Compaction and sowing date change soil physical properties and crop yield in a loamy temperate soil

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Abstract

Timing of tillage operations is of utmost importance in arable farming because tillage performed under inappropriate soil water conditions results in soil structural damage and creation of undesirable seedbeds for crop establishment and growth. In a field experiment on a loamy soil in Ås, Norway, we investigated the effect of compaction and sowing dates on (i) seedbed physical properties, (ii) crop yield, and (iii) the range of water contents for tillage. The experiment was established in 2014 and the same experimental treatments were repeated in 2015, 2016 and 2017. The sowing dates included early (A1), normal/timely (A2) and late (A3) sowing dates. The compaction treatments applied each year were done wheel-by-wheel by a MF 4225 tractor weighing 4.5 Mg with a single pass (B1) and compared with a control treatment (B0). This study reported soil physical properties for only 2016 and small grain cereal yield for the four years. The soil pore characteristics measured were soil bulk density (ρb), volumetric water content (θ), air-filled porosity (ε_a), air permeability (k_a) and pore organization indices *($PO_1 = k_a/\varepsilon_a$ and $PO_2 = k_a/\varepsilon_a^2$)*; strength properties measured were tensile strength (Y), soil penetration resistance (PR), degree of soil fragmentation by drop-shatter test, and water contents for tillage by calculating the range of water content for tillage ($\Delta\theta_{\mathrm{RANGE}}$). The interaction of compaction with sowing date, generally affected soil pore characteristics, particularly at 1–5 cm depth. The A1 treatment significantly affected the strength characteristics of seedbed by decreasing soil friability and increasing Y at 1–10 cm depth, and PR down to 27 cm depth. The A3 treatment decreased yield of spring-sown small grain cereal crops, but this may be ascribed to a shorter growing season rather than an influence of soil physical properties. The A1 and A3 decreased the range of water contents for tillage compared to the A2, although the difference was not significant at any of the depths studied. Findings of the study have practical implications for cropping regimes in colder climates where farmers can be faced with a short growing period by showing that cultivation in wet soil conditions such as early spring can adversely affect seedbed physical properties and soil workability for subsequent tillage operations.

Keywords: Pore characteristics; soil fragmentation; soil workability

1. Introduction

Tillage is an integral part of arable farming practices— it induces changes in soil structure that may be beneficial or detrimental to soil physical properties and crop growth. In a conventional cultivation, secondary tillage means harrowing after primary tillage with the aim of preparing the soil for seeding, also called seedbed preparation, by creating optimum physical conditions for crop establishment and growth (Arvidsson et al., 2000). In this paper, the term "tillage" without an adjective refers to secondary tillage for seedbed preparation. One important aim of tillage is to fragment soil in order to minimize the proportion of large aggregates (Ojeniyi and Dexter, 1979). It is, generally accepted that soil aggregate size range of 1–5 mm is required for good seedbed that favors seed emergence and growth (Russell, 1961). This is because such seedbed has good aeration, water holding capacity, and improve soil-seed-contact area (Braunack and Dexter, 1989b).

Soil workability is a key condition in tillage. In seedbed preparation, soil workability is the ease with which a well-drained soil can be tilled to produce an optimum seedbed for crop establishment (Dexter, 1988). Moisture content at tillage is a major factor affecting soil workability. Soil is workable over a range of water content ($\Delta\theta_{RANGE}$) between an upper (wet tillage limit, θ_{WTL}) and a lower (dry tillage limit, θ_{DTL}). $\Delta\theta_{RANGE}$ decreases with decreasing soil organic matter content and with increasing clay content and soil bulk density (Dexter and Bird, 2001). This suggests that farmers can be faced with cultivation problems in regions with hard-setting soils (Mullins et al., 1988) and in colder climates with a short period for spring or autumn cultivation.

Improved tires and power of modern field machinery mean that farmers are able to till in less-than-ideal soil conditions such as early spring tillage in temperate regions like Northern Europe. Therefore, modern agricultural machinery might improve trafficability, that is, the ability of soil to support and withstand field traffic without irreversible soil degradation (Rounsevell, 1993), at the expense of increased risk of detrimental effects from tillage, and the farmers' decisions on tillage and sowing date become crucial.

When performed in less-than-ideal soil conditions, tillage can produce short- and long-term detrimental effects on soil. The described tillage effects on germination, emergence and growth of the current crop can be considered short-term effects. On the other hand, changes induced by tillage which persist over cropping seasons or years can be considered long-term effects. Structural degradation in the topsoil due to tillage in too wet conditions has been shown to persist until the following autumn (Munkholm and Schjønning, 2004), which can affect the water contents for tillage and seedbed preparation for a subsequent winter crop. Therefore, tillage-induced soil structural degradation in spring might reduce soil workability for autumn tillage and complicate scheduling of these operations. It must be emphasized that there is a lack of quantitative information on this effect as reviewed by Obour et al. (2017).

In addition to the short- and long-term effects, in too wet soil condition, tillage can create a seedbed composed of large and strong soil fragments because of kneading. According to Dexter and Birkas (2004), large soil fragments have less agronomic value because they do not favor good soil-seed-contact area. Further, large soil fragments can impede crop emergence and root growth (Nasr and Selles, 1995), which adversely affect crop yield. In too dry soil condition, soil becomes strong and high specific energy is required for soil crumbling. Also, tillage can produce undesirably finer fragments, which are susceptible to surface crusting, and wind and water erosion (Braunack and Dexter, 1989a). Therefore, knowledge of the effects of sowing date on seedbed physical properties is a pre-requisite for decision support for scheduling and planning tillage operations to create optimal seedbeds for crop establishment.

The objectives of the study were to quantify the effect of compaction and sowing dates on (i) seedbed physical properties, (ii) crop yield, and (iii) the range of water contents for tillage. Tillage is most often conducted in either spring or autumn, but in this study, only spring tillage is considered. Three sowing dates, namely early, timely/normal and late, were chosen as being representative of real farming practice of carrying out early, normal and delayed spring tillage. We focused on soil strength characteristics, namely tensile strength, friability, penetration resistance and soil fragmentation to assess soil workability. We hypothesized that the strength of soil aggregates and soil fragmentation will differ for different compaction treatments and sowing dates. The hypothesis was tested by comparing the strength properties of soil after early, normal and late sowing in spring.

2. Materials and methods

2.1. The experimental site

Soil samples were collected from a compaction experiment in Ås, Norway (59° 39′ 47″ N 10° 45′ 49″ E). Mean annual precipitation and temperature in the area are 785 mm and 5.3 ºC, respectively (Wolff et al., 2017). The monthly precipitation and temperature data covering the period September 2015 and September 2016 (Fig. 1) were obtained from a meteorological station located about 1 km from the experimental site. The period covers autumn plowing of the field in 2015, cultivation in the spring and harvest in autumn 2016. Daily precipitation and air temperature cycles prior to the specific field operations and sampling are also shown (Fig. 2a–d).

