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# Short-term effects of loosening and incorporation of straw slurry into the upper subsoil on soil physical properties and crop yield

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ABSTRACT

Subsoils that are compacted, nutrient-poor or low in soil organic matter (SOM) often limit crop growth and yield. Improvement of subsoil conditions by deep loosening is laborious and expensive and its positive effect may not last. This study investigated the effect of deep loosening and injection of slurry made from cereal straw (30 Mg dry mass ha$^{-1}$) at 25–34 cm depth on soil properties and crop performance in a Swedish field experiment that started in autumn 2015 and monitored soil and crop properties during 2016. Loosening + straw incorporation into subsoil resulted in significantly higher soil organic carbon (SOC) content, potential plant-available water and porosity and lower bulk density (BD) in spring 2016 compared with the control. In autumn 2016, penetrometer resistance (PR) and BD were both significantly lower and SOC and porosity were significantly higher in the loosening + straw treatment compared with the control and loosening only (29–34 cm). Furthermore, BD was significantly lower in the loosening + straw treated subsoil than in the top soil layer of the control (0–10 cm). Observations indicated that more continuous pores were found in the loosening + straw treatment than in other treatments. Roots and soil faunas were found more frequently where straw was incorporated. Grain yield increased by 5.6% due to loosening + straw addition ($P$ = 0.03) and by 4% due to loosening only ($P$ = 0.06). These results indicate that loosening + straw input into upper subsoil had a positive short-term influence on soil physical properties, potential plant-available water and grain yield. Straw addition prolonged the positive effect of loosening.

## 1. Introduction

Subsoil that is compacted, saline, acidic, nutrient-deficient or low in soil organic matter (SOM) can limit crop growth, yield and quality (Kautz et al., 2013; Rengasamy et al., 2003). However, previous research has mainly focused on topsoil horizons (Kautz et al., 2013; Lorenz and Lal, 2005; Rengasamy et al., 2003), probably due to lack of techniques and management options for subsoil improvement and to underestimation of the role of subsoil in plant nutrient acquisition (Kautz et al., 2013). Compacted soil has poor structure and is characterised by high bulk density (BD) and high penetration resistance (PR) (Etana and Håkansson, 1994; Hammel, 1994; Schjønning and Rasmussen, 1994), and reduced porosity (Hassan et al., 2007).

Improving subsoil by loosening is expensive (Håkansson and Reeder, 1994; Jones et al., 2003) and its effect may not last, as soils recompact (Kooistra and Boersma, 1994; Larney and Fortune, 1986; Munkholm et al., 2005). Therefore, combining loosening with other soil amelioration practices may be relevant (Hamza and Anderson, 2005).

Subsoil improvement was achieved in a Swedish study when loosening of clay subsoil was combined with addition of burned lime to stabilise soil structure, which increased crop yields by about 7% over a 10-year period (Westlin, 2010). Structural stabilisation of loosened subsoil may also be achievable through addition of organic material, thereby forming new aggregates (Gill et al., 2008; Khalilian et al., 2002; Leskiw et al., 2012), minimising re-compaction (Hamza and Anderson, 2005; Leskiw et al., 2012) and enhancing soil fertility. However, combining deep loosening and incorporation of organic material into subsoil is not common practice due to lack of scientific results and technical solutions (Hamza and Anderson, 2005).

The aims of the present study were to investigate the short-term effect of deep loosening and injection of straw slurry (30 Mg dry mass ha$^{-1}$) into the upper subsoil on soil physical properties, crop growth

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and yield.

## 2. Material and methods

### 2.1. Experimental site and treatments

The field study was carried out on a Eutric Cambisol (FAO, 2014) at Säby (Uppsala, Sweden; 59°49′N, 17°42′E) used for arable crops for more than 100 years. The upper subsoil (25–35 cm) at the site consists of silt loam (20.5% clay, 60.6% silt, 18.9% sand) and the pH in $H_2O$ (1:2.5) is 6.5. The field study was laid out in a randomised block design with four blocks as replicates and a plot size of 75 m square (3 m width and 25 m length) and five treatments, of which three treatments (subsoil loosening, subsoil loosening + straw incorporation and control) are reported in this paper.

