedbed preparation for spring cereals may strongly influence soil structure, leading to the risk of yield loss. In such regions, farmers have traditionally adapted to a short growing season by ploughing their soil in autumn and starting seedbed preparation as early as possible in the following spring (Peltonen-Sainio et al. 2009). The decision on when to start spring fieldwork presents farmers with a dilemma of timeliness. If the fieldwork starts too early, when the soil is still wet, the farmer risks yield loss due to topsoil compaction (Njøs 1978, Marti 1983, Hofstra et al. 1986, Bakken et al. 1987, Håkansson 2005) and oxygen deficiency during germination. If the farmer waits until the soil is dry enough, there is a risk of yield loss due to delayed sowing and a shorter growing season (Riley 2016).

In the future, climate change may exacerbate this dilemma, due to projected increases in precipitation during winter and spring in Scandinavia (Trnka et al. 2011, Hov et al. 2013). At the optimum sowing date, the soil temperature is high and stable enough to sow locally adapted cereal varieties, with sufficient time left for the crop to reach full maturation during the growing season. After the optimum sowing date, the average risk of yield loss due to delayed sowing and shorter growing season increases even faster than the risk of yield loss due to soil compaction decreases (Riley 2016). This often leads farmers to accept some compaction loss in order to avoid larger loss due to delayed sowing. In order to enable farmers to adapt their spring fieldwork to climate change, research needs to include seedbed preparation at higher soil moisture conditions.

In earlier Scandinavian seedbed research, the most commonly used physical property describing seedbed quality was aggregate size distribution (Håkansson et al. 2002, Håkansson et al. 2011a,b). Aggregate size usually increases with increasing soil water content at the time of seedbed preparation (de Toro and Arvidsson 2003, Dexter and Birkas 2004). Traditionally, with normal dry conditions after sowing, seedbeds with larger aggregate size, i.e. more than 50% aggregates >5 mm, are considered to have poor quality for plant establishment (Håkansson et al. 2002). However, there has been too little attention to other physical properties that may be important for early plant growth, and how these are affected by soil moisture conditions or by traffic intensity during seedbed preparation.

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Earlier studies on effects of traffic intensity on soil physical properties and crop yield in Norway often represented traffic by wheeling under wet conditions in early spring. However, in these studies the seedbed preparation was conducted later in spring and at the same time for all treatments (Njøs 1978, Marti 1983, Hofstra et al. 1986, Bakken et al. 1987), which does not resemble agricultural practices. Moreover, the persistence of treatment effects has seldom been explored, even though soil structure degradation can persist for a long time (Håkansson and Reeder 1994, Håkansson 2005).

The aim of this project was to study the effects of timing and traffic intensity of spring fieldwork on soil physics in spring and autumn, and their consequences for cereal yield. Another aim was to gain more insight into which soil physical properties are most responsible for the negative effects of traffic at high soil moisture content. In addition, actual yields were compared with simulated yields, in order to assess the extent to which a springwork timeliness model reflects actual yields, relative to other factors that affect yields later in the growing season.

Material and methods

Study site

The field experiment was conducted at the Norwegian University of Life Sciences, Ås (59° 39′ 46″ N 10° 45′ 49″ E, 69 m above sea level), situated in southeastern Norway, which is the most important cereal-growing region in the country (Statistics Norway 2018). At the experimental site, spring cereals have dominated for at least 60 years. The climate in Ås is characterized as nemoral (NEM3) by Metzger et al. (2005). Selected weather variables from the nearest climate station (59° 39′ 37″ N 10° 46′ 56″ E, 93 m above sea level) are shown in Table 1. Calculations are based on daily precipitation, mean temperature, relative humidity, global radiation and wind speed, obtained from the Norwegian Institute of Bioeconomy Research (http://lmt.nibio.no/), the Norwegian Meteorological Institute (http://www.met.no) and the Norwegian University of Life Sciences (Wolff et al. 2018). Calculation of potential evaporation was made with an equation based on measured pan evaporation (Riley and Berentsen 2009).

Table 1. Mean (and standard deviation) of selected weather variables at the experimental site during spring in a 30-year reference period (1973–2012) and the experimental years (2014–2017)

	1973–2012	2014	2015	2016	2017
Mean temperature (°C)					
March	0.1 (2.3)	3.7	2.6	1.8	1.9
April	4.7 (1.5)	6.7	6.2	5.2	4.4
May	10.6 (1.2)	10.9	8.3	11.1	10.8
Precipitation (mm)					
March	55.2 (43.2)	38.7	62.9	56.9	41.3
April	43.8 (26.6)	62.8	11.9	68.9	33.7
May	55.0 (28.9)	39.8	101.7	71.7	69.3
Potential evaporation (mm)					
March	4.3 (4.9)	7.6	3.9	0.4	3.0
April	37.3 (9.7)	41.3	53.3	34.9	41.8
May	83.8 (14.0)	76.2	71.1	84.8	70.1

The soil at the experimental site is classified as Luvic Stagnosol (Siltic) in the World Reference Base classification system (FAO 2006), with a loam A horizon overlaying silt loam and silty clay loam. The topsoil (0–27 cm) consists of 21% clay (<2 μm), 42% silt (2–60 μm) and 37% sand (> 60 μm) (Hofstra et al. 1986). Soil organic matter content at 0–15 cm depth is 4.5% (Obour et al. 2018). The soil was been pipe-drained in 1983.

