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# Effects of loosening combined with straw incorporation into the upper subsoil on soil properties and crop yield in a three-year field experiment

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ABSTRACT

Subsoil management needs to be integrated into the current tillage regimes in order to access additional resources of water and nutrients and sustain crop production. However, arable subsoil is often deficient in nutrients and carbon, and it is compacted, affecting root growth and yield. In this study, crop yield and soil responses to loosening of the upper subsoil, without and with straw injection below the plough layer (25–34 cm), were studied during three crop cycles (2016–2018) in a field experiment near Uppsala, Sweden. Responses to straw injection after loosening were studied after single and triple consecutive applications of 24–30 Mg ha$^{-1}$ during 2015–2017 to spring-sown barley and oats. Subsoil loosening combined with one-time or repeated straw addition (LS treatments) significantly reduced soil bulk density (BD) and increased porosity, soil organic carbon (SOC) and total nitrogen (N) compared with loosening (L) alone (one-time or repeated annually) and the control. In treatment L, the soil re-compacted over time to a similar level as in the control.

Field inspections indicated higher abundance of earthworms and biopores in and close to straw incorporation strips. Aggregates readily crumbled/fragmented by hand and casts (fine crumbs) were frequently observed in earthworm burrows. The treatment LS improved soil properties (SOC and porosity) and water holding capacity, but had no significant influence on crop yield compared with the control.

Crop yield in all treatments was 6.5–6.8 Mg ha$^{-1}$ in 2017 and 3.8–4.0 Mg ha$^{-1}$ in 2018, and differences were non-significant. Absence of yield effect due to treatments could be possibly due to other confounding factors buffering expression of treatment effects on yield. Lower relative chlorophyll content in leaves in the loosening with straw treatment during early growth stages, did not affect final crop yield. Subsoil loosening performed three times gave no further improvement in soil properties and grain yield compared with one-time loosening. There was no difference in yield between repeated subsoil loosening + straw and one-time treatment. It will be interesting to study the long-term effects of deep straw injection and evaluate its impact under other soil and weather conditions.

## 1. Introduction

There is an increasing need to produce more food on existing arable land, due to the rising global population and limited arable land resources (Rengasamy et al., 2003). At the same time, soil moisture deficits due to warmer and drier summers induced by climate change are becoming a recurring problem (Hanel et al., 2018), challenging crop growth and yield. These challenges justify integration of subsoil management fully into tillage regimes, because managing the subsoil could allow roots to access a greater volume of soil and associated resources to sustain crop production (Frelih-Larsen et al., 2018). The subsoil could also help sequester more carbon compared to the surface soil because there is large volume of soil as well as mineral surface that is unsaturated with soil organic carbon, which can contribute to adapt and mitigate the adverse effect of climate change (Schneider et al., 2017).

However, the subsoil is often characterised by a dense structure that restricts root growth and limits utilisation of resources (Adcock et al., 2007; Kautz et al., 2013; Nicholson et al., 2015). Established subsoil

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tillage techniques to improve subsoil condition are still scarce and progress has been limited, mainly due to minimum concern and effort, requiring further work (Batey, 2009; Kautz et al., 2013).

Mechanical loosening is commonly used to loosen and shatter compacted soil layers, increase porosity and improve root growth conditions (Raper and Bergtold, 2007). However, its effect is inconsistent and varies with soil type, soil nutrients, fertilisation, pedo-climatic conditions and moisture content (Schneider et al., 2017). The positive impact of loosening such as reduced penetration resistance and improved yield are also transient, as soils are easily re-compacted (Adcock et al., 2007; Larney and Fortune, 1986).

Currently, the addition of straw to the surface soil has become a common practice because the organic material in straw plays an essential role to improve porosity, water retention, and biological activity (Cong et al., 2019; Van Donk et al., 2010). Increased microbial activity aids in the bonding of soil particles, promoting a more stable soil structure (Bhogal et al., 2009; Powlson et al., 2011). Over time, the formation of soil aggregates reduces bulk density and facilitates root growth, allowing access to more resources and consequently, increased root growth resulting in enhanced organic matter input and improved soil structure (Kautz et al., 2013).

However, adding straw to the subsoil may result in a priming effect, which means increased decomposition of native organic matter after incorporating fresh organic inputs (Kuzyakov et al., 2000; Löhnis, 1926). Fontaine et al. (2007) reported increased degradation of old, pre-existing soil organic matter upon addition of easily decomposable plant material. Nonetheless, subsoil priming has not been observed in all studies (Salome et al., 2010) and may not be a general response to the incorporation of plant materials.

Combined subsoil loosening and incorporation of organic amendments has been proposed to stabilise soil structure (Hamza and Anderson, 2005). Addition of organic materials can help maintain the structure of loosened soil and the positive effect of loosening (Hamza and Anderson, 2005; Zhang et al., 2020), which may improve crop yield (Gill et al., 2008; Leskiw et al., 2012; Sale and Malcolm, 2015).

The aim of the present study was to determine the three-year effect of subsoil improvement on soil physical properties, water storage capacity, crop performance and grain yield. The starting hypotheses were i) that the benefits of mechanical subsoil loosening decrease quickly over time and the soil re-compacts to its pre-loosened state and ii) that simultaneous straw injection and mechanical loosening improve soil properties and increase grain yield and the loosening effect persists for longer.

