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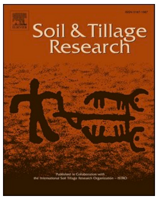

The legacy of deep ploughing and liming – A 1990s experimental site revisited

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ABSTRACT

Management of agricultural soils for increased productivity may exert positive or negative effects on soil structure, functions, and organic carbon (SOC) stocks. In this study, a field experiment established in 1993 on a clayey soil in southwest Finland was revisited to investigate the long-term effects of deep ploughing and liming on SOC concentration and stock, particulate (POC) and mineral-associated (MOC) fractions of SOC, pH, electrical conductivity (EC), bulk density (BD), porosity, critical pore size and cereal yield. The experiment comprised whole plots of conventional tillage (CT) to a maximum depth of ca. 20 cm, and plots deep ploughed to ca. 35 cm depth by a commercial (DP1) or by a self-made (DP2) plough. The tillage plots were divided into three split-plots assigned to liming treatments (low, medium and high). Three decades after implementation, the increasing liming rates still induced consistent differences in soil pH, a significant increasing effect on total porosity in the subsoil, and a marginally significant decrease in yield with an increase in soil acidity. The deep ploughing exerted a minor difference in topsoil texture, slightly lowered SOC concentration in the topsoil in DP2 in comparison to CT, and slightly higher subsoil SOC concentration in DP1 in comparison to CT, which indicated transfer of the topsoil SOC to deeper layers and dilution of the SOC in the new topsoil. However, no significant differences between the tillage treatments occurred in SOC stocks. In MOC and POC concentrations, there were no significant differences between the control and tillage treatments. The effects of deep ploughing on soil structural properties on the decadal time scale were minor and scattered. Cereal yield exhibited a slight negative trend for deep ploughing. For EC and BD, no treatment effects were recorded. Overall, the study showed that the legacy of soil management effects on soil properties can be persistent on decadal time scales, but no permanent structural damage due to deep ploughing nor gains in SOC stock accrual could be observed.

1. Introduction

Croplands are intensively managed to increase biomass production, which often involves trade-offs in sustainability and environmental impacts (DeFries et al., 2004; Vanwalleghem et al., 2017). In soil tillage, reduced shallow treatment and direct drilling minimizing soil disturbance have been long used for avoiding loss of soil by erosion and degradation of soil organic matter (SOM) (Cannell and Hawes, 1994). However, conventional ploughing, in which the soil is inverted, still serves in controlling perennial weeds, incorporating crop residues and soil amendments, and loosening compacted soil (Guul-Simonsen et al., 2002). Compacted soil layers reducing permeability to air, water and roots at different depths can form through natural processes or be caused by compression from wheels of the field machinery or of trampling animals (Batey, 2009). A ploughing depth of 20 cm or somewhat less is generally considered sufficient, but deeper loosening allowing deeper incorporation of organic material and deeper root development is also possible (Guul-Simonsen et al., 2002).

Several forms of deep tillage, i.e., mechanical modification of the soil profile below the typical tillage depth, have been developed (Schneider et al., 2017). In subsoiling or deep ripping, the soil structure is loosened with the aim of decreasing the bulk density and soil strength in the

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subsoil layer without inverting the soil horizons. Deep ploughing, in turn, leads to the inversion of the soil profile, whereby subsoil is brought up to the surface and the topsoil layer is buried deeper. In practice, after the deep ploughing operation the soil profile typically consists of inclined furrow slices, and after following tillage operations, a new topsoil layer mixing the old subsoil and topsoil is formed, while part of the old topsoil rich in SOM is left under the new tillage layer (Alcantara et al., 2016). Deep ploughing is mostly performed only once, and the common objective of the operation has been to loosen the compacted soil layers that limit root growth and water infiltration and thus facilitate access to nutrient and water resources stored in the subsoil (Baumhardt et al., 2008).