Experimental design and management

Prior to each of the experimental seasons of 2014–2017, the experimental site was mouldboard ploughed in autumn to a depth of approximately 22 cm. Twenty-four plots of 3.75 x 12 m were set up in a randomized split-plot design with two factors and two replications (Fig. 1). The main plot treatment was timing of spring fieldwork (harrowing and sowing) and the sub-plot treatment was traffic intensity during spring fieldwork.

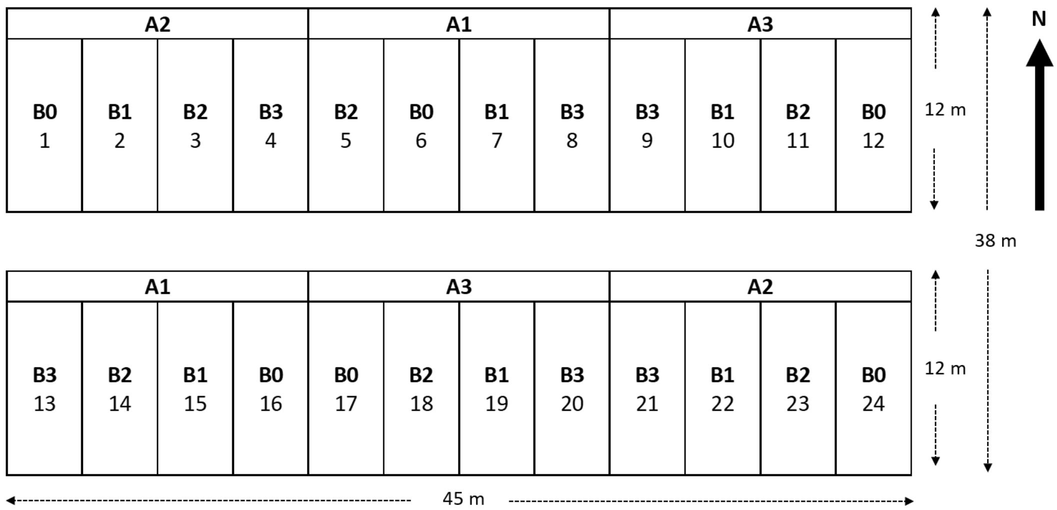

Fig. 1. Experimental split-plot design with factors timing (A) and traffic intensity (B)

The timing was either early (A1), medium (A2) or late (A3) harrowing and sowing date. Different degrees of traffic intensity were obtained by making different numbers of additional wheelings with a tractor just before harrowing. Traffic intensity levels were zero (B0), one (B1), two (B2) or three wheelings (B3). The decision on when to start fieldwork was based on perception of friability by manual kneading as practiced by farmers. The intention was to select an early sowing date with soil that was considered unfavourably wet (yield loss due to physical soil degradation expected), a medium date with soil that was considered favourably moist for tillage (no yield loss expected), and a late date with soil that was at least as dry as the medium date (yield loss due to shorter growing season expected). Actual volumetric water contents in the field were determined just before sowing with a hand-held time-domain reflectometer (TDR) (HH2-ML3, Delta-T Devices, Cambridge, England) at 5–10 cm depth. Means of 5 TDR measurements per sowing date were used, with the exception of values for early and medium fieldwork in 2014, which were determined by manual soil sampling, weighing and drying. Actual dates and soil water contents for different sowing time in the different years are presented in Table 2. Water contents are presented relative to the soil's water content at field capacity (FC, –100 hPa), which was assumed to be 35.0 vol% for depth of 0–20 cm in this soil type (Riley 2016) and agrees quite well with earlier laboratory measurements (Hofstra et al. 1986).

Table 2. Actual dates for different sowing time and their associated mean soil water content at 5–10 cm depth, presented in % of field capacity (FC), in spring 2014–2017 at Ås

	Sowing date		
	Early	Medium	Late
	Soil water content (% FC)		
2014	2 April	15 April	25 April
	60	56	52
2015	8 April	13 April	23 April
	90	73	63
2016	11 April	25 April	9 May
	104	69	78
2017	3 April	11 April	5 May
	103	74	69

The included traffic intensities represent mouldboard ploughing, harrowing, sowing and rolling, which are part of common spring fieldwork in Norway. In Swedish experiments, wheel track coverages of 115–395% during spring fieldwork have been reported (Håkansson 2005). In comparison, Norwegian fields are smaller and more irregular in shape, resulting in more turning and overlap. Furthermore, several harrowings and additional rolling are common, and wheel track coverage is not evenly distributed, all of which increase the total wheel track coverage during spring fieldwork. All experimental fieldwork, i.e. wheeling, harrowing, sowing and rolling, was done on the same day.