## 2. Materials and methods

### 2.1. Experimental background, study design and treatments

A three-year field experiment with subsoil loosening, or subsoil loosening combined with addition of straw, was conducted from autumn 2015 to autumn 2018 in Säby, Uppsala, Sweden (59°83′N, 17°71′E). The experiment comprised 20 plots arranged in a randomised complete block design with five treatments and four replicates. The treatments were a control receiving inorganic fertiliser only; subsoil loosening in the first year ($L_{1y}$); subsoil loosening annually for three years ($L_{3y}$); subsoil loosening with straw injection for one year ($LS_{1y}$); and subsoil loosening with straw injection for three years ($LS_{3y}$). Hereafter, treatments $L_{1y}$ and $L_{3y}$ are occasionally referred to more generally as 'treatment L′', and treatments $LS_{1y}$ and $LS_{3y}$ as 'treatment LS'. The crops investigated were spring-sown cereals, i.e. spring barley (*Hordeum vulgare* L. cv. Makof) in 2017 and oats (*Avena sativa* L. cv. Symfoni) in 2018. Autumn refers to the months of September, October and November, while spring refers to March, April and May. Preliminary results from the three treatments in 2016, after the first loosening and loosening with straw addition in autumn 2015, are reported in Getahun et al. (2018). The present study examined residual effects of the first-year loosening and loosening + straw incorporation treatments and effects of the treatments in 2017 and 2018.

### 2.2. Subsoil loosening and straw incorporation

Cereal straw pellets were used to make the straw slurry. Straw pellets were mixed with water until a pumpable slurry was obtained. Subsoil loosening combined with incorporation of straw was carried out in one pass with a tractor (pulling the system), slurry tanker (storing the straw), delivery hose, deep loosener/subsoiler (Combiplow Gold, AGRISEM International, France), metal injector and roller packer (for details, see Getahun et al., 2018). In the $LS_{3y}$ treatment, the straw was incorporated to 25–34 cm depth at a rate of about 24 and 29 Mg $ha^{-1}$ in autumn 2016 and 2017, respectively. Subsoil loosening and subsoil loosening + straw addition in autumn 2016 and 2017 were performed about 10 cm on either side of the first year's subsoil loosening and loosening + straw lines, to give enough space for straw incorporation. Thus, the plot area affected by the treatments increased from first to second and second to third year of repeated amendments. The intention with repeating the loosening + straw treatment for three years was to increase the area affected by straw addition in each plot, but during soil sampling, we noticed a possible overlap in some plots with preceding loosening + straw.

The upper and lower depth limit of treatment LS was not consistent between years. We observed deviations of about 2 cm in both directions for the upper and lower depth limits of 25 cm (± 2 cm) and 34 cm (± 2 cm), respectively. However, treatment depth was within this range (25–34 cm) at most points investigated. It was challenging to distribute the straw slurry evenly between and within straw lines, perhaps due to variations in injection pressure, soil moisture and tractor driving speed. These variations, coupled with limited space at places to accommodate the large pulse of straw, meant that a portion of the straw was pressed up to the soil surface. In treated plots, about 43% of the area was affected by treatment LS in the first year, with about 11% of the plot area enriched with straw. The proportion of treated area in the plot increased over the three years, to about 69% in the third year, of which 32% of the plot area was enriched with straw.

### 2.3. Soil management, sampling and analyses

Every year, the experimental plots were cultivated to a depth of 15 cm in autumn and harrowed to a depth of 4 cm in spring. Sowing and fertilisation were carried out in spring. In addition to cultivation, all plots were deep-ploughed in autumn 2017. Fertiliser (NPKS) was applied to treatments, including the control according to standard agricultural practices for the area. However, in the 2017 cropping season, 156 kg N $ha^{-1}$ (36 N kg $ha^{-1}$ more than in 2016 and 2018) were applied. Crops were harvested by a combine harvester at the end of the season.

Soil and crop sampling for the repeated subsoil loosening treatment was performed at points loosened two and three times, in the second and third year of the experiment period, respectively. At the end of the experiment, each plot in treatment $L_{3y}$ had sampling points loosened once, twice and three times. However, in the $LS_{3y}$ plots, treatments were repeated three times over the three years but following three separate lines 10 cm on either side of the $LS_{1y}$ lines. Therefore, measurements of soil properties in the second and third year for $LS_{3y}$ refer only to the latest incorporation line. Only combine-harvested crop yield data reflected the effect of repeated subsoil loosening with straw (treatment $LS_{3y}$).

The first soil samples for determination of soil organic carbon (SOC), total soil nitrogen (N) and bulk density (BD) were taken in spring 2016, at 29–34 cm soil depth, which was the bottom of the treatment zone. This layer was chosen to represent the deeper subsoil. The soil was sampled again in autumn and spring until autumn 2018, after three years of cropping.