In recent years, there has been interest in how deep tillage impacts soil organic carbon (SOC) stocks in soils (Feng et al., 2020). While reduced or zero tillage is frequently presented as a SOC sequestration measure (Merante et al., 2017 and references therein), these practices lead to the enrichment of SOC in the soil surface but limit the input of crop residues deeper into the soil. Consequently, several studies have reported no increase in the SOC stocks of the whole soil profile (Singh et al., 2015; Ogle et al., 2019; Honkanen et al., 2021). The concept of SOC saturation, which is still a topic of active debate (e.g., Begill et al., 2023; Cotrufo et al., 2023; Poeplau et al., 2023; Six et al., 2024) is based on the idea that soil mineral fraction has a finite capacity to protect C in soils (Stewart et al., 2007, 2008). Thus, after SOC saturation is reached, no additional reactive mineral-associated sites are available for physicochemical stabilization of SOC, whereby fine-textured soils with high specific surface area have a higher SOC saturation limit than soils formed of coarse particles (Hassink, 1997; Hassink and Whitmore, 1997; Dexter et al., 2008). The saturation concept also indicates that soils close to saturation have lower C sequestration efficiency than those with clearly lower SOC content (Six et al., 2002). The saturation concept thus suggests that subsoils low in SOC could provide a more efficient target for C sequestration measures than topsoils, although most measures aiming to sequester SOC focus on the topsoil layer. In addition, many radiocarbon studies with 14 C isotope have shown that C age increases with increasing soil depth (Gleixner, 2013; Balesdent et al., 2018; Shi et al., 2020), which indicates higher stability of C in the subsoil. From the SOC sequestration perspective, deep ploughing buries the SOC-rich topsoil into deeper layers where decomposition rates are lower (Alcantara et al., 2017; Wordell-Dietrich et al., 2017). Concurrently, after deep ploughing the SOC content of newly formed topsoil is decreased and carried farther away from saturation, which increases the SOC accrual potential of the topsoil for ‘conventional’ SOC sequestration measures, such as high residue crops, cover crops, and no-till.

Some results indicating remarkable increases in SOC stocks after deep ploughing have been reported. For example, Alcantara et al. (2016) considered several sites in Germany, which had been deep ploughed 35–50 years earlier and reported that deep ploughing resulted on average in 42 % higher SOC stocks. Schiedung et al. (2019), in turn, investigated deep flipping sites in New Zealand, where the soil profile had been inverted by excavators and reported an average increase of 69 % in SOC stocks 20 years after the deep flipping. Some studies have indicated a much more limited effect of deep ploughing (Feng et al., 2020; Button et al., 2022). Regarding the SOC accrual, the benefits of deep ploughing remain unclear as the effectiveness of deep ploughing has been found to be highly dependent on site-specific soil and environmental conditions (Feng et al., 2020).

While there is evidence that deep ploughing may under certain conditions have positive effects in terms of SOC accrual, there have been concerns that such a severe tillage operation may have negative influences on soil structure and functions (Baveye et al., 2020). SOC content is an important control for soil aggregate stability (Soinne et al., 2016), whereby SOC dilution resulting from deep ploughing may lead to weakened topsoil structure and increased risk for soil erosion. Weakened aggregate stability may also affect the SOC dynamics through the reduced physical protection of organic matter (Dungait et al., 2012; Kravchenko et al., 2015). Schneider et al. (2017) reviewed studies where the yield effects of deep tillage had been investigated and their meta-analysis showed on average a slight (+6 %) yield increase. However, they concluded that the yield effects of deep tillage are inconsistent and highly site-specific as 40 % of the reviewed studies had resulted in decreased yield.

In addition to tillage operations, external nutrient and lime inputs are management practices that exert an effect on soil properties (Fageria, 2002). Lime is applied to adjust the pH of acidic soils to the optimal range for plant growth and to maintain it by counterbalancing acidification caused by acidifying (ammonium-based) fertilizers and acidic precipitation and deposition (Goulding, 2016). In addition to pH increase-induced influence on the bioavailability of elements, liming may exhibit positive effects on soil structure, such as increased aggregate stability and decreased dispersion, via changes in cation composition and increased ionic strength of the soil solution (Holland et al., 2018). The net effect of liming on SOC stocks shows variability due to contrary effects (Paradelo et al., 2015). On one hand, liming can increase SOC mineralization through enhanced biological activity and on the other hand increase C input to soil through improved plant productivity.