The soil was compacted wheel-by-wheel with a MF 4225 tractor loaded to 4.5 Mg with tyre inflation pressure of 1.5 bar, and harrowed to a target depth of 5 cm with a Ferraboli rotary harrow. Wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), oats (*Avena sativa* L.) and barley were sown, in 2014, 2015, 2016 and 2017, respectively, with a Junkkari Simulta 2500 combined seed-fertilizer drill. Rolling was done with a light Cambridge roller.

Soil sampling and *in situ* measurements

Two litres of bulk soil per plot were sampled with a spade immediately after sowing, air-dried without further manipulation and stored dry until analysis. Furthermore, in May 2016 bulk soil and soil cores were sampled from B0 and B1 treatments plots and prepared as described in Obour et al. (2018). Three (2015) or two (2016 and 2017) undisturbed soil cores (5.8 cm diameter, 3.7 cm height, ≈ 100 cm^3) per plot were sampled after cereal harvest in autumn at a depth of 1–5 cm, covered with plastic lids and stored at 4 °C until analysis. Penetration resistance in the field was measured in spring 2016 (24 and 25 May) in non-compacted and once-compacted plots with 5 measurements by Eijkelkamp Penetrologger 06.15.31 (Giesbeek, NL), to a depth of 15 cm using a 60° cone with 11.28 mm base diameter and 2 cm s^{-1} penetration speed. In autumn 2016 (19 September) penetration resistance was measured in all plots with Eijkelkamp hand penetrometer (Giesbeek, NL), using a cone with 15.96 mm base diameter. Geometric mean values of penetration resistance were calculated for depths of 0–5, 5–10 and 10–15 cm.

Laboratory measurements and analyses

Air-dried bulk soil was sieved for 3 min (240 shakes min^{-1}, 12 mm amplitude) in a set of sieves with mesh sizes of 0.6, 2, 6 and 20 mm. The different fractions were weighed and their weight proportion of bulk soil minus stones was calculated. Mean weight diameter (MWD) was calculated as the sum of products of the mean diameter of each size fraction and the proportion of total sample in that fraction (van Bavel 1949). Soil cores were weighed, saturated from below and water retention was measured after desorption to different matric potentials. Desorption to –20 and –50 hPa (except 2017) was achieved in an Eijkelkamp sandbox (Giesbeek, NL), whilst –100, –1000 and –15000 hPa were achieved on ceramic pressure plates (Richards 1947, 1948). At –100 hPa, air-filled porosity and air permeability were measured by air pycnometer (Torstensson and Eriksson 1936) and with the method described by Green and Fordham (1975), respectively. The cores were dried at 105 °C and bulk density was calculated. Total porosity was calculated as air-filled porosity at –100 hPa plus water volume at –100 hPa. Plot-wise values of volumetric water content at –15000 hPa from 2017 were used for further calculations of bulk density in all years. Percentages of macropores, coarse medium pores and fine medium pores were calculated as total porosity minus water content at –100 hPa, water content at –100 hPa minus those at –1000 hPa, and water content at –1000 hPa minus those at –15000 hPa, respectively. Measurements of air-filled porosity, air permeability and aggregate tensile strength from May 2016, presented by Obour et al. (2018), were included for comparison. These parameters were measured as described in Obour et al. (2018).

Actual and simulated yield

Actual cereal yields were harvested with a plot combine on 1.5 m × 6 m of each plot and expressed relative to the maximum yield of each replication. For comparison, yield potential was simulated with a workability model (Riley 2016), that combines two functions of timeliness-related loss of yield potential, namely loss due to topsoil compaction (Fig. 2a) and loss due to delayed sowing (Fig. 2b). The former expresses whether the technical requirement of workability is met, assuming that spring fieldwork causes no compaction loss at moisture content of less than 66% of field capacity (FC, –100 hPa). The latter expresses whether plant requirement of growing season length for this region is met, assuming that spring fieldwork before 16 April causes no delay loss. For the simulations we selected soil type 3 (Riley 2016), representing loam with 10–25% clay and a water content of 70 mm at FC at 0–20 cm depth. Average recorded soil moisture contents on each sowing date were used as input.

Based on results from the field experiment, the study explored whether physical properties were correlated with actual yield. In addition, the relationship between the risk of yield loss, in terms of simulated yield, and actual yield was explored.