Using a hand auger, soil samples were taken at four sampling points

**Table 1**
Mean concentrations of soil organic carbon (SOC) and total nitrogen (N), bulk density (BD) and porosity at 29–34 cm soil depth in spring and autumn 2017 and 2018 in the five experimental treatments†. Different letters within rows indicate significant differences at $P < 0.05$ according to Tukey comparison test.

| Season | Soil parameter | 2017 | | | | | 2018 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $L_{1y}$ | $LS_{1y}$ | $L_{3y}$ | $LS_{3y}$ | Control | $L_{1y}$ | $LS_{1y}$ | $L_{3y}$ | $LS_{3y}$ | Control |
| Spring | SOC (g kg$^{-1}$) | 19.3$^{b}$ | 46.4$^{a}$ | 17.2$^{b}$ | 47.0$^{a}$ | 13.0$^{b}$ | 19.5$^{c}$ | 34.1$^{b}$ | 12.5$^{c}$ | 53.6$^{a}$ | 10.5$^{c}$ |
| | Total N (g kg$^{-1}$) | 1.6$^{b}$ | 2.6$^{a}$ | 1.5$^{c}$ | 2.3$^{ab}$ | 1.1$^{c}$ | 1.6$^{c}$ | 2.5$^{a}$ | 1.0 $^{cd}$ | 2.8$^{a}$ | 0.8$^{d}$ |
| | BD (Mg m$^{-3}$) | 1.34$^{b}$ | 1.04$^{a}$ | 1.36$^{b}$ | 0.97$^{a}$ | 1.49$^{b}$ | 1.36$^{c}$ | 1.10$^{b}$ | 1.46$^{c}$ | 0.87$^{a}$ | 1.51$^{c}$ |
| | Total porosity % | 50.0$^{b}$ | 60.0$^{a}$ | 49.0$^{b}$ | 63.0$^{a}$ | 44.0$^{b}$ | 49.0$^{c}$ | 57.0$^{b}$ | 45.0$^{c}$ | 66.0$^{a}$ | 43.0$^{c}$ |
| Autumn | SOC (g kg$^{-1}$) | 17.7 $^{cd}$ | 37.0$^{b}$ | 21.0$^{c}$ | 52.7$^{a}$ | 8.9$^{d}$ | 10.0 $^{cd}$ | 33.3$^{b}$ | 14.0$^{c}$ | 45.3$^{a}$ | 8.6$^{d}$ |
| | Total N (g kg$^{-1}$) | 1.5$^{b}$ | 2.6$^{a}$ | 1.8$^{b}$ | 2.7$^{a}$ | 0.8$^{c}$ | 0.8$^{bc}$ | 2.3$^{a}$ | 1.2$^{b}$ | 2.5$^{a}$ | 0.75$^{c}$ |
| | BD (Mg m$^{-3)}$ | 1.42$^{d}$ | 1.10$^{b}$ | 1.27$^{c}$ | 0.95$^{a}$ | 1.51$^{d}$ | 1.53$^{c}$ | 1.20$^{b}$ | 1.51$^{c}$ | 1.03$^{a}$ | 1.51$^{c}$ |
| | Total porosity % | 46$^{d}$ | 58$^{b}$ | 52$^{c}$ | 64$^{a}$ | 43$^{d}$ | 42$^{c}$ | 54$^{b}$ | 43$^{c}$ | 61$^{a}$ | 43$^{c}$ |

† $L_{1y}$ = loosening in 1 year; $LS_{1y}$ = loosening + straw in 1 year; $L_{3y}$ = loosening in 3 years; $LS_{3y}$ = loosening+ straw in 3 years and control.

(29–34 cm depth) within each plot and mixed thoroughly to give a composite sample. Analyses of SOC and total N were carried out on air-dried and sieved (2 mm mesh size) soil, using dry combustion (CNS Analyser; LECO Corporation). The SOC content in the straw treatment included organic materials at different stages of decomposition.

Samples for determination of dry BD (Mg m$^{-3}$) were taken at 29–34 cm depth using four soil cylinders per plot (inner diameter 7.2 cm, height 5 cm). The cylinders were oven-dried at 105 °C and weighed to calculate BD. Total porosity was calculated from BD, assuming a particle density of 2.65 g cm$^{-3}$. Particle density in treatment LS was corrected due to straw, using literature values (Guerif 1979 cited in Soane, 1990). The topsoil (0–10 cm) in the control was also sampled for SOC, total N and BD (using cylinders with inner diameter 7.2 cm and height 10 cm).

Penetrometer resistance (PR) and gravimetric water content were measured randomly in each plot in June 2017. The penetrometer was pushed into the soil by hand to about 40 cm depth and soil strength was measured at 10 points in each plot at depth resolution of 1 cm. The data were stored in a data logger and downloaded later. For gravimetric water content, three random samples per plot were collected with a soil auger. These soil cores were sectioned into 0–10, 10–20, 20–25, 25–29, 29–34 and 34–40 cm soil layers, oven-dried at 105 °C for 24 h and weighed. It was not possible to perform PR measurements in the very dry growing season of 2018, as the soil was too hard and difficult to penetrate.

Degree of compactness (DC) was determined as the ratio of measured BD to reference BD. For this purpose, data for the control plots in three years (2016–2018) were used. Reference BD was determined using four different pedotransfer functions (PTFs) developed by Keller and Håkansson (2010) and Naderi-Boldaji et al. (2016). The DC value was averaged across three years and seasons (spring and autumn), to obtain one DC value corresponding to each PTF used. Finally, to produce mean DC for the field, DC values across PTFs were averaged and compared against the optimal topsoil DC for barley, 87% as estimated by Håkansson and Lipiec (2000), to assess the root-restricting behaviour of soil in the field.