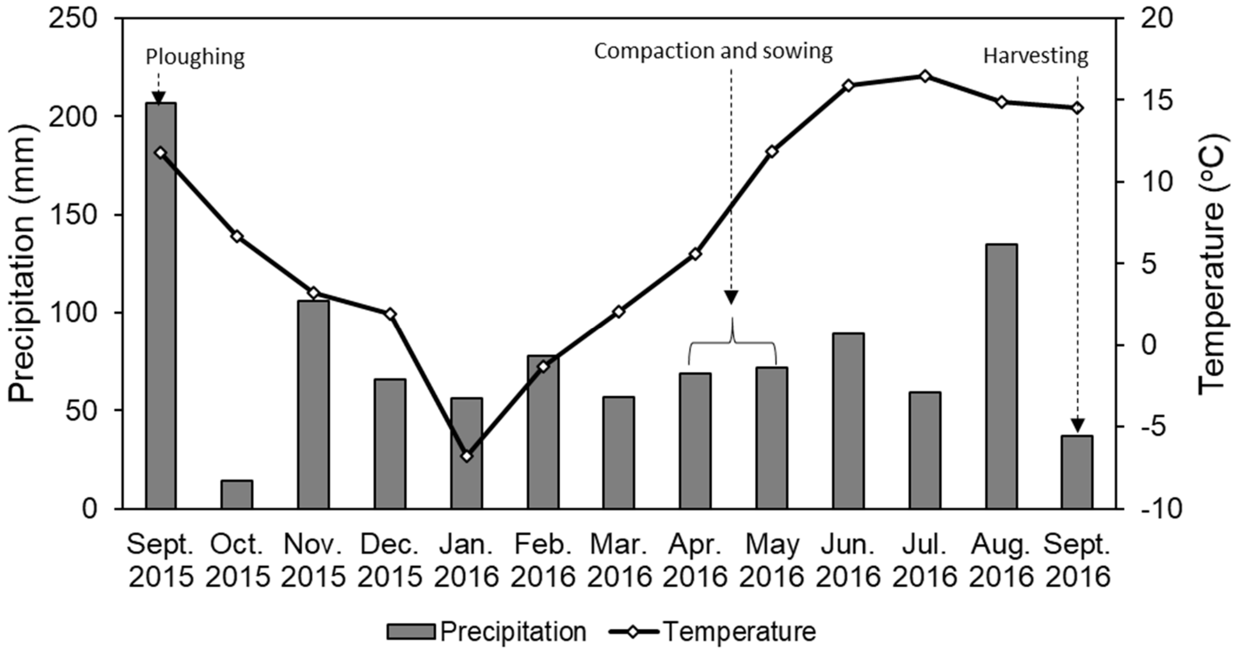

Fig. 1. Mean monthly precipitation and air temperature of the experimental site from September 2015 to September 2016. Source: Data from Wolff et al. (2017)

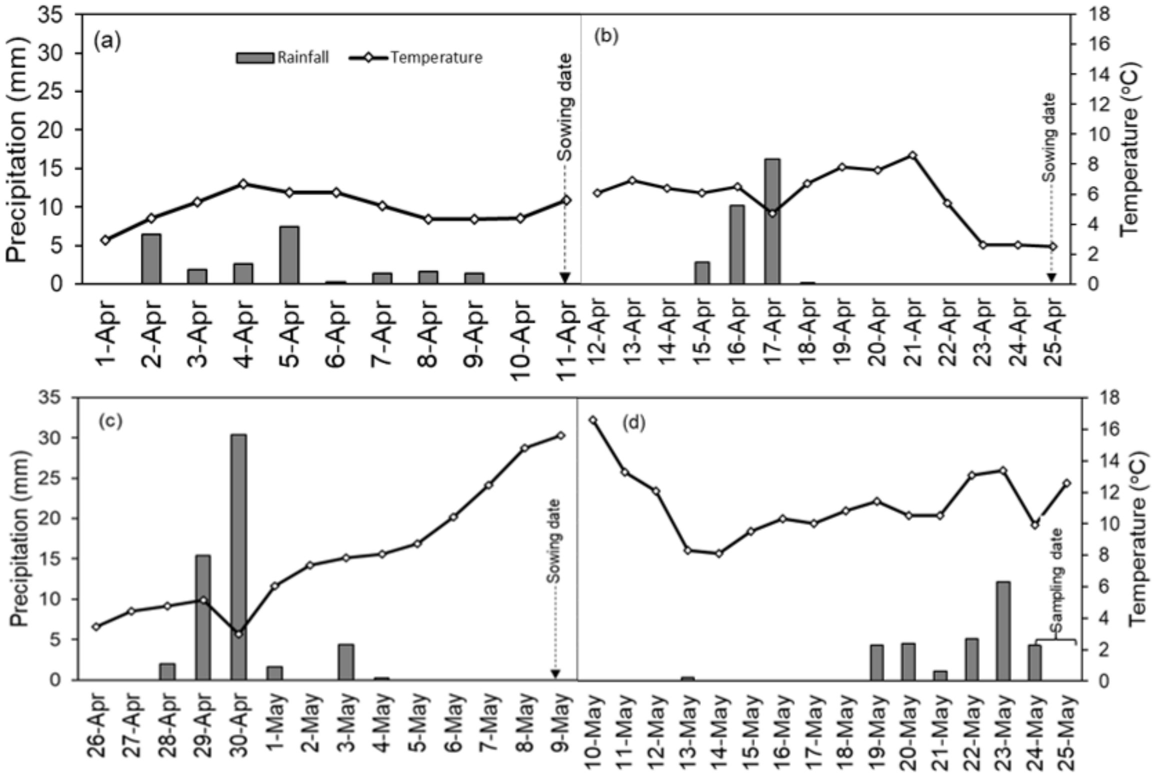

Fig. 2. Daily precipitation and air temperature before (a) early sowing date, (b) normal sowing date, (c) late sowing date and (d) sampling. No data for March 28–30, 2015. Source: Data from Wolff et al. (2017)

Soils at the site are characterized as loam over silt loam and silty clay loam and are classified as Luvic Stagnosol (Siltic) in the World Reference Base (WRB) classification system (WRB, 2006). Soil textural characteristics for the upper layer (0–15 cm depth) are: 22% clay (<2 µm), 29% silt (2–20 µm), 29% fine sand (20–200 µm), 15% coarse sand (200–2000 µm) and 4.5% soil organic matter.

2.2. Experimental design and treatments

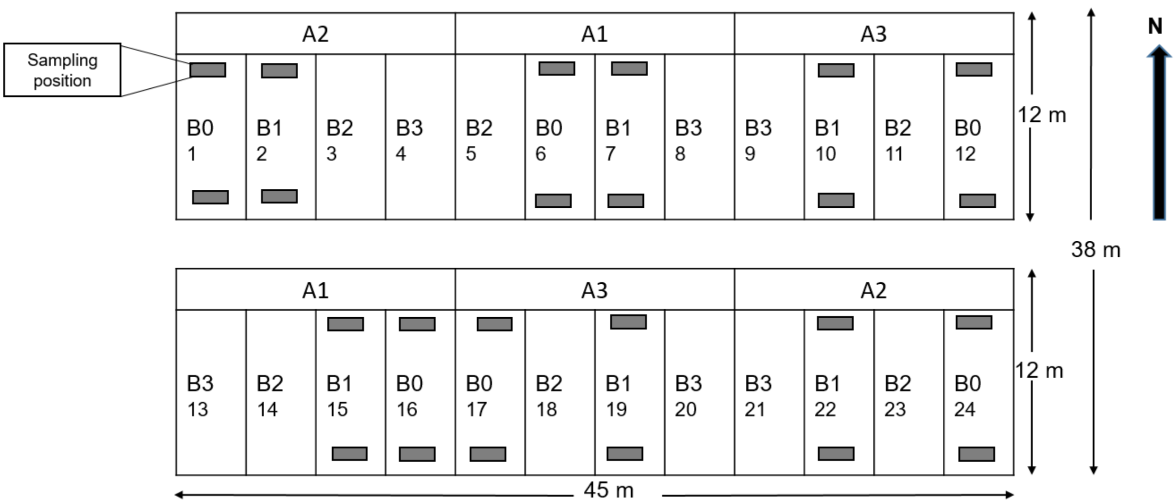

Fig. 3. Outline of experimental design used in this study. The figure also shows the sampling positions where soil samples were collected from each plot.

The experiment was established in 2014 and the same experimental treatments were repeated in 2015, 2016 and 2017. This study investigated results for soil physical properties for only 2016. The design was a randomized split-plot in two replications comprising two factors. The main plot treatment was sowing date and the split-plot treatment was compaction. The sowing dates included early (A1), normal/timely (A2) and late (A3) sowing dates (Fig. 3). The compaction treatments applied each year included no compaction (B0) and compaction by a MF 4225 tractor weighing 4.5 Mg with one pass (B1). Compaction was done wheel-by-wheel. The front and rear tires of the tractors were adjusted to an inflation pressure of 1.5 bars.

Prior to the experiment in 2016, the field was plowed to ~20 cm depth the previous autumn with a reversible plow with two moldboards. In A1, plots were either compacted or not compacted, and harrowed and seeded on the same day in the second week of April 2016 when the soil was wet to represent the worst-case scenario when farmers will sow early in spring. In the same manner, A2 plots were treated in the fourth week of April, i.e., two weeks after the A1 treatment, when the soil was expected to be in semi-moist condition. Finally, in A3, treatment was carried out in the second week of May 2016 when the soil was expected to be dry. Water content at sowing time (Table 1) was determined volumetrically in the field using a hand-held time-domain reflectometer (TDR, HH2-ML3, Delta-T Devices, Cambridge, England).