Data analyses and statistics

The data were analysed separately for each year in R version 3.5.1 (R Core Team 2018) by building mixed effects models in lmerTest package (Kuznetsova et al. 2017), with random “Replication” and considering the split-plot design by the interaction “Replication:Timing”. ANOVA type III was conducted with Satterthwaite’s method for degrees of freedom (DF). Least squares mean (lsmean) values were calculated and post hoc tests (Tukey HSD with Satterthwaite's method for DF) conducted by emmeans package (Lenth 2018), the latter only in cases with ANOVA F-test p-values <0.05. Significant differences are reported for α< 0.05. To allow direct comparisons with non-compacted and once compacted plots on the three different sowing dates in May 2016, some data from September 2016 were analysed separately for these plots. Correlation coefficients were calculated by the Spearman method. Graphics were created in ggplot2 (Wickham 2009), grid and gridExtra packages (Auguie and Antonov 2016).

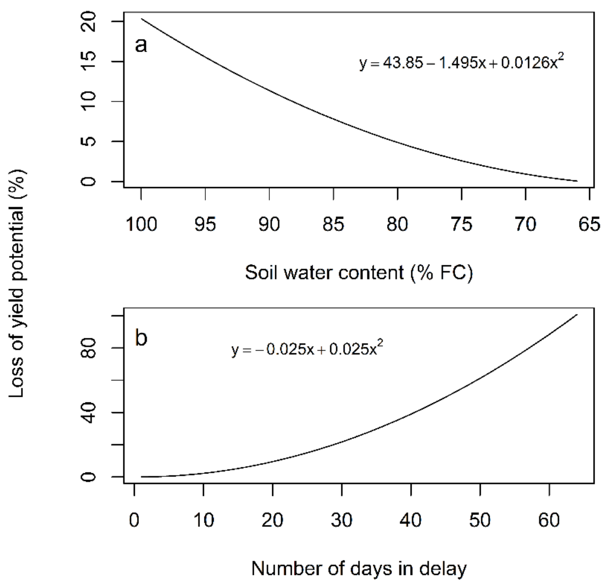

Fig. 2. Functions used for calculation of loss of yield potential affected by (a) soil water content in % of field capacity (FC, –100 hPa) at 0–20 cm soil depth during spring fieldwork, and (b) number of days after optimum sowing date 15 April (Riley 2016; redrawn from Kolberg et al. 2019)

Results

Effects of timing and traffic intensity of spring fieldwork on physical properties

Aggregate size distribution in spring

In general, we found larger aggregates after early seedbed preparation on wetter soil and larger aggregate size with increasing number of wheelings under the wettest conditions. In 2014 and 2015, there were minor differences in aggregate size distribution between sowing dates and traffic intensities (Fig. 3).

The largest differences were observed in 2016. In that year, we found a significantly larger proportion of >20 mm, 6–20 mm and 0.6–2 mm aggregates in A1 than in A2 and A3. In addition, we found a larger proportion of 2–6 mm aggregates in A2 and A3 than in double and triple compacted plots of A1, as well as a larger proportion of <0.6 in A2 and A3 than in A1.

In 2017, we recorded a significantly larger proportion of >20 mm aggregates in A1 than in A2 and A3, and a larger proportion in A1B3 and A1B2 than in A1B1 and A1B0. In addition, there was a larger proportion of 2–6mm in B0 and B1 than in B3, and a larger proportion of 0.6–2 mm in A2 and A3 than in A1.

In 2016, there was a significantly larger MWD after early than after medium and late seedbed preparation (data not shown). In 2017, there was a significantly larger MWD after A1 than after A3 and compacted A2. In addition, double and triple compacted A1 had larger MWD than non-compacted A1.