Water retention characteristics were determined using the same cylinders (inner diameter 7.2 cm, height 5 cm) as used for measuring BD in autumn 2018. The soil in the cylinders was wetted from the bottom until saturation and then drained to matric potential − 0.5 and − 10 kPa on sand beds and − 30 and − 60 kPa on pressure plates. Permanent wilting point was estimated using disturbed soil samples in a pressure plate extractor at − 1500 kPa. During this, one of the replicates from treatment $L_{3y}$ overflowed and was excluded. The missing value was handled with an appropriate code in the statistical analysis. The difference in water content between − 10 and − 1500 kPa (i.e. between field capacity and wilting point) was calculated to estimate the amount of plant-available water (PAW).

### 2.4. Crop sampling, measurements and analysis

Leaf relative chlorophyll content, determined using a SPAD-502 device (Soil Plant Analysis Development), and plant height were measured at several development stages in the spring barley and oat crops. Four sampling locations per plot were selected, and four plant shoots were measured, with three SPAD readings per leaf (48 measurements per plot). Plant height was measured on 12 randomly selected plant shoots per plot. Combine harvester data were used to measure grain yield and an Infratec™ NOVA grain analyser was used to determine grain protein content.

### 2.5. Subsoil structure, root and earthworm burrow and cast observations

Field and laboratory measurements were complemented with in situ observations. The subsoil layer (25–34 cm) was assessed in each replicate plot. In October 2018, after crop harvest, a soil pit was dug to about 60 cm depth in each plot for detailed subsoil investigations. The subsoil profile was evaluated qualitatively to assess soil strength (ease of fragmentation), porosity and aggregate size/shape, following the method described by Ball et al. (2015). Observations of root distribution were also made a few days before harvest in 2017 and 2018, using a simplified profile wall method where soil pits were dug to observe exposed roots at 10, 25 and 34 cm depth, intersecting a horizontal line around 12 cm in length (Böhm, 1979). Assessment of earthworm burrows and casts was carried out simultaneously.

### 2.6. Statistical analysis

Analysis of variance of the data was performed using R (R version 4.0.2) (RCoreTeam, 2020). Values at $P < 0.05$ were used for multiple treatment comparisons when treatment effects were significant based on a Tukey test. Pearson correlation coefficient was used to evaluate the relationships between soil BD and SOC, between BD and PR, and between PR and water content and SOC and water content.

## 3. Results and discussion

### 3.1. Weather conditions

The study area experienced mild winters in both 2017 and 2018. The growing season of 2017 was drier than the long-term average and that of 2018 was very dry, with record-breaking temperatures in July (mean 21.6 °C). Mean temperature during May to September 2018 was 16.8 °C, which was higher than the long-term average (1961–1990) of 13.5 °C. Mean annual temperature was 6.9 °C in 2017 and 7.6 °C in 2018, which was also higher than the long-term average (5.5 °C).

Total precipitation was 507 and 429 mm in 2017 and 2018, respectively, which was lower than the long-term average of 528 mm. Precipitation during May to September in 2017 and 2018 was also lower than the long-term average. In 2018, precipitation was scarce and erratic, with a dry spell between 22 June and 28 July only interrupted by two small showers of rain, about 5 mm in total, before ending with heavy rain (79 mm) on 29 July.

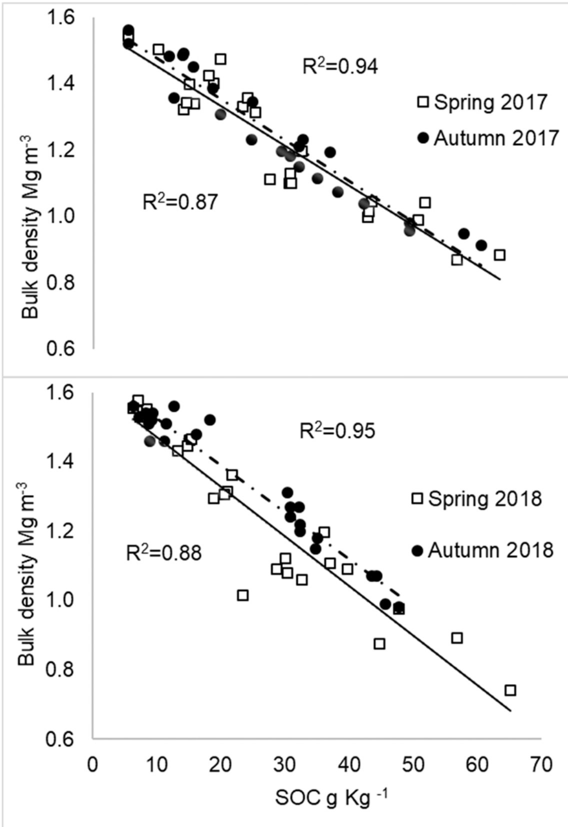


**Fig. 1.** Relationship between soil organic carbon (SOC) content and bulk density at 29–34 cm depth and control top soil (0–10 cm) in 2017 and 2018, with corresponding regression lines (solid lines for spring, dashed lines for autumn measurements).