The six treatment combinations were labelled A1+B1, A1+B0, A2+B1, A2+B0, A3+B1 and A3+B0. Secondary tillage was done to a depth of ~5 cm using a Ferraboli rotary power harrow (rotorharv). A small grain cereal crop was established on each of the experimental plots: Wheat (*Triticum aestivum* L.) in 2014, barley (*Hordeum vulgare* L.) in 2015, oats (*Avena sativa* L.) in 2016 and barley in 2017. For each year, the crop was harvested at full maturity using a plot harvester. The harvested area was 9 m^2 (1.5 m × 6 m) for each plot. The grain yield for each experimental plot was recorded.

Table 1. Sowing dates and soil water content during treatment in 2016.

Depth (cm)	Early sowing (April 11)	Normal/timely sowing (April 25)	Late sowing (May 9)
	Water content (m^3 m^{-3})		
0–5	0.35	0.19	0.19
5–10	0.36	0.24	0.27

2.3. Sampling

Sampling was carried out in spring of 2016 from May 24–25, two weeks after the late sowing date. Undisturbed soil cores (9.6 cm diameter, 8 cm high, 580 cm^3, hereafter called 'large soil cores') and (6.1 cm diameter, 3.4 cm high, 100 cm^3, hereafter called 'small soil cores') were sampled. The large soil cores were sampled at only one depth (~5–15 cm), i.e., below the harrowed layer. The small soil cores were sampled from two depths: ~1–5 cm and at ~5–10 cm. Bulk soil was taken from each sampling position and depth using a spade and were placed in plastic boxes. All soil samples were covered with plastic lids and stored in a 2 ºC room until laboratory analyses.

2.4. Penetration resistance

To determine soil strength in the seedbed layer and the layer below, soil penetration resistance (PR) was measured in the field on July 4, 2016 down to 27 cm depth with a hand-held cone penetrometer (Eijkelkamp Penetrologger 06.15.SA, Eijkelkamp Soil and Water, Giesbeek, The Netherlands). It has a cone angle of 60° and a penetration speed of 2 cm s^{-1}. Average soil water content at penetration was 0.28 m^3 m^{-3}. Fifteen replicate penetration measurements were taken in each experimental plot. The geometric mean of PR was computed at the following soil depths per plot: 1–5, 7–15, 15–20 and 20–27 cm. The depths represent the seedbed layer, seedbed bottom, lower part of the tilled layer and the bottom of the plow layer, respectively. The depths were chosen on the basis that given the small size of the machinery used in this experiment, we did not expect a remarkable effect of compaction in the subsoil, below the plow layer.

2.5. Laboratory measurements

The bulk soil samples were gently fractured by hands along planes of natural weakness, and left to air-dry in a ventilated room at a temperature of ~20 °C. Portions of the air-dry soil samples were crushed and passed through a 2 mm sieve to determine soil texture. The rest of the air-dry samples were crushed using the roller method (Hartge, 1971) before sieving through a nest of sieves to obtain 8–16, 4–8, 2–4 and 1–2 mm soil aggregate size fractions. Some of the 8–16 mm aggregates were capillary-adjusted to -100, -300 and -1000 hPa matric potentials using tension tables, vacuum pots and pressure plates, respectively (Dane and Hopmans, 2002). A batch of 15 aggregates were randomly selected from each plot and size fraction to test their tensile strength (*Y*) using the indirect tension test (Rogowski, 1964). In brief, each of the aggregates was weighed and thereafter subjected to indirect tensile testing by crushing the aggregates between two parallel plates (Rogowski, 1964) using a mechanical press (Instron Model 5969, Instron, MA,USA) at a constant rate of displacement of 1 mm min^{-1}. The point of failure for each aggregate was automatically detected when there was a continuous crack in the aggregate. The maximum force at failure was automatically recorded.

The small soil cores were saturated and drained to -10, -30, -100, -300, and -1000 hPa matric potentials to obtain water retention data. Water content at -15000 hPa was determined on oven-dried soil sieved to 2 mm at 105° C for 24 h. Briefly, soil was crushed and sieved to 2 mm. Subsamples (~10 g) were placed in PVC rings on ceramic pressure plates (Richards, 1948), water-saturated and drained to -15000 hPa. After 10 days, the subsamples were weighed before and after oven-drying. Water content was then calculated.

The large soil cores were drained to -100, -300 and -1000 hPa and thereafter subjected to a drop-shatter test (Schjønning et al., 2002) in the laboratory to determine how the soil fragmented upon energy application. The soil was removed from the metal ring using a special plastic flange so that it dropped from a height of 200 cm onto a concrete floor covered with a plastic sheet to avoid losing the soil fragments. The dropped samples were collected and left to air-dry before sieving through a nest of sieves with apertures of 16, 8, 4 and 2 mm to determine fragment size distribution. The degree of soil fragmentation from the drop-shatter test was expressed as geometric mean diameter (GMD). Following equilibrium at each water potential the small soil cores and soil fragments obtained from dropped large soil cores were oven dried at 105° C for 24 h.

2.6. Calculations

Soil bulk density (ρb) was calculated from the oven-dried mass of each soil core (both large and small soil cores) divided by the total soil volume. Total porosity (Φ) was calculated from ρb and particle density (ρd) as Φ = 1- ρb/ρd. A particle density of 2.54 Mg m^{-3} reported for the experimental site by Hofstra et al. (1986) was used. In addition, the volumetric water content (θ, m^3 m^{-3}) at -100 hPa was calculated by multiplying ρb and gravimetric water content at -100 hPa. Air-filled porosity (ε_a) at -100 hPa was calculated by subtracting θ at -100 hPa from Φ.

Air permeability (k_a) was measured on the small soil cores using the Forchheimer approach for soil air permeability measurement recently developed by Schjønning and Koppelgaard (2017). Individual soil samples were attached to the measuring chamber by a polyurethane tube. The sample was kept airtight by means of an inflatable rubber O-ring. The apparatus measures air flow through the sample at a range of pressure differences across the sample. A polynomial regression of flow-pressure data was then used to determine the true Darcian flow based on the coefficient to the linear part of the relation (Schjønning and Koppelgaard, 2017). Two indices of pore characteristics were derived from the relation between k_a and ε_a (Groenevelt et al., 1984), which relate to the term pore organization (*PO*) (Blackwell et al., 1990): $PO_1 = k_a/\varepsilon_a$ *and* $PO_2 = k_a/\varepsilon_a^2$. The indices are explained in detail in section 4.1.

Tensile strength (*Y*) was calculated according to Dexter and Kroesbergen (1985):

$$Y=0.567F/d^2 \tag{1}$$

where *F* is the maximum force (N) required to fracture the aggregate and *d* is the effective diameter of the spherical aggregate (m) obtained by adjusting the aggregate diameter according to the individual masses (Dexter and Kroesbergen, 1985):

$$d=d_1(m_0/m_1)^{1/3} \tag{2}$$

where d_1= is the diameter of aggregates defined by the average sieve sizes, m_0 is the mass (g) of the individual aggregate and m_1 is the mean mass of a batch of aggregates of the same size class.

The friability index (k_Y) for the air-dry aggregates was taken as the slope of the plot of the natural logarithm of Y (kPa) for all size fractions and the natural logarithm of aggregate volume (Utomo and Dexter, 1981):

$$\mathrm{Ln}\ (Y) = -k\ \mathrm{Ln}\ (V) + A \qquad (3)$$

where Ln is the natural logarithm, k is an estimate of friability (large value of k indicates that large aggregates are much weaker than smaller aggregates and are easily fragmented into small and stronger aggregates, whereas a small value of k shows that the strength of the large aggregates does not differ from that of smaller aggregates (Utomo and Dexter, 1981). A is the intercept of the regression and denotes the predicted Ln tensile strength (kPa) of 1 m^3 of bulk soil, and V (m^3) is the estimated aggregate volume. Friability of the treatments was classified according to Imhoff et al. (2002) where F<0.1 = not friable, 0.1–0.2 = slightly friable, 0.2–0.5 = friable, 0.5–0.8 = very friable and >0.8 = mechanically unstable.

The water contents for tillage (dry tillage limit, θ_{DTL}; optimum water contents for tillage, θ_{OPT}; and wet tillage limit, θ_{WTL}) were determined using the consistency approach described by Obour et al. (2018). The range of water contents for tillage was calculated as the difference between θ_{WTL} and θ_{DTL}.