### 2.2. Subsoiling and incorporation of straw slurry

Straw with a density of 0.39 kg dm$^{-3}$, consisting of 0.53% nitrogen (N), 0.042% phosphorus (P), 0.74% potassium (K) and 45% carbon (C), with pH 6.6 and C:N ratio 85, was submerged in water to produce slurry (91% water and 9% straw of total volume) for injection. The water-holding capacity was about 5.5 mL g$^{-1}$ straw. The deep loosening machine used (Combiplow Gold, AGRISEM International, France) had a working width of around 3 m, with four vertical tines spaced 74 cm apart and bearing a winged tip 32 cm wide (Fig. 1). The net subsoil area affected by loosening was 43% per plot (32 cm width x 9 cm depth). Loosening and straw incorporation were performed at a speed of 1.5 km per hour to 25–34 cm depth. During loosening of the soil, the straw slurry was injected under pressure into the upper subsoil through rectangular openings in metal pipes welded behind each vertical tine and mounted on the back of a slurry tank.

The organic amendment was applied at about 30 Mg dry mass ha$^{-1}$. Due to the small openings in the injector pipes, incorporation of the straw slurry was limited to lines of about 8 cm width x 9 cm depth. The distance between straw lines in the upper subsoil was 68.5 cm. At places where space in the upper subsoil to accommodate the large pulse of straw was limited, around 15–20% of the slurry ended up on the soil surface. Moreover, variations in injection pressure and driving speed of the tractor caused uneven distribution of straw slurry between and within straw lines. The soil area affected by loosening + straw treatment was 43%, of which 11% was enriched with straw slurry. On a volume basis, considering a soil depth of 50 cm, the proportion of soil affected by loosening was 15% and the proportion affected by loosening + straw was 15%, of which 4% was treated with straw slurry. Loosening and loosening + straw injection lines were marked and soil and crops were sampled randomly along the lines. Final yield was measured from combine-harvester data for the whole plot.

### 2.3. Soil sampling

Soil samples for analysis of soil organic carbon (SOC), total soil N and bulk density (BD) were taken in spring before sowing and in autumn after harvest in 2016. Four samples were taken with an auger at 29–34 cm in each plot and pooled to a composite sample. The topsoil (0–10 cm) was only sampled in the control because top soil in the other treatments was affected by the loosening operation. Soil samples were collected on the same occasion and close to the spot where BD cylinders were sampled. Chemical analyses were carried out on air-dried and sieved (2 mm mesh size) soil using dry combustion (LECO CNS Analyser; LECO Corporation, St. Joseph, MI 49085, USA) (Nelson and Sommers, 1996).

Soil BD was determined as described by Blake and Hartge (1986) by extracting four samples per plot, using cylinders (inner diameter 7.2 cm) of 10 cm height for the topsoil (0–10 cm) and 5 cm for the upper subsoil (29–34 cm). Gravimetric water content in spring and total porosity (% pore space) in spring and autumn were determined on the same soil samples used for BD measurements. Total porosity was calculated using the formula proposed by Vomocil (1965), assuming a particle density of 2.65 g cm$^{-3}$. Particle density was corrected for straw addition in the loosening + straw slurry treatment, which was denoted as 1.41 g cm$^{-3}$ (average of decomposed and undecomposed straw) (Guerif cited in Soane, 1990). Saturated water content ($\theta_{sat}$), water content at field capacity ($\theta_{fc}$) and wilting point ($\theta_{wp}$) were estimated from a pedotransfer function (PTF) used to predict hydraulic properties of Swedish soils (Model 8 in Kätterer et al., 2006). The results were associated with different soil pores to calculate pore size distribution. The difference between $\theta_{fc}$ and $\theta_{wp}$ multiplied by the thickness of the soil layer was considered to represent plant-available water in that specific soil layer (Allen et al., 1998). Penetration resistance (PR) was