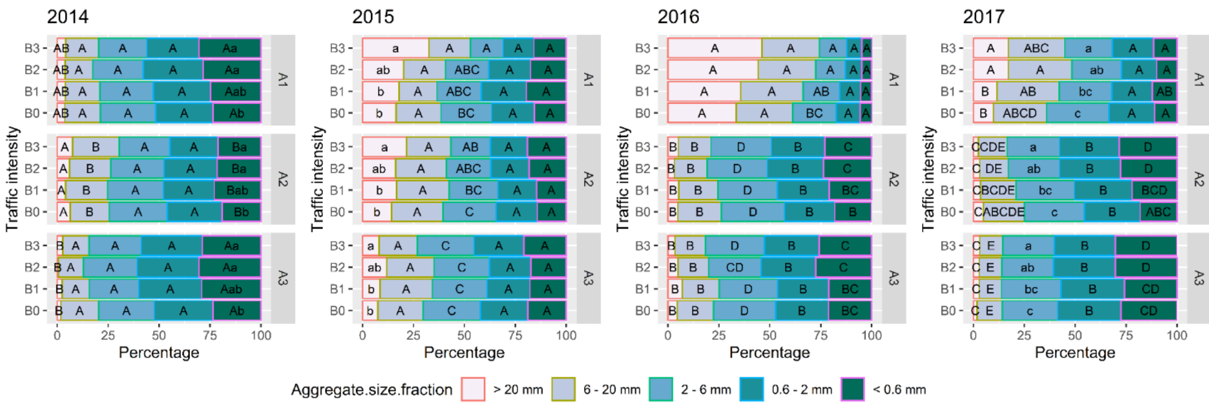

Fig. 3. Percentage of different aggregate size fractions (>20 mm, 6–20 mm, 2–6 mm, 0.6–2 mm, <0.6 mm), affected by timing (Sowing date: A1 = early, A2 = medium, A3 = late) and traffic intensity (B0 = no, B1 = one, B2 = two, B3 = three wheelings) during spring fieldwork in 2014–2017. Different letters indicate significant differences in Tukey comparison within each aggregate size fraction and year, with capital letters for effect of sowing date and interaction between sowing date and traffic intensity, uncapitalised letters for effect of traffic intensity only.

Soil pore characteristics

In general, largest effects of timing and traffic intensity of spring fieldwork on soil pore characteristics were found in 2016. In 2016, there was a significantly higher total porosity in autumn after medium fieldwork (51.8 vol%) than after early (48.0 vol%) and late spring fieldwork (47.1 vol%). In that year, soil samples also had a significantly lower volumetric water content at –100 (in pores <30 µm) and –1000 hPa (in pores <3 µm) matric potential in autumn after late than after early spring fieldwork. There was no effect on the proportion of macropores (>30 µm) in spring (Table 3), but a significant interaction effect between traffic intensity and timing on the proportion of macropores in autumn 2016. The proportion of macropores was greater after non-compacted medium spring fieldwork than after zero, once and triple compacted early and once compacted late spring fieldwork.

There was no significant influence on the proportions of micro (<0.2 µm), fine medium (0.2–3 µm) or coarse medium (3–30 µm) pores. There was no significant effect of timing or traffic intensity of spring fieldwork on air permeability through macropores in 2016.

Table 3. Proportion of macro pores (>30 µm) and their corresponding air permeability (AirPerm), measured at –100 hPa matric potential at a depth of 0–5 cm in May and September 2016, affected by timing (Sowing date: A1 = early, A2 = medium, A3 = late) and traffic intensity (B0 = zero, B1 = one, B2 = two, B3 = three wheelings) during spring fieldwork in 2016

		Macro pores (vol%)		Air permeability (µm^2)	
Timing	Traffic	May	Sept*	May	Sept
A1	B0	25	$^{\alpha}$7.1^{a}	541	2.2
A1	B1	26	$^{\alpha}$8.2^{ab}	725	1.7
A1	B2	-	11.1^{abc}	-	2.3
A1	B3	-	4.9^{a}	-	0.9
A2	B0	28	$^{\beta}$18.2^{c}	783	12.6
A2	B1	28	$^{\beta}$10.5^{abc}	386	6.9
A2	B2	-	15.7^{bc}	-	12.2
A2	B3	-	10.2^{abc}	-	4.2
A3	B0	27	$^{\alpha\beta}$7.8^{ab}	491	3.9
A3	B1	21	$^{\alpha\beta}$11.4^{abc}	254	4.5
A3	B2	-	10.2^{abc}	-	4.4
A3	B3	-	11.1^{abc}	-	4.1

* Different letters indicate significant difference in Tukey comparison; Greek letters for comparisons including non-compacted and once compacted plots only, Latin letters for comparisons including all plots.

In other years, there were some cases of significant effects on pore characteristics (not shown). In autumn 2015, volumetric water contents at –20, –50 and –100 hPa were significantly lower after late than after early spring fieldwork, though without any impact on the proportions of micro (<0.2 µm), fine medium (0.2–3 µm), coarse medium (3–30 µm) or macro (>30 µm) pores. In autumn 2017, the proportion of coarse medium pores (3–30 µm) was significantly larger after medium and late fieldwork than after early fieldwork. During the crop growing season of 2016, when comparing autumn to spring measurements, the proportion of macropores and their corresponding air permeability decreased from May to September (Table 3). The interaction effect on the proportion of macropores in spring did not persist consistently until autumn, and the described effect on air permeability of macropores was no longer significant in autumn.

Strength of aggregates and bulk soil

The only year with a significant effect of timing on bulk density was 2016. We observed a significantly lower bulk density at 0–5 cm depth in the following autumn after medium (1.26 g cm^{-3}) than after early (1.37 g cm^{-3}) and late (1.36 g cm^{-3}) spring fieldwork.

In 2016, we also found significant effects of timing (p = 0.007) and traffic intensity (p = 0.035) on aggregate tensile strength at a depth of 5–10 cm (Table 4). Aggregates were significantly stronger after early than after medium and late spring fieldwork, and significantly stronger after wheeling.