2.7. Statistical analysis

Data analyses were done in the R software package version 3.4.1 (R Core Team, 2017). Tensile strength, air permeability and pore organization indices (PO_1 and PO_2) data were log-transformed to yield normality. The data were analyzed using a generalized linear model. The family, gaussian and link, identity functions implemented in R were used. The ANOVA F-test was used to determine the statistical significance of compaction, sowing dates and their interaction effect. When interaction between the treatments was significant, we carried out further analyses to identify differences between treatment combinations using the Tukey method. When interaction between treatments was not significant, further analyses with interaction term excluded from the model were also carried out to identify which of the main effects was significantly different. We applied $p<0.05$ as a criterion for statistical significance. A parallel lines test was conducted to determine if the regression slopes indicating friability index were significantly different from each other.

3. Results

3.1. Soil pore characteristics

At 1–5 cm depth, sowing date significantly affected soil soil bulk density (ρb) (p<0.001). The early (A1) and late (A3) sowing treatments had higher ρb values compared to the normal/timely sowing (A2) treatment (Table 2). Neither the compaction × sowing date interaction nor compaction on its own significantly affected ρb (p>0.05). The parameters volumetric water content (θ), air-filled porosity (ε_a), air permeability (k_a), and pore organization indices (PO_1 and PO_2) at -100 hPa were significantly affected by the compaction × sowing date interaction (p<0.05). The θ and ε_a at -100 hPa are taken to represent the volume of pores below and above the 30 µm tube-equivalent pore diameter, respectively (Hillel, 1982). Overall, the results for the interaction effect at 1–5 cm depth were inconsistent (Table 2).

At 5–10 cm depth, ρb was higher for the A1+B1 treatment than for A1+B0, A2+B0 and A2+B1. Further, the A1+B1 treatment had the highest volume of pores < 30 µm. For A1+B1, ε_a was significantly reduced compared to the other treatments, except A3+B1 (Table 2). Compaction significantly reduced k_a, PO_1 and PO_2 (p<0.001), and the A1 treatment had a lower k_a than A2 (p=0.04).

3.2. Tensile strength

At -100 hPa, sowing date significantly affected Y (p=0.03), but only at 1–5 cm depth. Tensile strength was lower for A2 than for the A1 treatment (Table 3). At both 1–5 and 5–10 cm depths, the interaction effect of compaction × sowing date was significant (p<0.05) when Y was tested at -300 and -1000 hPa and in the air-dry state. At 1–5 cm depth, Y was consistently lower for A2+B0 than for A1+B1, A1+B0 and A2+B1 when tested at -300 and -1000 hPa. At 5–10 cm depth, A1+B1 consistently yielded a higher Y than the other treatments at -1000 hPa and in the air-dry state (Table 3).

Table 2. Arithmetic mean of bulk density (ρ_b), volumetric water content (θ), air-filled porosity (ε_a), and geometric means of air permeability (k_a) and pore organization indices ($PO_1 = k_a/\varepsilon_a$ and $PO_2 = k_a/\varepsilon_a^2$) at -100 hPa matric potential (data from small soil cores).

Depth (cm)	**Treatment**	**ρ_b (Mg m^{-3})**	**θ, $_{-100\ hPa}$ (m^3 m^{-3})**	**ε_a, $_{-100\ hPa}$ (m^3 m^{-3})**	**k_a, $_{-100\ hPa}$ (µm^2)**	**PO_1, $_{-100\ hPa}$ (µm^2)**	**PO_2, $_{-100\ hPa}$ (µm^2)**
1–5	A1+B1	1.09	0.31ab	0.26b	539bc	2140ab	8503ab
	A1+B0	1.10	0.32ab	0.25ab	337ac	1389ab	5721ab
	A2+B1	1.05	0.30a	0.28b	327ab	1187a	4310a
	A2+B0	1.05	0.31ab	0.28b	735c	2674b	9732b
	A3+B1	1.17	0.33b	0.21a	215a	1082a	5452ab
	A3+B0	1.11	0.30a	0.27b	415ac	1562ab	5873ab
	Average compaction						
	B1	1.10	0.32	0.25	336	1401	5846
	B0	1.09	0.31	0.27	469	1797	6889
	Average sowing date						
	A1	1.10b	0.31	0.25	426	1724	6975
	A2	1.05a	0.31	0.28	490	1782	6476
	A3	1.14b	0.31	0.24	299	1300	5658
5–10	A1+B1	1.28d	0.38c	0.12a	32	310	3004
	A1+B0	1.20ac	0.35ab	0.18bc	206	1254	7626
	A2+B1	1.12a	0.34ab	0.21c	174	830	3972
	A2+B0	1.14ab	0.35ab	0.20c	231	1162	5835
	A3+B1	1.27cd	0.36b	0.14ab	48	350	2529
	A3+B0	1.21bcd	0.33a	0.19c	155	830	4434
	Average compaction						
	B1	1.23	0.36	0.16	64a	448a	3113b
	B0	1.19	0.34	0.19	196b	1071b	5856a
	Average sowing date						
	A1	1.24	0.36	0.15	81a	623	4787
	A2	1.13	0.35	0.21	200b	982	4814
	A3	1.24	0.34	0.17	85ab	531	3318

Values with different letters are significantly different at $p<0.05$. A1, early sowing date; A2, normal sowing date; and A3, late sowing date; B0, control and B1, compaction with a single pass by a tractor weighing ~4.5 Mg.

Table 3. Geometric means of tensile strength (Y) of 8–16 mm soil aggregates.

Depth (cm)	**Treatment**	***Y* (kPa)**			
		-100 hPa	-300 hPa	-1000 hPa	Air-dry
1–5	A1+B1	6.9	11.4bc	24.2b	135b
	A1+B0	5.8	12.9c	22.8b	96ab
	A2+B1	4.3	11.4bc	19.6b	76a
	A2+B0	4.4	6.7a	10.9a	93ab
	A3+B1	5.3	7.4ab	19.3b	112b
	A3+B0	4.9	9.4ac	18.3b	69a
	Average compaction				
	B1	5.4	9.9	20.9	105
	B0	5.0	9.3	16.6	85
	Average sowing date				
	A1	6.3b	12.1	23.5	114
	A2	4.4a	8.7	14.6	84
	A3	5.1ab	8.4	18.8	88
5–10	A1+B1	7.6	18.2b	41.9c	175c
	A1+B0	5.8	13.5b	23.3b	110b
	A2+B1	5.5	6.9a	14.1a	98ab
	A2+B0	4.7	11.2ab	12.1a	71a
	A3+B1	5.8	12.9b	22.8b	87ab
	A3+B0	6.7	11.3ab	20.8b	94ab
	Average compaction				
	B1	6.3	11.8	23.8	114
	B0	5.7	12.0	18.0	90
	Average sowing date				
	A1	6.6	15.6	31.3	138
	A2	5.1	8.8	13.1	84
	A3	6.3	12.1	21.8	91

Values with different letters are significantly different at $p<0.05$. A1, early sowing date; A2, normal sowing date; and A3, late sowing date; B0, control and B1, compaction with a single pass by a tractor weighing ~4.5 Mg.

3.3. Friability indices and soil fragmentation

At 1–5 cm depth, higher friability (k_Y), indicated by the steepest slope, was found for the A2 treatment, and for the A2 and A3 treatments at 5–10 cm depth (Fig. 4a and c). Regardless of depth, there was a significant difference of k_Y between the compacted and control soil (Fig. 4b and d).