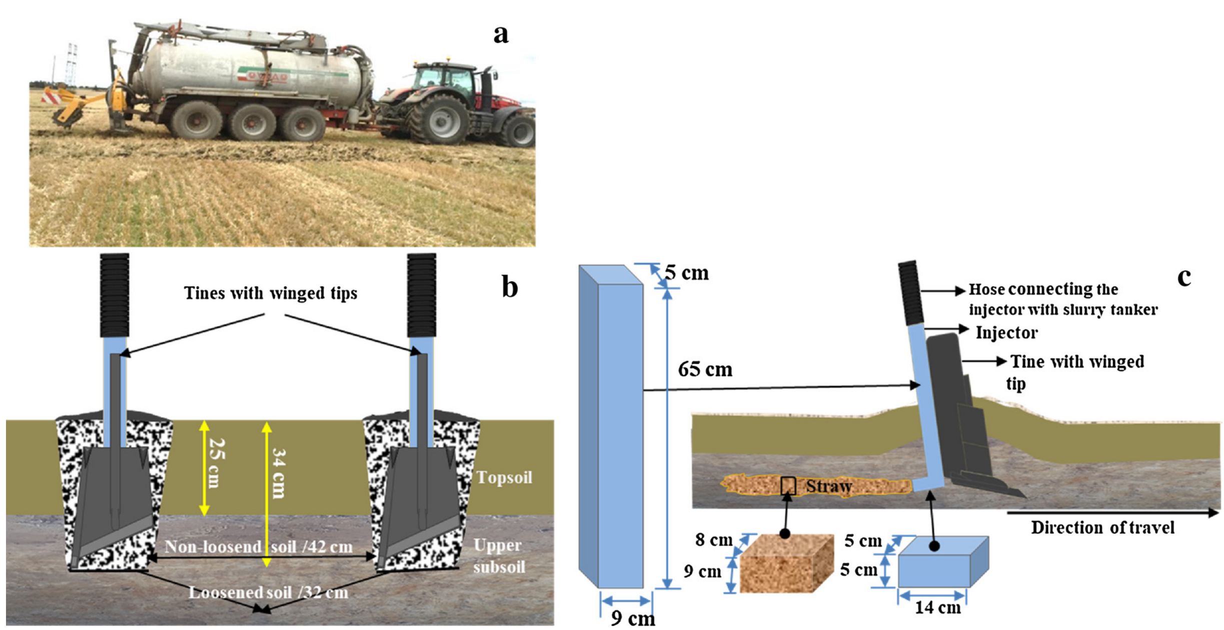


**Fig. 1.** The loosening and straw slurry injection system: (a) tractor-mounted equipment (b) front view of tines with injectors (there are two additional tines and injectors) and (c) side view of tine with its injector.

determined after crop harvest (October 2016) with a hand-held electronic cone penetrometer (Royal Eijkelkamp Company, Netherland) fitted with an 11 mm diameter 60° cone with basal area 1 $cm^2$. When the penetrometer is pushed vertically and slowly into the soil profile at a steady speed of 2 cm $s^{-1}$, software records the resistance across a depth of 40 cm. Average PR in the 29–34 cm layer was calculated from 10 sampling spots (following crop lines) in each plot. On the next day, soil was sampled to determine gravimetric water content. Three representative samples per plot were collected with a soil auger from the 0 to 10, 10 to 20, 20 to 25, 25 to 30, 30 to 35 and 35 to 40 cm soil layers, oven-dried at 105 °C for 24 h and weighed.

### 2.4. Crop growth, sampling and measurements

Spring wheat (*Triticum aestivum* L. cv. Qvarna) was sown at a row spacing of 12 cm and fertilised with 120 kg N, 20 kg P, 30 kg K and 15 kg sulphur (S) per hectare in the form of AXAN (27% N + 9% S) and P-K 11–21 according to common agricultural practice. Crop growth dynamics were monitored during 2016 by repeated sampling of above-ground biomass. Five randomly selected areas of 25 cm x 25 cm per plot were cut, using scissors close to the soil surface, at Zadok's growth scale (ZGS) 53 (ear emergence), 65 (flowering) and 78 (milk stage) (Zadoks et al., 1974). A combine-harvester designed for experimental plots was used to measure grain yield in each plot from 40.8 $m^2$ (2.4 m width x 17 m length) size. The working width of the combine has the capacity to accommodate four loosening only and loosening + straw treated lines in each plot. Plant samples were dried, threshed at final sampling, milled and weighed. Data from one of the plots had to be omitted due to weed infestation, an omission which was considered in the statistical analysis.

Relative chlorophyll content in leaves was estimated with a hand-held bi-spectral based Soil Plant Analysis Development (SPAD-502) meter (Minolta Camera Co., Osaka, Japan) at ZGS 45 (booting), 59 (heading) and 69 (flowering stage), using the last fully expanded leaf at the top. Five sampling points per plot were selected and five plants were measured, with three readings per leaf (75 measurements per plot). Plant height was measured on 15 randomly selected plants per plot.

To observe root growth and distribution in the soil layer, a very simple modified form of the profile wall method was applied (Bohm, 1979). Three soil pits of about 40 cm depth were dug one day before harvest in each treatment. Any visible roots exposed by digging and levelling the soil with a knife were observed *in situ* at 10 cm, 25 cm and 34 cm depth along a horizontal line of 12 cm width. Basic field operations and lists of machineries are described in Table 1.

**Table 2**
Mean temperature and sum of precipitation during the growing season in 2016 (May–August) and in the long term.(1961–1990)

| Variables | 2016* | | Long-term (1961-1990)* | |
|---|---|---|---|---|
| | May-August | Annual | May-August | Annual |
| Temperature (°C) | 15.4 | 7.1 | 14.2 | 5.5 |
| Precipitation (mm) | 173 | 472 | 215 | 528 |

*Ultuna meteorological station.