### 3.2. Soil properties

#### 3.2.1. Soil organic carbon, total N and soil strength

The large amount of straw applied to the subsoil in treatment LS resulted in a significant increase ($P < 0.05$) in SOC content in spring and autumn 2017 and 2018 relative to the control and treatment L. This confirms previous findings that addition of straw increases SOC status in arable soil (Kätterer et al., 2012; Schjønning et al., 1994; Singh et al., 1998; Thomsen and Christensen, 2004). Total soil N accumulation followed a similar trend to SOC. Although the straw applied had a low N content, its application at high rates improved total N over the three years, confirming previous reports of an increase in N due to straw addition (Liu et al., 2014; Thomsen and Christensen, 2004).

The SOC content in the field varied from 5 to 20 g kg$^{-1}$ and total N from 0.5 to 1.5 g kg$^{-1}$, according to measurements at 29–34 cm soil depth in the control plots ( Unpublished data, Table 1 and Getahun et al., 2018), illustrating the variability in the subsoil. Although subsoil is often SOC-poor, SOC sources such as preferential organic matter transport through vertical cracks (Rumpel and Kögel-Knabner, 2011), deposition of carbon from plant roots and differences in ploughing depth over the years are recognised sources of heterogeneous SOC distribution in subsoil horizons. Thus, microsites enriched with SOM and nutrients can be found in the subsoil (Kautz et al., 2013).

At the last measurement (autumn 2018), in the $LS_{1y}$ treatment SOC and total N had reached 33 g kg$^{-1}$ and 2.3 g kg$^{-1}$, respectively. The SOC content in the topsoil (0–10 cm), which regularly received organic material inputs, was 29–31.4 g kg$^{-1}$ over the two years and total N content was 2.48–2.64 g kg$^{-1}$.

Subsoil loosening combined with straw injection (treatment LS) resulted in significantly lower BD at 29–34 cm depth and a concomitant porosity increase compared with the control and treatment L. Mean BD varied from 0.90 (in $LS_{3y}$) to 1.53 (in $L_{1y}$). The decrease in BD in treatment LS was driven by lower particle density of organic material compared with mineral matter, thus causing dilution (Soane, 1990). It was presumably also driven by the loosening (Varsa et al., 1997) and by decomposition products from the straw acting as a binding agent, thus promoting soil aggregation over time and improving porosity (Cogger, 2005; Nicholson et al., 2014). For comparison, BD in the topsoil (0–10 cm) in 2017–2018 ranged from 1.08 to 1.26 Mg m$^{-3}$.

Decreases in BD and increases in porosity due to organic matter inputs have also been reported in other studies (Rasool et al., 2008; Schjønning et al., 1994; Zhao et al., 2009). Except for autumn 2017, loosening alone did not result in a significant difference in BD values compared with the control, confirming our hypothesis that loosening effects are relatively weak and short-term. Soil BD values in treatment L increased gradually, to a similar level as in the control after three years, as found in other studies (Carter et al., 1996; Evans et al., 1996; Soane et al., 1986; Twomlow et al., 1994). The likely explanation for this

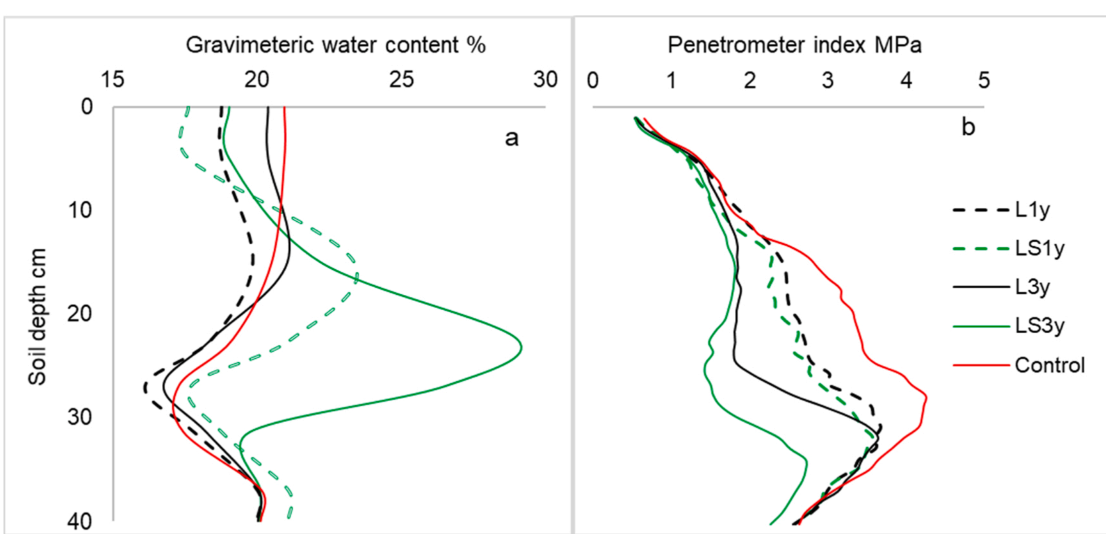


**Fig. 2.** Effects of treatments on (left) gravimetric water content and (right) penetrometer resistance in the soil profile in the growing season of 2017. L1y = loosening in 1 year, LS1y = loosening + straw in 1 year), L3y = loosening in 3 years, LS3y = loosening + straw in 3 years) and control. For each depth, ten vertical PR measurements were averaged (1 cm depth resolution). In the 29–34 cm soil layer, data on water content and PR were statistically compared.