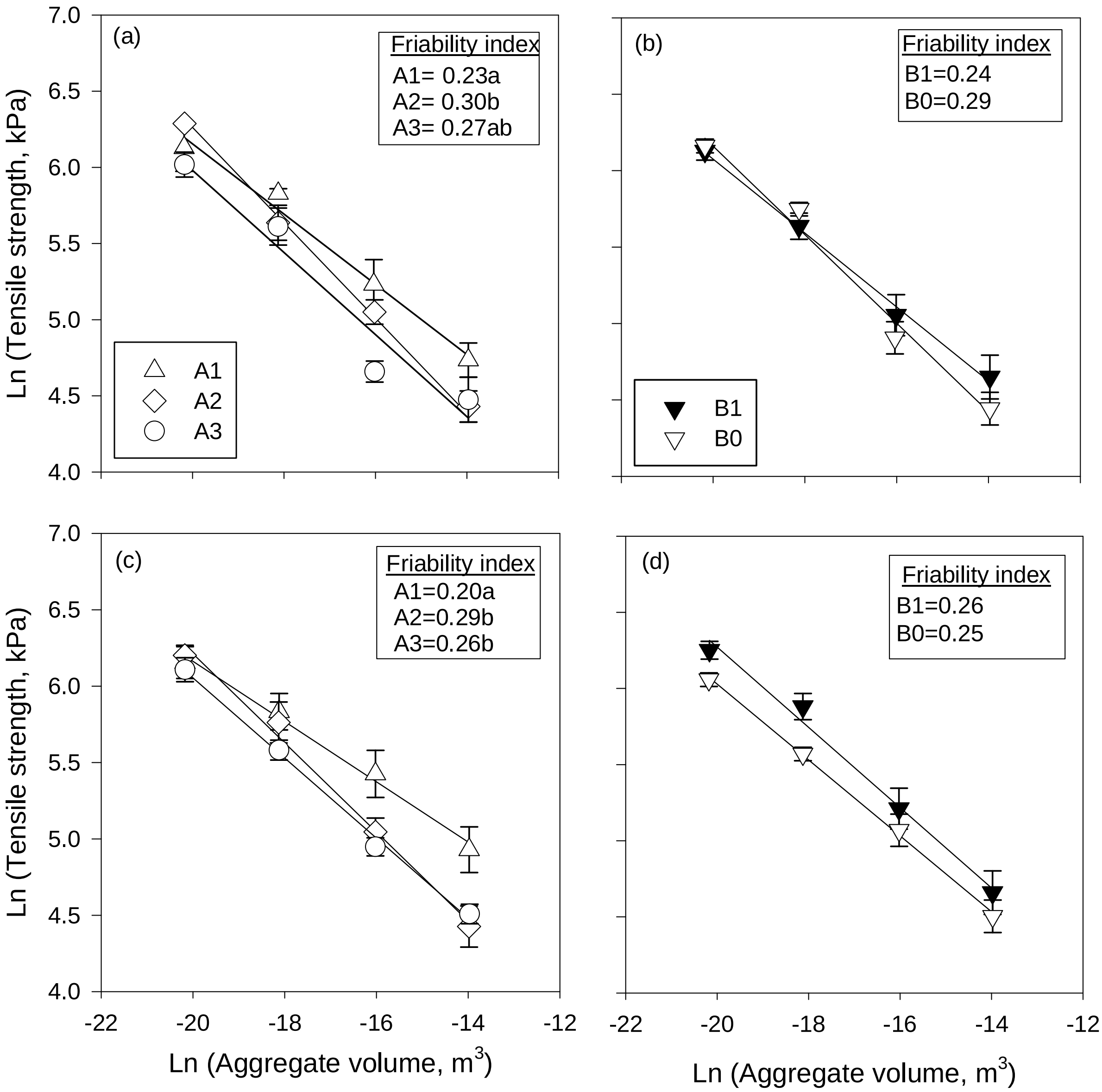

Fig. 4. Natural logarithm (Ln) of tensile strength, Y (kPa), as a function of Ln aggregate volume, V (m3), for air-dry aggregates. Soil friability index (kY), determined as the slope of the regression equation, is shown for each treatment: Averages of kY for sowing dates (a and c) and for compaction (b and d). A1, early sowing date; A2, normal sowing date; and A3, late sowing date. B0, control and B1, compaction with a single pass by a tractor weighing ~4.5 Mg. Values with different letters are significantly different at $p<0.05$. Error bars indicate the standard errors of the mean.

Table 4. Fragmentation of soil cores dropped at -100, -300 and -1000 hPa matric potentials (data from large soil cores). Geometric mean diameter (GMD) and the fraction of soil fragments <5 and >32 mm in diameter after the drop-shatter test are shown.

	-100 hPa			-300 hPa			-1000 hPa		
		Soil fragments			Soil fragments			Soil fragments	
Treatment	GMD (mm)	<5 mm	>32 mm	GMD (mm)	<5 mm	>32 mm	GMD (mm)	<5 mm	>32 mm
A1+B1	50.5b	0.03a	0.84b	52.3b	0.03a	0.86b	51.3c	0.03a	0.85b
A1+B0	29.4a	0.09ab	0.48ab	41.1ab	0.06ab	0.68ab	34.8ab	0.09ab	0.58b
A2+B1	27.8a	0.11ab	0.43a	32.4ab	0.11ab	0.55ab	-	-	-
A2+B0	25.9a	0.14ab	0.44a	24.7a	0.14ab	0.39a	-	-	-
A3+B1	25.7a	0.15b	0.38a	39.8ab	0.08ab	0.68ab	37.6bc	0.08a	0.64b
A3+B0	23.1a	0.13ab	0.34a	21.7a	0.15b	0.30a	20.7a	0.15b	0.30a
Average compaction									
B0	26.1	0.12	0.42	29.2	0.12	0.46	27.8	0.12	0.44
B1	34.6	0.09	0.55	41.5	0.07	0.70	44.4	0.05	0.75
Average sowing date									
A1	39.9	0.06	0.66	46.7	0.05	0.77	43.0	0.06	0.72
A2	26.9	0.12	0.44	28.6	0.12	0.47	-	-	-
A3	24.4	0.14	0.36	30.7	0.12	0.49	29.2	0.12	0.47

Values with different letters are significantly different at $p<0.05$. A1, early sowing date; A2, normal sowing date; and A3, late sowing date; B0, control and B1, compaction with a single pass by a tractor weighing ~4.5 Mg

There was a significant ($p<0.05$) compaction × sowing date interaction effect on soil fragmentation at all the matric potentials studied. At -100 hPa, the A1+B1 treatment resulted in poor fragmentation compared to the other treatments, indicated by the larger geometric mean diameter (GMD) values, i.e., soil cloddiness (Table 4). However, at -300 hPa, the GMD for the A1+B1 treatment significantly differed only from A3+B0 (Table 4). A similar trend of significantly larger GMD values was obtained at -1000 hPa for the A1+B1 compared to the A1+B0 and A3+B0 treatments. Further, the poor fragmentation of the A1+B1 treatment is illustrated by a generally smaller proportion of small soil fragments (<5 mm in diameter) and larger proportion of large soil fragments (>32 mm in diameter) for the matric potentials studied (Table 4).

3.4. Grain yield

Table 5: Yield of spring-sown small grain cereal crops (2014–2017).

Treatment	Yield (Mg ha^{-1})			
	2014 (Wheat)	2015 (Barley)	2016 (Oats)	2017 (Barley)
A1+B0	5.5	7.3	5.8	5.0
A1+B1	5.2	6.9	5.5	4.9
A2+B0	5.8	7.8	6.5	5.9
A2+B1	5.1	6.8	6.8	5.2
A3+B0	5.0	7.0	6.5	5.0
A3+B1	4.8	6.1	5.9	4.8
Average compaction				
B1	5.0a	6.6a	6.1	5.0
B0	5.5b	7.3b	6.3	5.3
Average sowing date				
A1	5.3b	7.1b	5.7	5.0
A2	5.5b	7.3b	6.6	5.5
A3	4.9a	6.5a	6.2	4.9

Values with different letters are significantly different at $p<0.05$. A1, early sowing date; A2, normal sowing date; and A3, late sowing date; B0, control and B1, compaction with a single pass by a tractor weighing ~4.5 Mg.

Compaction and late sowing significantly affected yield of wheat and barley ($p<0.05$) in 2014 and 2015, respectively (Table 5). There was a trend showing that compaction and late sowing reduced yield of oats in 2016, and barley in 2017 compared to the control and the early and normal sowing treatments, respectively, albeit not statistically significant ($p>0.05$). Yield of the small grain cereals for the A1 and A2 treatments, however, did not differ significantly for any of the years studied (Table 5).

3.5. Drop-shatter results, soil pore and aggregate characteristics vs yield

Across all treatments, the yield of oats in 2016 negatively related to the GMD of soil fragments and *Y* tested at -100 hPa. On the other hand, there was a positive linear relationship between yield of oats and porosity (Φ). Overall, only 27% of the variation in the yield of oats can be explained by the GMD of soil fragments produced from dropped soil cores at -100 hPa, and 37% and 51% by Φ and *Y*, respectively (Fig. 5a, b and c).