### 2.5. Statistical analysis

Analysis of variance was performed with the R-software, version 3.4.0. Results are presented as averages of treatment values. Treatment effects were analysed using a linear model. The statistical significance of treatment effects was determined at $P < 0.05$. Pearson correlation coefficient was calculated to assess the relationships between soil BD and SOC, PR and BD, PR and SOC and PR and water content.

## 3. Results and discussion

### 3.1. Weather conditions

Meteorological data (Lantmet vid SLU/Fältforsk, 2016 and SMHI, 1961–1990) showed that precipitation during the crop growing season (May to August) was considerably lower (42 mm) and mean temperature higher (1.2 °C) than the long-term average (1961–1990) (Table 2).

### 3.2. Carbon and nitrogen concentrations and bulk density in soil

The concentration of SOC at 29–34 cm was higher in the loosening + straw treatment than in the control in spring ($P = 0.01$) and autumn ($P = 0.01$). This is consistent with findings in other studies (Gill et al., 2008; Khalilian et al., 2002; Leskiw et al., 2012), where the large amount of straw added increased SOC (Liu et al., 2014; Thomsen and Christensen, 2004). Although we expected a decrease in SOC over time, the concentration in autumn 2016 was higher than in spring 2016, most likely due to variation between sampling lines.

Bulk density in the 29–34 cm layer was lower for loosening + straw than for the loosening only treatment ($P = 0.006$) and for the control (both in 0–10 cm and 29–34 cm) in autumn (Table 3). Lower subsoil BD values were due to the combined effects of the large amount of organic material added (Chen et al., 1998; Gassel, 1982) being less dense than soil mineral particles (Bodson et al., 2016; Soane, 1990; Zhang, 1994) enhancing soil porosity (Arvidsson, 1998), and deep loosening. Bulk density in the loosening + straw treatment remained almost unchanged

**Table 1**
Time table for field operations, soil sampling and machineries used.

| Activities | Date | Machineries |
|---|---|---|
| Deep loosening and incorporation of straw | October 20–21, 2015 | (Combiplow Gold, AGRISEM International, France |
| Cultivation (15 cm) | November 5, 2015 | Swift 560 6 meter working width |
| Soil sampling | May 4–5, 2016 | |
| Fertiliser application | May, 2016 | Combi version Rapid 300C seed drills with fertilizer 3 meter |
| Seedbed preparation and sowing | May 18–19, 2016 | Väderstad NZ aggressive 600 powerful harrow with 6 meter working width and Combi version Rapid 300C seed drills with fertilizer 3 meter respectively |
| Herbicide application (pre and post crop emergence) | May 19 and June 9, 2016 | HARDI MASTER plus 12 meter wide mounted sprayer |
| Crop sampling | June–August 2016 | |
| Harvesting | September 2, 2016 | Sampo Rosenlew SR 2010 (Finland) |
| Soil sampling after harvest | October 3 and 6, 2016 | |

**Table 3**
Treatment effects on soil organic carbon (SOC), total nitrogen (N), bulk density (BD) and total porosity in the 29–34 cm soil layer in spring and autumn 2016. The SOC content includes undecomposed and partly decomposed straw.

| Season | Soil parameter | Loosening + straw | Loosening | Control |
|---|---|---|---|---|
| Spring | SOC (g $kg^{-1}$) | 40.1[a] | 27.5[ab] | 19.7[b] |
| | Total N (g $kg^{-1}$) | 2.1 | 2.1 | 1.4 |
| | BD (kg $dm^{-3}$) | 1.05[a] | 1.29[ab] | 1.46[b] |
| | Total porosity (%) | 60[a] | 51[ab] | 45[b] |
| Autumn | SOC (g $kg^{-1}$) | 55.9[a] | 24.1[b] | 16.7[b] |
| | Total N (g $kg^{-1}$) | 2.5[a] | 2.1[ab] | 1.5[b] |
| | BD (kg $dm^{-3}$) | 1.02[a] | 1.39[b] | 1.42[b] |
| | Total porosity (%)* | 61[a] | 48[b] | 46[b] |

*Total porosity (% pore space) was determined on the same soil samples used for BD measurements. Means with the same lettering was not significant. Different lower case letters indicate statistical significance at $p < 0.05$