In addition, soil penetration resistance was significantly affected by the experimental treatments in July and September. In July, penetration resistance at 0–5 cm depth was affected by timing (p = 0.028), while at 5–10 cm depth it was affected by timing (p = 0.001) and wheeling (p = 0.008). There was a significantly greater penetration resistance in July after early than after medium and late spring fieldwork at 0–5, 5–10, and 10–15 cm depth. At the same time in July, there was a significantly higher penetration resistance in compacted than in non-compacted plots at the 5–10 cm depth. In September, penetration resistance was affected (p = 0.031) by timing at 5–10 cm depth. There was a significantly greater penetration resistance after early than after medium spring fieldwork at all depths (Table 4). Penetration resistance generally increased during the growing season (Greek letters), while the timing effect of seedbed preparation on penetration resistance either decreased (0–5 cm) or increased (5–10 and 10–15 cm depth), and the effect of wheeling at 5–10 cm depth disappeared between July and September. Among all correlations between aggregate size distribution and other physical properties, the strongest relationship was observed between the proportion of 2–6 mm aggregates and penetration resistance at 5–10 cm depth.

Table 4. Lsmean values of geometric mean tensile strength (kPa) of air-dried 8–16 mm aggregates in May and penetration resistance (MPa) measured at different depths (0–5 cm, 5–10 cm, 10–15 cm) in July (27.5 vol% water) and September 2016 (29.1 vol% water), affected by timing (Sowing date: A1 = early, A2 = medium, A3 = late) and traffic intensity (B0 = zero, B1 = one, B2 = two, B3 = three wheelings)

		Aggregate tensile strength (kPa)		Penetration resistance (MPa)					
		May		July			September		
Timing	Traffic	0–5	5–10	0–5	5–10	10–15	0–5	5–10	10–15
A1	B0	97	$^{\alpha A}$ 111	$^{\alpha}$ 0.6	$^{\alpha A}$ 1.2	$^{\alpha}$ 1.3	1.4 ^{a}	$^{\alpha}$ 1.5 ^{a}	$^{\alpha}$ 1.6 ^{a}
A1	B1	135	$^{\alpha B}$ 175	$^{\alpha}$ 0.6	$^{\alpha B}$ 1.3	$^{\alpha}$ 1.5	1.2 ^{a}	$^{\alpha}$ 1.5 ^{a}	$^{\alpha}$ 1.6 ^{a}
A1	B2	–	–	–	–	–	1.9 ^{a}	1.9 ^{a}	1.8 ^{a}
A1	B3	–	–	–	–	–	1.7 ^{a}	1.9 ^{a}	1.9 ^{a}
A2	B0	95	$^{\beta A}$ 74	$^{\beta}$ 0.4	$^{\beta A}$ 0.7	$^{\beta}$ 0.9	0.7 ^{b}	$^{\beta}$ 0.9 ^{b}	$^{\beta}$ 1.0 ^{b}
A2	B1	76	$^{\beta B}$ 98	$^{\beta}$ 0.4	$^{\beta B}$ 0.7	$^{\beta}$ 1.0	0.8 ^{b}	$^{\beta}$ 0.9 ^{b}	$^{\beta}$ 1.0 ^{b}
A2	B2	–	–	–	–	–	0.7 ^{b}	0.9 ^{b}	1.1 ^{b}
A2	B3	–	–	–	–	–	0.8 ^{b}	1.1 ^{b}	1.1 ^{b}
A3	B0	69	$^{\beta A}$ 94	$^{\beta}$ 0.3	$^{\beta A}$ 0.7	$^{\beta}$ 0.9	1.0 ^{ab}	$^{\alpha\beta}$ 1.3 ^{c}	$^{\alpha\beta}$ 1.4 ^{ab}
A3	B1	113	$^{\beta B}$ 88	$^{\beta}$ 0.4	$^{\beta B}$ 0.9	$^{\beta}$ 1.0	1.0 ^{ab}	$^{\alpha\beta}$ 1.2 ^{c}	$^{\alpha\beta}$ 1.1 ^{ab}
A3	B2	–	–	–	–	–	1.0 ^{ab}	1.3 ^{c}	1.4 ^{ab}
A3	B3	–	–	–	–	–	1.2 ^{ab}	1.2 ^{c}	1.3 ^{ab}

Different letters indicate significant differences in ANOVA F-test or Tukey comparison; with Greek letters for comparisons including non-compacted and once compacted plots on the three sowing dates, with Latin letters for comparisons including all plots.

Effects on actual and simulated cereal yield

There was no significant effect of timing or traffic intensity on actual cereal yield, except for the effect of timing in 2016 (Table 5). In 2016, actual cereal yield was significantly lower after early fieldwork than after medium (p=0.02) and late fieldwork.