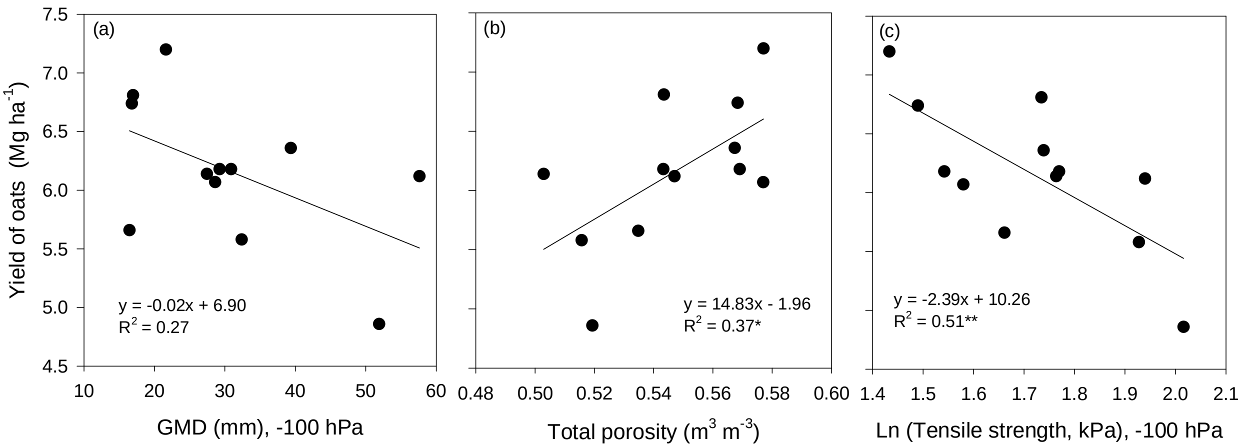

Fig. 5. Relationship between yield of oats and (a) geometric mean diameter (GMD) of soil fragments produced from drop-shatter test at -100 hPa, and (b) porosity and (c) tensile strength of aggregates from 1–10 cm depth measured at -100 hPa. ** $p<0.01$ and *$p<0.05$.

3.6. Soil penetration resistance and yield

There was a significant effect of sowing date and depth on penetration resistance (PR) (p=0.002) (data not shown). The early sowing date treatment consistently had a higher PR in the seedbed layer (1–5 cm depth) and below (at 5, 15, 20 and 27 cm depth). In contrast, the PR for the compacted treatment was higher than the control only at 15 cm depth (data not shown). In general, mean PR measured on July 4, 2016 in the topsoil for all experimental plots was 0.43 and 1.02 MPa for 1–5 and 7–15 cm depth, respectively.

Yield of oats was significantly and inversely related to PR at 1–5 cm (p=0.004) and 7–15 cm depth (p= 0.021). A similar – although not significant – negative relationship between yield and PR was found at 15–20, 20–27 cm as well as the overall PR at 1–27 cm depth (Fig. 6a–e).

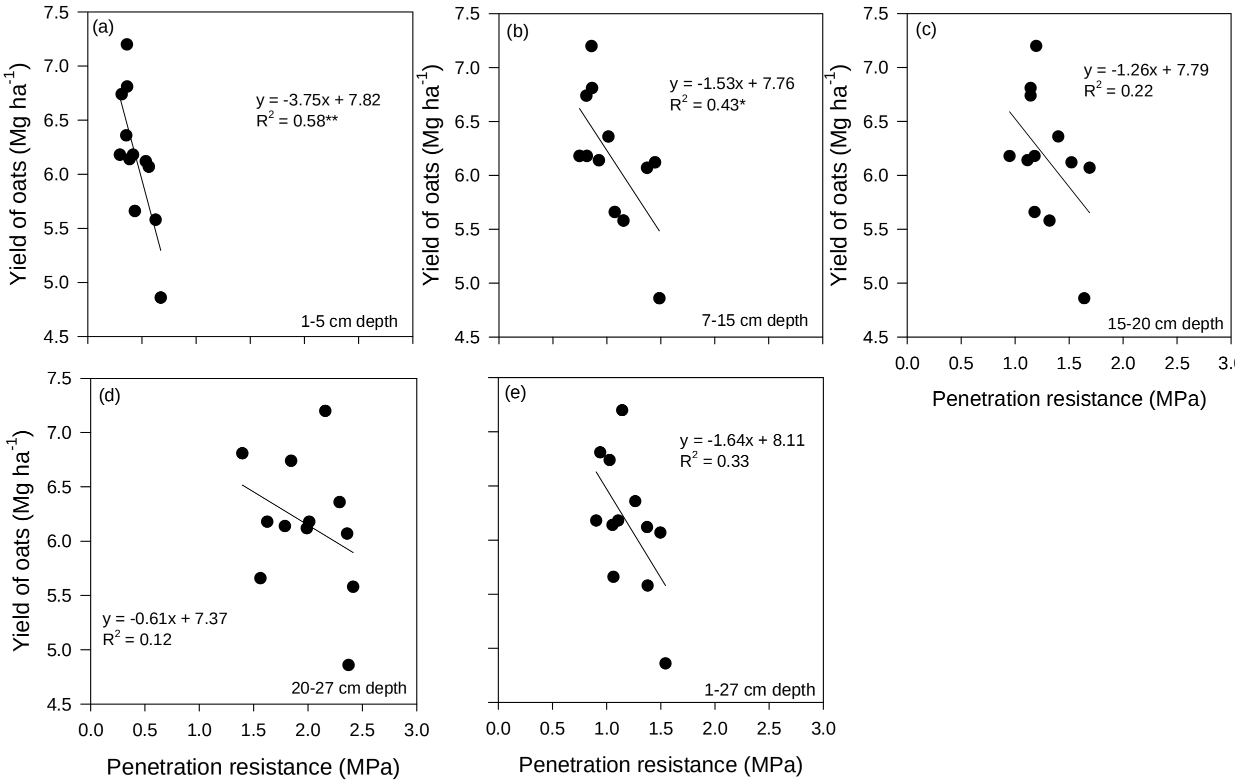

Fig. 6. Yield of oats related to penetration resistance (PR) at (a) 1–5, (b) 7–15, (c) 15–20 cm, (d) 20–27 cm depth and (e) average PR at 1–27 cm. Data points show observation for each individual experimental plot. Penetrometer measurements were done on July 4, 2016 which means 56, 70 and 84 days after the establishment of A3, late sowing date; A2, normal sowing date and A1, early sowing date, respectively. Lines indicate regression. $^{**}p<0.01$ and $^{*}p<0.05$.

3.7. Water contents for tillage

At both 1–5 and 5–10 cm depths, the range of water contents for tillage ($\Delta\theta_{RANGE}$) was similar for the compacted and the control treatments. With respect to sowing date, the early and late sowing reduced $\Delta\theta_{RANGE}$ compared to the normal sowing, although the difference was not significant at any of the depths studied (Fig. 7a–d). $\Delta\theta_{RANGE}$ was positively related to soil porosity at both 1–5 and 5–10 cm depth, although not statistically significant (Fig. 8a and b).