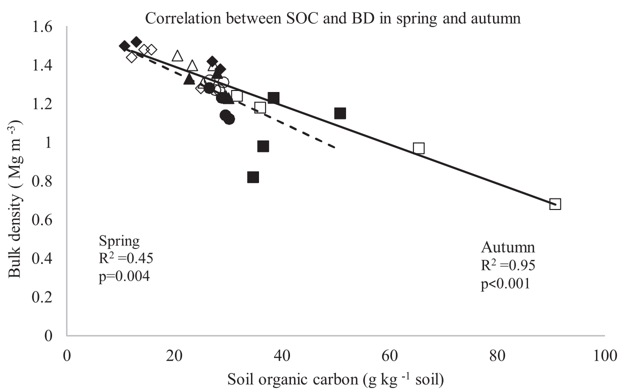


**Fig. 2.** Correlation between soil organic carbon (SOC) and soil bulk density (BD) in the upper subsoil layer of treated plots and in the topsoil and upper subsoil layer of the control (n = 16). Loosening + straw (rectangle), loosening (triangle), control top soil 0–10 cm (circle) and control upper subsoil 29–34 cm (diamond). Spring (filled symbols and dotted line) and autumn (hollow symbols and solid line).

even after a number of field operations during 2016, showing that organic material incorporation plus loosening had a more positive effect than loosening only and probably modified the root physical environment (Ishaq et al., 2001). There was a statistically significant negative correlation between SOC and BD ($R^2 = 0.45$ in spring, $R^2 = 0.95$ in autumn) (Fig. 2). The C:N ratio in the loosening + straw treatment was 19.8 and 22 in spring and autumn 2016, respectively. For comparison, SOC, BD and porosity values in the 0–10 cm topsoil layer were 28.7 and 27.9 g $kg^{-1}$, 1.19 and 1.29 kg $dm^{-3}$ and 55 and 51% in spring and autumn, respectively.

**Table 4**
Plant-available water content (AWC) and porosity in spring 2016, estimated using a Swedish pedotransfer (PTF) model.

| Treatment | Swedish PTF Model 8 in.(Kätterer et.,[a] 2006) | |
|---|---|---|
| | [a]Total porosity % | AWC (mm) in the 29–34 cm layer |
| Loosening + straw | 56[a] | 20.9[a] |
| Loosening | 51[ab] | 16.9[ab] |
| Control | 47[b] | 14.5[b] |

[a] The porosity data were within the range determined for soil samples as depicted in Table 3Means with the same lettering was not significant. Different lower case letters indicate statistical significance at $p < 0.05$

**Table 5**
Treatment effects on relative leaf chlorophyll content (SPAD-index) and plant height at different Zadok's growth scales (ZGS).

| Parameters | Zadok's growth scale | Loosening + straw | Loosening | Control |
|---|---|---|---|---|
| SPAD-index | 45 | 49.1 | 49.2 | 48.9 |
| | 59 | 55.3 | 55.5 | 55.4 |
| | 69 | 54.8 | 55.5 | 55.2 |
| Plant height (cm) | 45 | 52.5 | 51.9 | 51.9 |
| | 59 | 75.1 | 72.8 | 72.7 |
| | 69 | 79.1[a] | 76.7[ab] | 75.9[b] |

### 3.3. Penetration resistance and related gravimetric water content

In spring 2016, water content in the 29–34 cm soil layer was 41.3, 25.3 and 22.5% in the loosening + straw, loosening only and control treatments, respectively, with loosening + straw being significantly different from the other two treatments. In autumn, differences in water content (30–35 cm) were not significant, although somewhat higher than in the control ($P = 0.08$). However, penetration resistance was significantly lower in the loosening + straw treatment than in the control and loosening only (Fig. 3).

Penetration resistance in autumn 2016 was positively related to soil BD $R^2 = 0.48$ ($P = 0.01$) and negatively to water content $R^2 = 0.56$ ($P = 0.005$) and SOC $R^2 = 0.53$ ($P = 0.007$) (data not shown), as previously found by Khan et al. (2001). Lower BD, higher porosity and a tendency for higher water content in the loosening + straw treatment most likely caused the lower PR values (Unger and Jones, 1998; Vaz et al., 2001). In general, resistance increased with soil depth in all treatments and was highest in the subsoil (below 25 cm soil depth), with values greater than 3 MPa (Fig. 3).

### 3.4. Estimation of plant-available water and pore size distribution

The amount of cereal straw added, with a water-holding capacity of 5.5 mL $g^{-1}$ dry weight, was expected to increase the water-holding