The strongest relationship with actual yield was observed for the proportion of 2–6 mm aggregates (data not shown). The strongest relationship with simulated yield was observed for penetration resistance at 5–10 cm depth, if we disregard its strong relationship with moisture content at 5–10 cm depth. The latter was used as simulation input and was therefore bound to be highly correlated. Correlation coefficients for 2016 were larger than for 2014–2017 collectively.

Table 5. Lsmean values of actual yield (ActYield[1]) and simulated yield (SimYield[2]) affected by timing (Sowing date: A1 = early, A2 = medium, A3 = late)

	2014: wheat		2015: barley		2016: oats		2017: barley	
Timing	ActYield	SimYield	ActYield	SimYield	ActYield	SimYield	ActYield	SimYield
A1	0.92	1.00	0.89	0.86	0.75 a	0.71	0.74	0.76
A2	0.82	1.00	0.91	0.97	0.96 b	0.96	0.88	0.97
A3	0.66	0.96	0.85	0.98	0.93 b	0.80	0.85	0.89

[1] Expressed as relative to highest yield in respective replication; different letters indicating significant difference in Tukey comparison.
[2] Based on average recorded moisture content at 5–10 cm depth during spring fieldwork and optimum sowing date 15 April used in combined functions of yield loss due to too wet and too late spring fieldwork (Fig. 2).

Discussion

Effects of timing and intensity of spring traffic on physical properties in spring and summer

The observed treatment effects on aggregate size distribution shortly after spring fieldwork are in accordance with results of previous seedbed research. The larger aggregates after spring fieldwork in wet soil (Fig. 3) are in line with several earlier studies (Håkansson et al. 2002, de Toro and Arvidsson 2003, Dexter and Birkas 2004, Keller et al. 2007), while the larger aggregates after higher traffic intensity under the wettest conditions are in line with Marti (1983) and Njøs (1978), and with tendencies seen in Obour et al. (2018). In contrast to the latter, our study did not reveal any significant treatment effects on air-filled porosity, air permeability (Table 3) or tensile strength of air-dried 8–16 mm aggregates sampled at 0–5 cm (Table 4) in May 2016. The most important reason for this is probably that Obour et al. (2018) did not consider the experiment's split plot design in their statistical analyses. On the other hand, we observed stronger treatment effects than Obour et al. (2018) on aggregate tensile strength at 5–10 cm depth. At this depth, we observed an increase in aggregate tensile strength after early spring fieldwork and after a single wheeling.

In addition to increases in soil strength at the aggregate level, the more compacted state of the soil after early spring fieldwork is confirmed by increased penetration resistance in July 2016 at all depths and at 5–10 cm depth after one wheeling (Table 4). The effect of wheeling on penetration resistance is in line with more than three wheelings in Reintam et al. (2009). The effect of soil moisture content during spring fieldwork is similar to increases in shear strength observed in earlier research (Njøs 1978, Marti 1983, Hofstra et al. 1986). The observed tendency of increased aggregate tensile strength after too wet (early and late) spring fieldwork in 2016 is in line with Munkholm and Schjønning (2004). The latter study also reports larger increases in penetration resistance in their second year of high traffic intensity. Larger and stronger aggregates or higher penetration resistance can be negative for plant growth and nutrient uptake under normal conditions after sowing (Misra et al. 1988, Arvidsson 1999, Håkansson et al. 2002). Larger and stronger aggregates and higher penetration resistance may be reasons for the risk of yield loss in soil tilled while still too wet, as described by Riley (2016).

Effects of timing and intensity of spring traffic on physical properties in autumn

Generally, the decreases in air-filled porosity and air permeability from May to September fit well with increases in penetration resistance, but the decreases may have several explanations. Firstly, the measurements were made in two laboratories with different routines and methods. Another, and probably more important, explanation may be soil settlement due to wetting and drying cycles throughout the crop growing season (Lapen et al. 2004, Daigh and DeJong-Hughes 2017, Sandin et al. 2017). The increase in treatment effect on air-filled porosity from spring to autumn may be relevant for crop growth if it persists after ploughing in autumn. With reduced air-filled porosity one might expect reduced air permeability, but this was not found to be the case in autumn (Table 3). A possible explanation may be that air permeability also depends on tortuosity and connectivity, as discussed by Tang et al. (2011). Volumetric water content measurements at the highest matric potentials (lowest pressure) in autumn 2015 and 2016 indicate that there were more of the very large pores after late than after early fieldwork. In 2015, this had no influence on total porosity or any of the calculated pore sizes and was not consistently reflected in the effects on total porosity or macropores in 2016. Lower bulk density and higher total porosity in autumn 2016 after medium than after early and late spring fieldwork are in line with Reintam et al. 2009. High bulk density and low porosity indicate soil compaction (Håkansson et al. 1988) during early spring fieldwork.