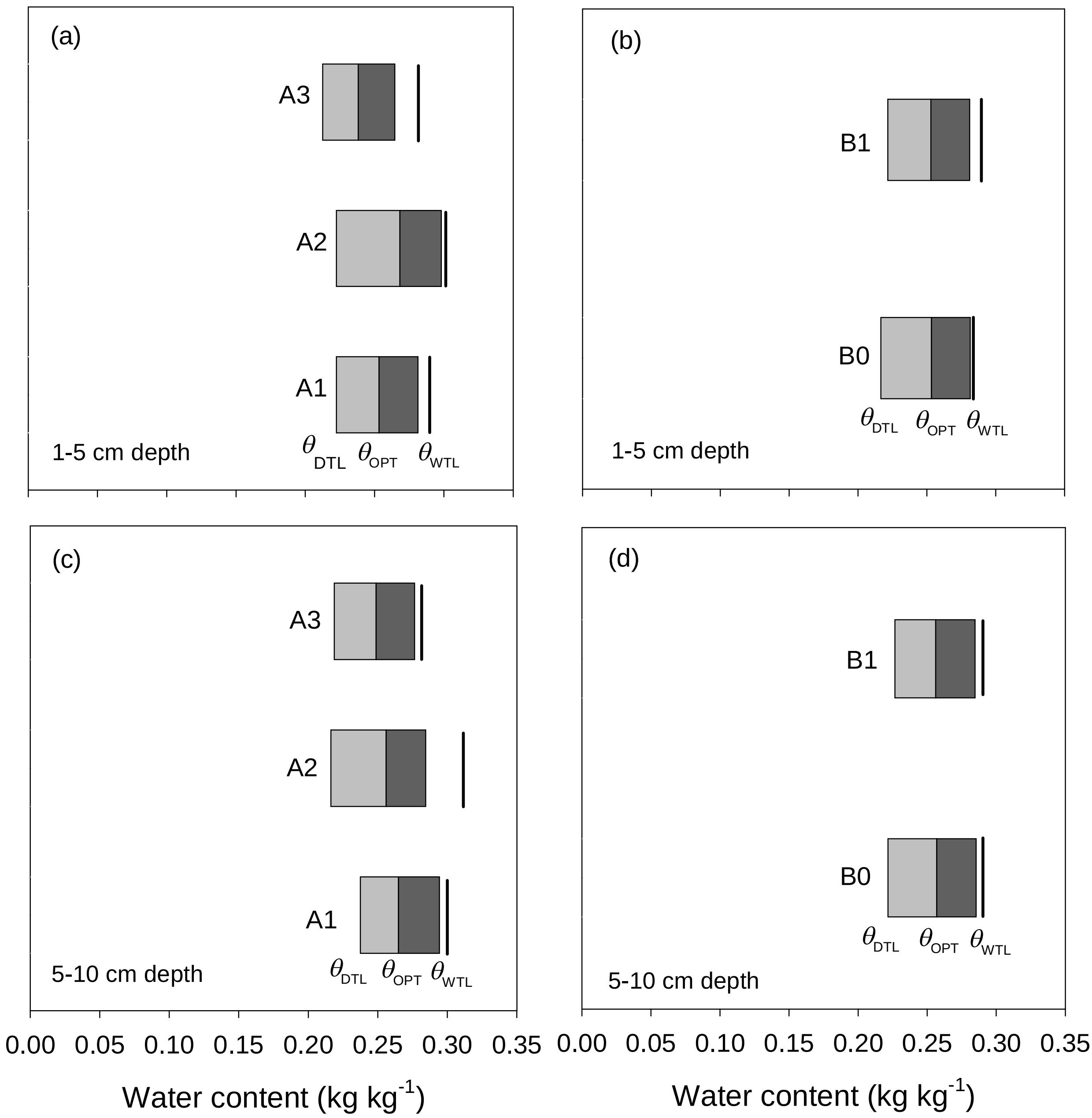

Fig. 7. Water contents for tillage. A1, early sowing date; A2, normal sowing date; and A3, late sowing date; B0, control and B1, compaction with a single pass by a tractor weighing ~4.5 Mg. θDTL: dry tillage limit, θOPT: optimum water content for tillage and θWTL: wet tillage limit. Solid short vertical lines show water contents at -100 hPa.

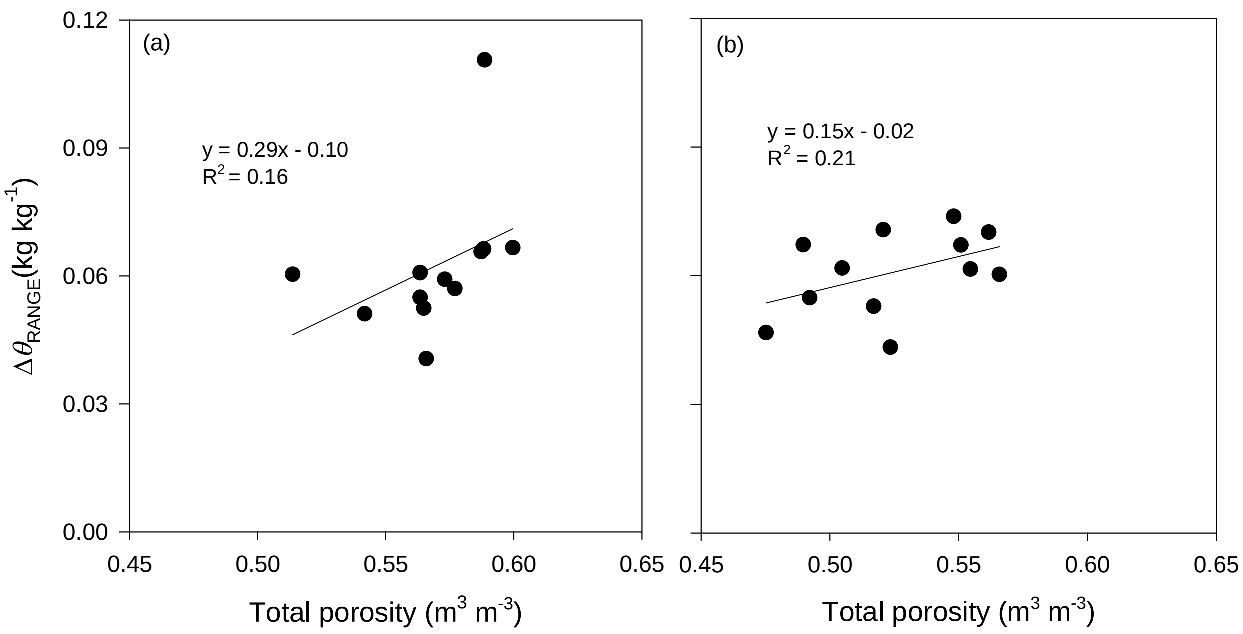

Fig. 8. Range of water contents for tillage as a function of soil porosity at (a) 1–5 cm and (b) 5–10 cm depth.

4. Discussion

4.1. Effect of compaction and sowing dates on seedbed physical properties

To assess the effect of treatment on pore structure characteristics of the seedbed, soil bulk density, water retention, aeration and pore organization indices (k_a/ε_a (PO_1) and k_a/ε_a^2 (PO_2) were determined. At 1–5 cm depth, the compaction × sowing date interaction significantly affected volumetric water content (θ), air-filled porosity (ε_a), air permeability (k_a) and pore organization indices (k_a/ε_a (PO_1) and k_a/ε_a^2 (PO_2)) although not bulk density (Table 2). The effects observed were not consistent for all the treatment combinations. A higher volume of pores <30 µm and lower volume of pores >30 µm were found for the A3+B1 compared to, for instance, the A2+B1 and A3+B0 treatments. This may be interpreted as compaction combined with late sowing (A3) reducing ε_a at -100 hPa.

The pore organization indices, PO_1 and PO_2, can be used to describe the effects of soil management on pore size distribution, tortuosity and continuity of ε_a (Groenevelt et al., 1984). These authors proposed that soils with similar PO_1 values have identical pore-size distributions and pore continuities because k_a is normalized only with respect to the volume of air-conducting pores. Soils with similar PO_2 values, on the other hand, only have identical pore size distributions. This implies that the difference between PO_1 and PO_2 mainly relates to the pore continuity, independent of the pore size distribution (Ball et al., 1988). At 5–10 cm depth, compaction reduced k_a, PO_1 and PO_2 (Table 2). Generally, a value of k_a of less than 1 μm^2 has been suggested as a critical limit, inferring soil impermeability, which restricts water and air transport necessary for many biological processes. The results showed k_a values above the critical limit in all cases (Table 2).

Effect of compaction and sowing dates on soil strength characteristics of seedbed was quantified by measuring the tensile strength (*Y*) of aggregates and soil penetration resistance (PR). At -100 hPa, compaction and sowing date affected *Y* of aggregates. For the latter, the difference was only significant between early sowing date (A1) and normal sowing date (A2) at 1–5 cm depth (Table 3). At both 1–5 cm and 5–10 cm depths, *Y* was lower for the A2+B0 treatment, whereas the A1+B1 treatment, in general, increased *Y* at -300, -1000 hPa and at air-dry state (Table 3). The higher *Y* for the compacted and A1 treatments can be explained by structural damage due to kneading by tillage implements in wet conditions, which consequently increased *Y* following the drying of soil fragments produced by tillage (Watts et al., 1996). The results are consistent with the Munkholm and Schjønning (2004) study. These authors also showed that the effect of structural damage on *Y* can be persistent, and further found that after six months, aggregates produced by intensive rotary tillage when soil was too wet for optimal tillage remained stronger than a reference soil, which was tilled when the soil had dried to a friable condition. Håkansson et al. (1988) found that the effects of compaction in the topsoil may persist even after mechanical loosening such as plowing and harrowing.