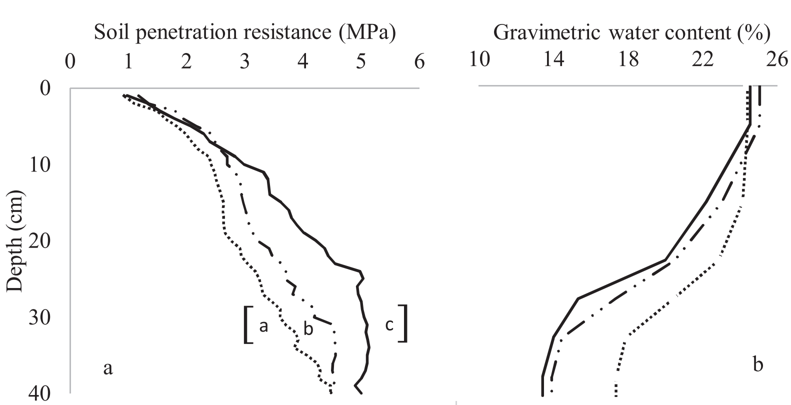


**Fig. 3.** Average values of (a) penetrometer resistance (PR) and (b) gravimetric water content (%) after crop harvest in autumn 2016 in the loosening + straw (dotted line) and loosening only (long dash with two dots) treatments and in the control (solid line). Square brackets indicate the 29–34 cm soil layer for PR and small letters significant levels.

**Table 6**
Response of aboveground biomass and grain yield of spring wheat to subsoil treatments.

| Crop production | Harvesting | Zadok's growth scale | Loosening + straw | Loosening | Control |
|---|---|---|---|---|---|
| Aboveground biomass (Mg $ha^{-1}$) | Frames within plots | 53 | 5.4 | 4.6 | 4.9 |
| | | 65 | 7.9 | 8.1 | 7.8 |
| | | 78 | 11.4 | 12 | 11 |
| Grain yield (Mg $ha^{-1}$) | Whole plot, combine-harvester | 93 | $4.91^{a}$ | $4.84^{ab}$ | $4.65^{b}$ |
| Grain protein content (%) | | | $15.7^{b}$ | $16.2^{a}$ | $16.1^{a}$ |

capacity in the 25–34 cm soil layer by 15 mm. Estimation of potential available water in the 29–34 cm layer using a PTF showed that the loosening + straw treatment increased plant-available water significantly, by e.g. 6.4 mm in spring ($P = 0.01$), compared with the control (Table 4). A yield increase of 5.6% in the loosening + straw treatment could be partly explained by having 6.4 mm more plant-available water, which reflected the ability of SOC to store more water than soil only (Hamza and Anderson, 2005; Powlson et al., 2012).Thus, longer periods of moist conditions in the straw slurry lines than in untreated soil could have favoured root and plant growth in general. Pore volume in which roots could grow (macro and meso) was 37% higher in the loosening + straw treatment than in the control, while plant-available water was 56% higher (data not shown). These results indicate that the plant-available water in the loosening + straw soil contributed more to the yield increase than porosity, which provides channels for roots to grow. In the loosening treatment, both pore volume (macro and meso) and plant-available water contributed to a similar extent to the yield increase.

### 3.5. Relative leaf chlorophyll

The SPAD index showed no significant differences. Measurements of plant height revealed that plants in the loosening + straw treatment were taller than those in the control ($P = 0.03$) at ZGS 69 and there was a tendency for a height difference compared with the control and loosening treatments ($P = 0.08$) at ZGS 59(Table 5).

### 3.6. Root observations

In field observations, more continuous pores were found in the loosening + straw treatment than in the other treatments. These pores may serve as channels for roots and hence enhance soil fertility and crop yield (Colombi et al., 2017). Roots and soil faunas were found more frequently where straw was incorporated, which indicates that the straw slurry lines were a favourable environment for root growth and soil organisms.

### 3.7. Plant biomass and crop yield

Biomass data from frame sampling showed no significant differences between treatments, although there was a tendency for higher yield on the treated soil. However, whole plot grain yield records showed that loosening + straw resulted in a small but significantly higher yield (5.6%, $P = 0.03$) than the control. This result confirms previous findings (Gill et al., 2008; Leskiw et al., 2012). However, the increase in yield may have been underestimated, since there was weed infestation in the loosening + straw treatment. According to SPAD index measurements there was no sign of N immobilisation in the crop until ZGS 69. In the meantime, the soil C:N ratio in the straw lines was 19.8 and 22 in spring and autumn 2016, respectively. However, grain N (protein) content was significantly lower in the loosening + straw treatment (15.7%) than in the loosening only (16.2%, $P = 0.02$) and control treatments (16.1%, $P = 0.03$), which showed that immobilisation of N took place (Table 6). However, the N (protein) content was still high in all treatments. The yield response due to loosening also tended to be significantly higher than in the control (4%, $P = 0.06$) (Table 6).