Even though the treatment effects for some physical properties and at some depths disappeared during the season, penetration resistance was still significantly greater after early than after medium spring fieldwork at 5–10 and 10–15 cm depth. When considering all plots (Latin letters in Table 4), the increased penetration resistance in September 2016 after early fieldwork at all depths is in line with de Toro and Arvidsson (2003). According to short-term results in spring shown by Munkholm and Schjønning (2004), intensive tillage and intensive traffic created denser aggregates and larger penetration resistance at 0–20 cm depth. However, according to their long-term results in autumn, intensive tillage seemed to densify single aggregates, whilst the effect of intensive traffic on aggregate tensile strength did not last as long. Unfortunately, in our study we did not explore whether the densification of bulk soil, in terms of penetration resistance, is as persistent as the densification of aggregates, in terms of tensile strength.

In this study, the effect of traffic intensity was not as strong as the effect of timing. This is probably due to relatively low traffic intensities, compared to those that are common during traditional seedbed preparation (Håkansson 2005).

Importance of physical properties and effects on yield

The year 2016 stands out with its effect of timing on soil physical properties and yield. The reason for that is not quite clear. In both 2016 and 2017 we expected yield effects due to the high water content on early sowing date. Possibly, incidents of heavy rain (25 mm) just 5 days after each of early and medium sowing dates in 2016 may be the reason for significant effects of spring fieldwork timing on yield that year.

In 2016, the strongest correlation was found between the proportion of 2–6 mm aggregates and yield. This fits in well with the strongest correlations of the 2–6 mm fraction with other physical properties, and its importance for seedbed quality and crop establishment, as found in traditional Scandinavian seedbed research (Håkansson et al. 2002, Keller et al. 2007, Håkansson et al. 2011b). The opposite correlations for penetration resistance to smaller size fractions compared to larger size fractions illustrate that smaller aggregates are related to lower penetration resistance, as reported by Misra et al. (1988). The importance of penetration resistance for soil physical properties and crop yield is in line with Bölenius et al. (2017) and Lapen et al. (2004), who found penetration resistance to be the most important property for variations in cereal yield and a property representative of soil quality. Based on their strong correlations with many other physical properties, the 2–6 mm fraction and the penetration resistance may be regarded as properties that cover well many different aspects of soil physics and thus its overall variation.

In contrast to Obour et al. (2018), we did not find any effect of traffic intensity on actual cereal yield in any of the experimental years, but we found an effect of timing on actual yield in 2016, probably due to the mentioned differences in the statistical methods used. There may be several reasons why the only year with an effect of timing on actual yield was 2016. In 2014 soil moisture content during spring fieldwork was low on all three sowing dates. In 2015 and 2017, the small effects on soil physical properties were probably outweighed by other yield-forming factors, such as moisture, temperature, nutrient availability and plant health during critical growth stages throughout the growing season.

Comparing actual yield to the simulated yield gives an impression of how much the actual yield is influenced by spring fieldwork timeliness (Fig. 2) and how much it is influenced by other yield-forming factors. The most important reason for deviations between actual and simulated yield is that the model considers only risk of yield loss due to timeliness of spring fieldwork, i.e. compaction loss in too wet soil and loss due to delayed sowing. Other factors like management and climate throughout the crop growing season are disregarded, even though the actual yield depends on the combination of specific conditions through all growth stages. Cereals have a great capability to compensate for inadequate establishment by a number of yield-forming components, especially those that contribute to the number of grains per square meter (Peltonen-Sainio et al. 2007), i.e. number of tillers, spikes per plant, spikelets per spike and grains per spikelet. In the unusually wet and cold May 2015 (Table 1), the crop may have been able to compensate for initial limitations related to spring fieldwork timeliness by increased tillering. Similarly, the stronger relationship between relative recorded and simulated yield in 2016 than in 2014–2017, and the stronger correlations with physical properties, both mean that growth conditions in 2016 were closer to the experimental conditions upon which the simulation functions were based. This implies that actual yields are not necessarily a good measure to evaluate the effect of spring fieldwork timeliness. A theoretical approach on yield or risk of yield loss based on soil physical properties or the recording of emergence may be a better indicator to evaluate physical conditions in spring.

Conclusions

Spring fieldwork that is performed too early, especially when combined with excessive wheeling, reduces the physical seedbed quality for early plant growth in spring. Our results show that soil degrading effects can persist until autumn, some becoming weaker, but others becoming even stronger. Under high soil moisture conditions in spring, soil strength was found to be the most important physical property for seedbed quality, besides the proportion of 2–6 mm aggregates. In the future, farmers should strive to avoid topsoil compaction even more than they do today. Appropriate timing and traffic intensity of spring fieldwork may be tools to limit soil physical degradation and yield loss.

Performance of this type of field experiment in Central Norway and on a heavier clay soil is considered appropriate further research in Norway. It would also be interesting to explore a larger range of traffic intensities. Furthermore, one should study whether the order of importance of soil physical properties changes if the experimental range of traffic intensity or soil moisture content is widened, or when high soil moisture conditions continue after sowing.

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