The results in this study showing significant effects of the compaction × early sowing interaction on *Y* tested at -300, -1000 hPa and in air-dry state at 1–5 cm depth are, however, surprising, because such a significant interaction effect was not observed for soil bulk density (ρ_b) at the same depth (Table 2). This can be explained by *Y*, unlike ρ_b, being highly affected by the particle-particle bonds participating in the particular mode of failure as well as the presence of micro-cracks serving as planes of weakness to initiate tensile failure (Chakraborty et al., 2014).

Interestingly, even though the A2 and A3 treatments had similar water contents at 1–5 cm depth at the time of compaction and/or sowing operations (Table 1), *Y* differed between the two treatments. For instance, *Y* at -1000 hPa for A2+B0 was significantly different from

A3+B0 at 1–5 cm depth (Table 3). This may be ascribed to soil 'memory' of antecedent preciptiation events prior to treatments and sampling. Thus, maximum rainfall amounts of 10.2 and 16.2 mm on April 16–17, 2016 before the A2 treatment (Fig. 2b) compared to 15.4 and 30.4 mm on April 29–30, 2016 prior to the A3 treatment (Fig. 2c) may have differently influenced the spontaneous and mechanical dispersion of clay as well as wetting and drying cycles, which in turn affect the temporal variation of Y (Kay and Dexter, 1992).

Penetration resistance was significantly affected by sowing date ($p<0.05$). The A1 treatment had a higher PR in the seedbed and down to 27 cm depth compared to the A2 and A3 treatments (data not shown). As expected, compaction increased PR down to 27 cm depth, although the effect was significant ($p=0.02$) only at 7–15 cm depth (data not shown). de Toro and Arvidsson (2003) also found an increased PR down to a depth of 18 cm after harrowing operations for seedbed preparation were performed on clayey soil in Sweden at different water contents in spring. In the upper soil layers, tire inflation pressure is the major driver of stresses exerted on soil by agricultural machinery (Schjønning et al., 2012). Thus, the effect of the A1 treatment on PR measured at 1–5 cm and below the seedbed down to 27 cm depth can be due to stresses exerted by tractor wheels and tillage implement, but could also be an accumulated effect over the three years of experimental treatments (Håkansson et al., 1988) despite soil loosening by plowing each autumn as well as freezing and thawing cycles prior to the experimental treatments in spring.

In general, the soil aggregates studied can be described as friable according to the classification by Imhoff et al. (2002). Notwithstanding this, the A1 treatment reduced friability (k_Y) at both soil depths studied compared to the A2 treatment. Compaction also reduced k_Y, particularly at 1–5 cm depth, although not significantly (Fig. 4). The results illustrate that tilling soil in wet condition reduces k_Y due to soil structural degradation. Higher k_Y values for the A2 treatment imply that bulk soil or soil clods produced after primary tillage can be more easily fragmented into smaller fragments, whereas smaller aggregates are difficult to further fragment into undesirably smaller elements (Munkholm, 2011).

Measurement of soil fragmentation at 5–15 cm depth, i.e., below the seedbed, yielded information on soil compaction and fragment size distribution. Compaction × early sowing date resulted in poor soil fragmentation, evidenced by the large geometric mean diameters (GMD) of soil fragments, the smaller proportion of small soil fragments (<5 mm in diameter) and larger proportion of soil clods (>32 mm in diameter) (Table 4). Seedbeds consisting of fragments <5 mm in size increase the number of plants and crop yield of small grain cereals by 5% compared to coarse seedbeds in silty soil in Sweden (Håkansson et al., 2002). Our results showed that, in general, the proportion of soil fragments <5 mm in diameter produced from the dropped soil cores was small (maximum of 15% at all the matric potentials studied). This implies that, in practice, larger number of successive seedbed harrowings, including their negative impact on soil physical properties, would be required to fragment the soil into a suitable seedbed for spring-sown small grain cereal crops.

4.2. Effect of compacton and sowing dates on crop yield

Compaction and late sowing reduced the yield of spring-sown small grain cereal crops, but the effect was significant only in 2014 and 2015 for wheat and barley, respectively (Table 5). This may be ascribed to a short growing season rather than the influence of soil physical properties. Riley (2016) also explained a yield loss after late sowing by a shorter growing season. Likewise Perez-Bidegain et al. (2007) found that the yield of corn in Newton, USA was not significantly affected by sowing date in the first two years, but was in the third year. However, their study did not include compaction treatment, in contrast to our study. The insignificant effect of compaction and sowing dates in 2016 and 2017 for oats and barley, respectively, can be interpreted as multiple factors affecting the final yield of crops (Perez-Bidegain et al., 2007) —not least the specific weather conditions during the growing season.

Simple regression analyses showed that when tested at -100 hPa, the yield of oats in 2016 was negatively related to the GMD of soil fragments produced from the drop-shatter test and to Y, but positively related to Φ (Fig. 5a–c). In relation to soil strength, the yield of oats was negatively related to PR (Fig. 6a–e). Overall, the relationship was significant for Φ and Y as well as for PR at 1–5 and 7–15 cm depth, explaining 37–58% of the variation in the yield of oats. The negative and significant relationship between yield and Y and PR can be explained by the effect of soil strength on root growth and penetration, which can adversely affect crop yield (Taylor et al., 1966). The negative and weak linear relation between yield and GMD is indicative of the generally negative effect of poor soil fragmentation on plant growth.

4.3. Effect of compaction and sowing dates on water contents for tillage

Compaction, and early and late sowing dates reduced the range of water contents for tillage ($\Delta\theta_{\mathrm{RANGE}}$), but the effect was not significant at any of the depths studied (Fig. 7a–d). $\Delta\theta_{\mathrm{RANGE}}$ was positively related to soil porosity (Φ) (Fig. 8a and b), which agrees with the results of

Dexter and Bird (2001) who showed that the range of water contents for tillage and its upper (θ_{WTL}) and lower limits (θ_{DTL}) decrease with increasing soil bulk density (ρ_b), an indication of a reduced Φ. However, in their study, θ_{WTL} and θ_{DTL} were predicted using pedotransfer functions, in contrast to the consistency approach used in this study.

From our results it could be deduced that compaction and early sowing date reduce macroporosity. Air-filled pores and cracks elongate and coalesce under mechanical stress, resulting in soil fragmentation during tillage (Dexter and Richard, 2009). This means soil structural degradation due to disturbances by tillage implements and stresses exerted by the wheels of machinery in less-than-ideal soil moisture conditions will increase soil ρ_b and, consequently, reduce the $\Delta\theta_{RANGE}$.

It should be pointed out that the presented results only provide a snap-shot of soil workability, assessed as the $\Delta\theta_{RANGE}$ within which tillage can be executed satisfactorily after a secondary tillage in spring. As mentioned previously, we expect a relatively small residual effect of treatment on soil workability in the following spring after plowing and freezing and thawing cycles during the winter. Nevertheless, a narrowing of the $\Delta\theta_{RANGE}$ for the early and late sowing can reduce the water contents at which soil is suitable for primary tillage in the following autumn (Munkholm and Schjønning, 2004). Findings of the study indicate that a combination of quantitative information on soil structural and strength characteristics provide useful criteria for assessing soil workability and fragmentation during tillage.

5. Conclusions and practical implications of the results

Results from this study confirmed, to some extent, the hypothesis that soil fragmentation and the strength of soil aggregates differ for different compaction treatments and sowing dates. The main conclusions were that the interaction of compaction with sowing date significantly affected soil pore characteristics, particularly at 1–5 cm depth, although the effect was not consistent for all treatment combinations. Compaction combined with early sowing increased tensile strength at both 1–5 and 5–10 cm depth, whereas the dropped soil cores, in general, fragmented poorly for all treatments and at all matric potentials studied. Early sowing significantly decreased soil friability and increased soil penetration resistance in the seedbed layer and down to 27 cm depth. Late sowing decreased yield of spring-sown small grain cereal crops, but this may mainly be ascribed to a shorter growing season rather than an influence of soil physical properties and compaction. Finally, early and late sowing decreased the range of water contents for tillage, which can reduce soil workability for subsequent tillage operations, especially autumn plowing.

The overall findings of the study have practical implications for cropping regimes in colder climates, where the growing period for cereals is short by showing that cultivation in less-than-ideal moisture conditions such as early spring when soil is still wet limits the capacity of soil to produce desirable seedbeds after tillage. It also adversely affects soil physical properties of a seedbed, which in turn affect crop yield. Present and future farm managers need to consider the implications of compaction and sowing dates on soil physical conditions even more than in the past.

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Conflicts of interest: None.

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