## 4. Conclusions

Our results suggest that loosening and incorporation of straw slurry into the upper subsoil has the potential to improve soil physical conditions in the short term. It resulted in a significant accumulation of organic matter, lower soil bulk density and penetration resistance. Bulk density remained almost constant over the year even after a number of field operations during spring and autumn of 2016. Potential available water in the loosening + straw treatment increased significantly. The above change in soil properties favoured crop growth and resulted in a small but significantly higher yield (5.6%). Calculations addressing the question if more soil water or increased pore volume in which roots could grow was the main cause for higher yields indicated that plant available water contributed to a larger extent. On the other hand, grain N (protein) content, was significantly lower in the loosening + straw treatment, which showed that immobilisation of N took place at the later crop stage.

Incorporation of straw has helped the effects of subsoiling to persist but a central question is how long lasting will benefits from these management changes be. Continuous research to identify if and how long the possible benefits lasts is indispensable. Thus, a subsequent study will monitor the residual effect of loosening only and loosening and straw addition over time on soil properties considered in the present study and crop yield, along with other soil structural properties.

Lantmet vid SLU/Fältforsk, 2016. http://www.ffe.slu.se/lm/LMHome.cfm?LMSUB=1 (Accessed 13 June 2018).

SMHI, 1961-1990. http://data.smhi.se/met/climate/time_series/month_year/normal_1961_1990/ (Accessed 13 June 2018).

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## References

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop Evapotranspiration-Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage Paper No. 56. FAO, Rome. http://www.fao.org/docrep/X0490E/x0490e00.htm.
Arvidsson, J., 1998. Influence of soil texture and organic matter content on bulk density, air content, compression index and crop yield in field and laboratory compression experiments. Soil Tillage Res. 49, 159–170.
Blake, G.R., Hartge, K.H., 1986. Bulk density. In: Klute, A. (Ed.), Methods of Soil Analysis, Part 1—Physical and Mineralogical Methods, 2nd Edition. Agronomy Mono- graph 9, American Society of Agronomy—Soil Science Society of America, Madison, pp. 363–382.
Bodson, B., Degré, A., Colinet, G., Lemtiri, A., Hiel, M.-P., Chélin, M., Parvin, N., Barbieux, S., Degrune, F., Garré, S., 2016. Crop residue management in arable cropping systems under a temperate climate. Part 2: soil physical properties and crop production. A review. Biotechnol. Agron. Soc. Environ. 20, 245–256.
Bohm, W., 1979. Methods of Studying Root Systems. Springer-Verlag, Berlin, pp. 188.