**Table 2**
Volumetric water content ($m^3m^{-3}$) at different matric potentials and plant-available water (mm) at 29–34 cm depth as measured in soil sampled in autumn 2018. Values shown are means, significant differences between treatments ($P < 0.05$, Tukey comparison test) are indicated by different letters within rows.

| Treatment | Volumetric water content (g cm-3) at different suctions | | | | | Plant-available water (mm) |
|---|---|---|---|---|---|---|
| | -0.5 kPa | -10 kPa‡ | -30 kPa | -60 kPa | -1500 kPa‡‡ | |
| $L_{1y}^{\dagger}$ | $0.386^{b}$ | $0.325^{c}$ | $0.207^{b}$ | $0.190^{bc}$ | $0.135^{a}$ | $9.5^{c}$ |
| $LS_{1y}$ | $0.473^{a}$ | $0.373^{ab}$ | $0.271^{a}$ | $0.238^{ab}$ | $0.126^{a}$ | $12.3^{ab}$ |
| $L_{3y}$ | $0.401^{b}$ | $0.347^{b}$ | $0.270^{a}$ | $0.235^{ab}$ | $0.136^{a}$ | $10.6^{bc}$ |
| $LS_{3y}$ | $0.498^{a}$ | $0.380^{a}$ | $0.303^{a}$ | $0.257^{a}$ | $0.117^{a}$ | $13.2^{a}$ |
| Control | $0.392^{b}$ | $0.318^{c}$ | $0.215^{b}$ | $0.185^{c}$ | $0.135^{a}$ | $9.2^{c}$ |

† $L_{1y}$ = loosening in 1 year; $LS_{1y}$ = loosening + straw; in 1 year $L_{3y}$ = loosening in 3 years; $LS_{3y}$ = loosening + straw in 3 years and control
‡ field capacity
‡‡ wilting point

short-lived loosening effect was probably re-compaction induced by field operations and over burden pressure returning the soil to its original density (Evans et al., 1996; Larney and Fortune, 1986; Munkholm et al., 2005). However, treatment LS resulted in significantly reduced BD compared with the other treatments, and this effect persisted to 2018, supporting our hypothesis that simultaneous straw injection and mechanical subsoil loosening improve soil properties and that the loosening effect persists for longer. Leskiw et al. (2012) observed similar effects by subsoiling with pelleted organic amendments.

Further analysis of SOC and BD revealed a strong negative correlation ($R^2$ =0.87–0.95) between these parameters in both spring and autumn 2017 and 2018 (Fig. 1). The slope of the regression line was statistically significant, confirming the close link between SOC and BD found also in previous studies (Kätterer et al., 2011).

In all treatments, soil PR peaked at about 30–35 cm depth, indicating a dense structure in all cases. As expected, soil in treatment $LS_{3y}$ had consistently lower PR values than other treatments. The difference at 29–34 cm depth was significant compared with treatment $L_{1y}$ and the control ($P < 0.05$), and tended to be significant compared with treatments $LS_{1y}$ and $L_{3y}$ ($P = 0.06$–$0.07$) (Fig. 2b). Mean gravimetric water content at 29–34 cm depth was significantly higher in treatment $LS_{3y}$ than in the control. Differences in PR between the single and repeated loosening treatments ($L_{1y}$ and $L_{3y}$) were not significant (Fig. 2a &b). The PR values at 29–34 cm soil depth were positively related to soil BD ($R^2$ =0.34, $P < 0.05$) and negatively to water content ($R^2$ =0.37, $P < 0.05$).

Penetration resistance and DC values were used to assess the current compaction status of the subsoil in Säby field. Most individual PR measurements at 25–34 cm depth exceeded 3 MPa except in the $LS_{3y}$ treatment (Fig. 2b). In the control, the mean PR value was around 3.9 MPa, i.e. higher than the threshold limiting root growth (~3 MPa) (Håkansson and Lipiec, 2000). The mean DC value from the four PTFs across years and seasons was 89%, which was again above the critical value (87%) in the topsoil at which root growth of barley is restricted (Håkansson and Lipiec, 2000). However, roots can grow into dense subsoil layers via macropores and previous root channels (Ehlers et al., 1983; Håkansson and Lipiec, 2000). Thus, the limiting PR for root growth and the optimum DC in the subsoil may be higher than the reported threshold, although most bulk soil is dense (Ehlers et al., 1983; Håkansson and Lipiec, 2000). Studies by Comia et al. (1994) and Etana et al. (1999) found higher DC values, of about 95% and above, in deeper parts of a previous ploughed layer that were less detrimental for crop growth. In a review, Håkansson (2005) pointed out that a soil can be categorised as very intensively compacted when the DC value is 100 or above. Based on this information, the subsoil (29–34 cm) in the present study can be suggested as moderately compacted, rather than severely compacted.