Chen, Y., Tessier, S., Rouffignat, J., 1998. Soil bulk density estimation for tillage systems and soil textures. Am. Soc. Agric. Biol. Eng. 41, 1601–1610.
Colombi, T., Braun, S., Keller, T., Walter, A., 2017. Artificial macropores attract crop roots and enhance plant productivity on compacted soils. Sci. Total Environ. 574, 1283–1293.
Etana, A., Håkansson, I., 1994. Swedish experiments on the persistence of subsoil compaction caused by vehicles with high axle load. Soil Tillage Res. 29, 167–172.
FAO, 2014. World Reference Base for Soil Resources 2014. International Soil Classification System for Naming Soils and Creating Legends for Soil Maps. FAO, Rome. http://www.fao.org.
Gassel, D., 1982. Tillage effects on soil bulk density and mechanical impedance. In: Unger, P.W., Van Doren, D.M. (Eds.), Predicting Tillage Effects on Soil Physical Properties and Processes. ASA-SSSA, Madison, USA, pp. 45–67.
Gill, J.S., Sale, P.W.G., Tang, C., 2008. Amelioration of dense sodic subsoil using organic amendments increases wheat yield more than using gypsum in a high rainfall zone of southern Australia. Field Crops Res. 107, 265–275.
Håkansson, I., Reeder, R.C., 1994. Subsoil compaction by vehicles with high axle load—extent, persistence and crop response. Soil Tillage Res. 29, 277–304.
Hammel, J., 1994. Effect of high-axle load traffic on subsoil physical properties and crop yields in the pacific Northwest USA. Soil Tillage Res. 29, 195–203.
Hamza, M., Anderson, W., 2005. Soil compaction in cropping systems: a review of the nature, causes and possible solutions. Soil Tillage Res. 82, 121–145.
Hassan, F., Ahmad, M., Ahmad, N., Abbasi, M.K., 2007. Effects of subsoil compaction on yield and yield attributes of wheat in the sub-humid region of Pakistan. Soil Tillage Res. 96, 361–366.
Ishaq, M., Hassan, A., Saeed, M., Ibrahim, M., Lal, R., 2001. Subsoil compaction effects on crops in Punjab, Pakistan: I. Soil physical properties and crop yield. Soil Tillage Res. 59, 57–65.
Jones, R.J., Spoor, G., Thomasson, A., 2003. Vulnerability of subsoils in Europe to compaction: a preliminary analysis. Soil Tillage Res. 73, 131–143.
Kätterer, T., Andrén, O., Jansson, P.-E., 2006. Pedotransfer functions for estimating plant available water and bulk density in Swedish agricultural soils. Acta Agric. Scand. B-Soil Plant Sci. 56, 263–276.
Kautz, T., Amelung, W., Ewert, F., Gaiser, T., Horn, R., Jahn, R., Javaux, M., Kemna, A., Kuzyakov, Y., Munch, J.-C., 2013. Nutrient acquisition from arable subsoils in temperate climates: a review. Soil Biol. Biochem. 57, 1003–1022.
Khalilian, A., Williamson, R., Sullivan, M., Mueller, J., Wolak, F., 2002. Injected and broadcast application of composted municipal solid waste in cotton. Appl. Eng. Agric. 18, 17–22.
Khan, F., Tahir, A., Yule, I., 2001. Intrinsic implication of different tillage practices on soil penetration resistance and crop growth. Int. J. Agric. Biol. 1, 23–26.
Kooistra, M., Boersma, O., 1994. Subsoil compaction in Dutch marine sandy loams: loosening practices and effects. Soil Tillage Res. 29, 237–247.
Larney, F., Fortune, R., 1986. Recompaction effects of mouldboard ploughing and seedbed cultivations on four deep loosened soils. Soil. Tillage Res. 8, 77–87.
Leskiw, L.A., Welsh, C.M., Zeleke, T.B., 2012. Effect of subsoiling and injection of pelletized organic matter on soil quality and productivity. Can. J. Soil Sci. 92, 269–276.
Liu, C., Lu, M., Cui, J., Li, B., Fang, C., 2014. Effects of straw carbon input on carbon dynamics in agricultural soils: a meta-analysis. Glob. Change Biol. 20, 1366–1381.
Lorenz, K., Lal, R., 2005. The depth distribution of soil organic carbon in relation to land use and management and the potential of carbon sequestration in subsoil horizons. Adv. Agron. 88, 35–66.
Munkholm, L.J., Schjønning, P., Jørgensen, M.H., Thorup-Kristensen, K., 2005. Mitigation of subsoil recompaction by light traffic and on-land ploughing: II. Root and yield response. Soil Tillage Res. 80, 159–170.
Nelson, D.W., Sommers, L.E., 1996. Total carbon, organic carbon, and organic matter. Methods Soil. Anal. Part. 3—Chem. Methods 961–1010.
Powlson, D., Bhogal, A., Chambers, B., Coleman, K., Macdonald, A., Goulding, K., Whitmore, A., 2012. The potential to increase soil carbon stocks through reduced tillage or organic material additions in England and Wales: a case study. Agric. Ecosyst. Environ. 146, 23–33.
Rengasamy, P., Chittleborough, D., Helyar, K., 2003. Root-zone constraints and plant-based solutions for dryland salinity. Plant Soil 257, 249–260.
Schjønning, P., Rasmussen, K.J., 1994. Danish experiments on subsoil compaction by vehicles with high axle load. Soil Tillage Res. 29, 215–227.
Soane, B., 1990. The role of organic matter in soil compactibility: a review of some practical aspects. Soil Tillage Res. 16, 179–201.
Thomsen, I.K., Christensen, B.T., 2004. Yields of wheat and soil carbon and nitrogen contents following long-term incorporation of barley straw and ryegrass catch crops. Soil Use Manage. 20, 432–438.
Unger, P.W., Jones, O.R., 1998. Long-term tillage and cropping systems affect bulk density and penetration resistance of soil cropped to dryland wheat and grain sorghum. Soil Tillage Res. 45, 39–57.
Vaz, C.M., Bassoi, L.H., Hopmans, J.W., 2001. Contribution of water content and bulk density to field soil penetration resistance as measured by a combined cone penetrometer–TDR probe. Soil Tillage Res. 60, 35–42.
Vomocil, J.A., 1965. Porosity. In: Black, C.A. (Ed.), Methods of Soil Analysis. Madison: Wisc., USA, pp. 299–314.
Westlin, A., 2010. Ekoskär och Kalk. In: Arvidsson, Johan (Ed.), Jordbearbetningens årsrapport 2010. SLU, Uppsala, pp. 19–20 Reports from Soil and Environment Department. No.120.
Zadoks, J.C., Chang, T.T., Konzak, C.F., 1974. A decimal code for the growth stages of cereals. Weed Res. 14, 415–421.
Zhang, H., 1994. Organic matter incorporation affects mechanical properties of soil aggregates. Soil. Tillage Res. 31, 263–275.