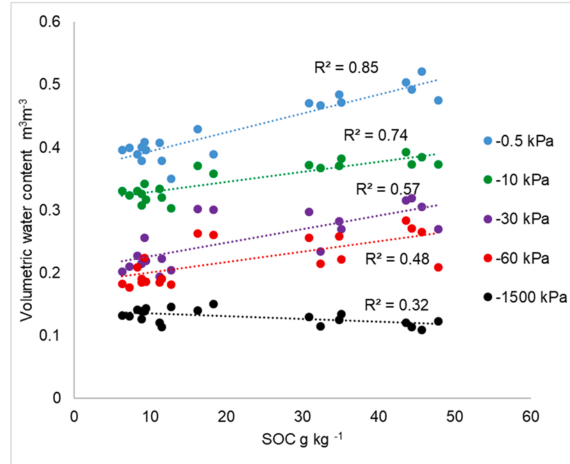


**Fig. 3.** Soil volumetric water content ($m^3m^{-3}$) at different matric potentials as a function of soil organic carbon (SOC) content at 29–34 cm depth measured in autumn 2018 in five subsoil treatments.

### *3.2.2. Water retention characteristics*

Water content in the 29–34 cm depth layer in $LS_{3y}$ was higher at different matric potentials than the $L_{1y}$ and control treatments ($P < 0.5$). The water content in $LS_{1y}$ was second highest of all treatments. The third-largest water content was identified in $L_{3y}$, and the lowest in the control and $L_{1y}$.

The higher water content in treatment LS was probably due to the combined effect of straw addition and loosening, resulting in an added benefit. Twomlow et al. (1994) also observed enhanced water content due to soil loosening. As mentioned above, straw injection increased SOC content, which affected soil physical properties and water retention. Other studies have also reported positive impacts on water content after addition of organic materials (Gill et al., 2008; Sale and Malcolm, 2015; Zhao et al., 2009).

As indicated in Table 2, treatment LS increased PAW compared with treatment L and the control. Plant-available water in $LS_{3y}$ was higher than in the control and treatment L. The second-largest PAW was noted in the $LS_{1y}$ treatment, higher than in the control and $L_{1y}$. Sandy soil might show a larger relative difference in PAW than obtained here, reflecting the importance of SOC for soils limited in fine particles (Minasny and McBratney, 2018).

The control had the lowest PAW content, compared with which there was an extra gain of about 3–4 mm in treatment LS. The water retention curve value at − 10 kPa (field capacity) for $LS_{3y}$ was significantly higher than for the control and treatment L (Table 2).

The degree of correlation between SOC and volumetric water content ($m^3m^{-3}$) showed a decreasing trend with increasing matric potential level (Fig. 3), which means that SOC had the lowest influence at − 1500 kPa and the highest at − 0.5 kPa. The weak correlation between SOC and wilting point indicates that soil water content at higher matric potential may be determined by soil texture rather than SOC content. In PTFs used for estimating wilting point, clay content is often the best predictor of wilting point (e.g., Kätterer et al., 2006). A review by Minasny and McBratney (2018) concluded that SOC has most effect on large pores, probably due to formation of macroaggregates, and that the effect decreases with decreasing pore size.

### *3.3. Crop growth and grain yield*

The SPAD readings and plant height in 2017 did not differ between treatments except around anthesis, when plant height was significantly lower in the control than in the $L_{1y}$ treatment. However, in 2018 the SPAD readings were significantly lowest in the $LS_{3y}$ treatment, which indicates possible N limitation due to immobilisation caused by straw

**Table 3**
Leaf relative chlorophyll content, plant height at different Zadok growth stages (ZGS) and grain yield (standard water content) and grain protein at harvest in 2017 (spring barley) and 2018 (oats) in the different treatments†. Values shown are means, significant differences between treatments ($P < 0.05$, Tukey comparison test) are indicated by different letters within columns.

| Year | Crop parameter | ZGS | $L_{1y}$ | $LS_{1y}$ | $L_{3y}$ | $LS_{3y}$ | Control |
|---|---|---|---|---|---|---|---|
| 2017 | SPAD-index | 49 | 55.3 | 55.4 | 55.6 | 56.0 | 55.2 |
| | | 56/57 | 56.8 | 56.9 | 56.8 | 55.9 | 57.2 |
| | | 62/63 | 58.7 | 57.7 | 57.8 | 58.0 | 57.2 |
| | Plant height (cm) | 49 | 52.6 | 53.0 | 53.6 | 53.5 | 51.8 |
| | | 56/57 | 63.5 | 62.9 | 62.6 | 65.2 | 63.8 |
| | | 62/63 | 79[a] | 75.7[ab] | 76.1[ab] | 76.8[ab] | 74.5[b] |
| | Grain yield (Mg $ha^{-1}$) | Harvest | 6.7 | 6.8 | 6.6 | 6.5 | 6.5 |
| | Grain protein (%) | Harvest | 14.5[a] | 14.2[ab] | 14.7[a] | 13.8[b] | 14.6[a] |
| 2018 | SPAD-index | 55/56 | 59.4[a] | 58.9[a] | 60.1[a] | 55.6[b] | 59.7[a] |
| | | 59/60 | 64.3[a] | 63.3[ab] | 63.0[ab] | 61.6[b] | 63.9[a] |
| | | 69/70 | 65.6[a] | 65.9[a] | 64.7[ab] | 63[b] | 64.3[ab] |
| | | 77–79 | 49.4 | 50.1 | 50.8 | 48.8 | 50.5 |
| | Plant height (cm) | 55/56 | 55.2 | 55.8 | 56.7 | 56 | 56.5 |
| | | 59/60 | 72.6 | 71.9 | 71.3 | 70.4 | 72.2 |
| | | 69/70 | 79.4 | 77.6 | 75.4 | 75.9 | 77.6 |
| | | 77–79 | 76.2 | 74.9 | 75.4 | 76.2 | 78.2 |
| | Grain yield (Mg $ha^{-1}$) | Harvest | 3.94 | 3.88 | 3.97 | 3.96 | 3.83 |
| | Grain protein (%) | Harvest | 15.1[a] | 15.1[a] | 15.0[a] | 14.6[b] | 15.0[a] |

$L_{1y}$ = loosening in 1 year; $LS_{1y}$ = loosening + straw in 1 year; $L_{3y}$ = loosening in 3 years; $LS_{3y}$ = loosening + straw in 3 years and control.


**Fig. 4.** Visual observations of subsoil treated with loosening+straw over the years of the field study including 2019. The red arrows in (a) and (b) indicate earthworm (c) Insect eggs (d) moisture around the area where straw was incorporated, (e) to (h) roots growing towards the incorporation area and friable aggregates, (i) biopores, (j) roots growing towards the straw area, (k) occasional earthworms and biopores, (l) friable aggregates, (m) and (n) biopores and roots growing through biopores, and (o) and (p) friable aggregates.

addition. In the latter part of the growing season, the difference in SPAD readings disappeared. The lower SPAD index at the early crop stage did not result in lower crop yield when compared with other treatments. The protein content in $LS_{3y}$ grain was significantly lower in 2017 and 2018, but not to the point of affecting grain quality (Table 3). Grain yield of spring barley in 2017 varied from 6.5 to 6.8 Mg $ha^{-1}$ and that of oats in 2018 from 3.8 to 4.0 Mg $ha^{-1}$ in the different treatments. The lower oat yield resulted from the low moisture and high temperature in the dry season of 2018, could be due to drought sensitivity of the oat crop (Zhao et al., 2021) or possibly due to haying-off. Haying-off occurs when a high level of soil fertility promotes vegetative growth, while increasing water consumption. Subsequently, soil water is depleted during anthesis, and assimilation is decreased during grain filling (Van Herwaarden et al., 1998).

Following a detectable change in soil properties due to treatment LS, we expected an improvement in crop performance and higher grain yield, but yield was quite similar in all treatments. In contrast, others have reported higher grain yield following deep placement of organic material (Gill et al., 2008; Leskiw et al., 2012; Zhang et al., 2020). The absence of a significant increase in yield in our experiment suggests that there may have been other factors at play, such as weather, site conditions and relatively higher fertility of the topsoil (Celestina et al., 2018; Schneider et al., 2017). The cropping seasons in 2017 and 2018 had a prolonged dry period with rainfall below the long-term average (1961–90), which may have affected important crop physiological stages and weakened the effect of treatments LS and L on crop yield. In 2018, the dry growing season severely affected grain yield and the potential impact of the treatments. For example, the oat crop sown in 2018 had a shorter growing period than the normal growing season, as the 2018 season was hot and dry. In this regard, Celestina et al. (2018) suggest that there may be cases where subsoil amendments do not increase crop yield due to prolonged drought and N supply exceeding the water-limited crop demand. A larger effect on grain yield could have been obtained on severely compacted soil, where root growth is highly restricted (Schneider et al., 2017). In general, possible immobilization, higher fertility status of the topsoil, site-specific conditions and a possible moisture deficit (as capacity of the subsoil to supply water may have been impaired) may have buffered the effect of treatments.

### 3.4. Visual observations

More earthworms and biopores were visible in the subsoil layer where straw was incorporated (treatment LS) and close to that layer (Fig. 4). Aggregates were crumbled/fragmented by hand and casts (fine crumbs) in earthworm burrows were commonly observed. Roots were observed growing in the loosened + straw line, which indicates that this layer was not hostile for root growth. On occasions, we found roots following earthworm burrows (Fig. 4).

Soil aggregates in the control and treatment L was often coarser, with fewer fine aggregates and few biological pores than in treatment LS. There were very few earthworm channels, and available pores were very fine to medium. We also observed clods with an angular and platy structure. Higher SOC in treatment LS possibly contributed to the abundance of earthworm burrows and casts and friable soil aggregates seen in the treated lines of the plots.

## 4. Conclusions

After three cropping seasons, a considerable change in soil properties due to loosening + straw incorporation was observed. Changes in soil properties due to loosening were weak and probably have no long-term consequences for soil quality. Adding straw (as a slurry) helped to maintain the effect of loosening. Soil properties such as SOC, total N, water-holding capacity and BD were improved by subsoil loosening combined with straw incorporation, but this did not translate into increased crop yield. Comparison between one-time or repeated loosening did not make any difference to soil properties or grain yield and also one-time and repeated loosening + straw incorporation gave comparable grain yields. Although deep incorporation of straw did not bring considerable increase in crop yield in the soil studied here, the improvements seen in soil physical properties and water-holding capacity indicate that this treatment could be used in other soils. There is a critical need to evaluate the impact of deep placement of organic materials under different pedo-climatic conditions and over a longer period.

## Declaration of Competing Interest

The authors declare no conflict of interest.

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