Previous research shows that the effects of deep ploughing on C sequestration are inconsistent and further investigations in different environments are needed to understand the site-specific influences of deep ploughing. In addition, it would be important to unravel the structural effects of deep ploughing to avoid oversimplified solutions for SOC accrual which forget the possible negative effects of deep ploughing on soil functioning. To this end, we revisited an old experiment located in southwest Finland and investigated the long-term effects of deep ploughing and liming on SOC stocks as well as soil structure 29 years after the treatments. The studied site has high clay content and manure has been frequently used in fertilization after the active experimental period. Therefore, our study also provides information on how SOC-depleted topsoil recovered after deep ploughing when the soil has plenty of mineral surfaces available for SOC stabilization due to fine texture and there is an additional external C input due to manure application. In addition, we studied the soil structure both in topsoil and subsoil to assess whether structural differences can be observed three decades after deep ploughing. Our study thus considered the persistence of soil management practices on the decadal time scale for boreal clay soil and aimed at answering the following primary research questions: (1) Does deep ploughing positively affect C stocks? (2) Does deep ploughing lead to negative soil structure and/or yield effects? (3) Does liming induce long-term differences in soil pH and crop yield?

2. Material and methods

2.1. Field experiment

The experiment exploited in the current study was originally established in August 1993 on a clay soil in Jokioinen, south-western Finland (60.858° N, 23.433° E), to explore possibilities of improving the availability of phosphorus (P) during drought periods by deep soil incorporation (Saarela et al., 2000). A split-plot design was applied such that three tillage treatments each in three replicates were assigned to whole plots of 14 m × 63 m in size. These whole plots were divided into three split-plots assigned to liming treatments aiming at pH levels of 6.1 (LL), 6.5 (ML) and 7.0 (HL). The soil pH before the treatments was 6.1 and the amount of lime added to reach the elevated pH level for ML and HL treatments ranged between 12 and 36 t ha^{-1} depending on the aimed level and plough depth (Saarela et al., 2000). The split-plots were further divided into four split-split-plots of different P fertilization rates, which were later split once more for investigating fertilizer application methods. These P fertilization split-split-plots were not considered in the present study.

In 1993, the tillage treatments were (1) shallow cultivation to 12 cm,

(2) deep ploughing to 32 cm, and (3) conventional ploughing to 22 cm. In autumn 1994, the tillage treatments were repeated as in 1993. In autumn 1995, all plots were cultivated to 10 cm depth and in 1996 rotovated to sowing depth. In autumn 1997, the shallow rotovating was repeated except for the original conventional ploughing treatment, which was now deep ploughed using a self-made special plough designed to cut a shallow (ca. 5 cm) slice of the topsoil and drop it at the bottom of the furrow. The ploughing was carried out twice in a row, first to 30 cm depth and after that aiming at 40 cm depth, but at the end, a ploughing depth of 35 cm was reached (Saarela et al., 2000). The tillage treatments are summarized in the supplementary material, Table S1. The experimental plots were maintained until 2007.

After the field experiment was discontinued, the whole area has been under uniform agricultural management (see supplementary material, Table S2). The experimental field was under grass production for a four-year period 2008–2012. Thereafter the field has been in cereal production except for 2021 when fava bean was cultivated. After 2013, manure has been spread on the field annually with additional mineral nitrogen fertilization, but no lime has been applied. Tillage methods extending under the normal ploughing depth (ca. 20 cm) have not been used after the termination of the field experiment. The experimental area thus encompasses control plots of conventional tillage depth (CT) and two sets of plots deep ploughed in the 1990s (DP1 and DP2). DP1 refers to deep plough treatment with a commercial moldboard plough for deep ploughing (Fiskars 1×20") and DP2 to ploughing with a self-made plough.

2.2. *Site relocation and sampling*

While the field map and order of the tillage and liming plots were available in the documentation of the experiment, the accurate position of the experimental site was not documented. However, the site was visible in aerial photographs taken from the region in 2004 and 2006/2007 when the experimental plots were still maintained in the field. The aerial photographs are available in the Finnish national geoportal Paikkatietoikkuna maintained by the National Land Survey of Finland (https://kartta.paikkatietoikkuna.fi). Although there is a small inaccuracy in the positioning of the site corners (ca. 1 m), the large size of the plots made it possible to target the soil sampling to correct treatments.

Soil samples were collected from the relocated experimental site in June 2022. On the longitudinal central line of each main plot, three sampling points were set such that one point was placed in the centre of each three split-plots of different liming treatments (in total 27 sampling points, see Fig. 1). All sample types were taken from the same sampling locations. The small split-split-(split) plots of varying P fertilization could not be considered in the sampling. Soil core samples were taken separately from each of the sampling points in 10-cm segments down to 50-cm depth with an auger of 4.8 cm in diameter. In addition, disturbed composite samples were collected from 0 to 20 cm topsoil and 20–40 cm subsoil layers by bulking soil cores of ca. 2 cm in diameter from all three sampling points of the main plot.

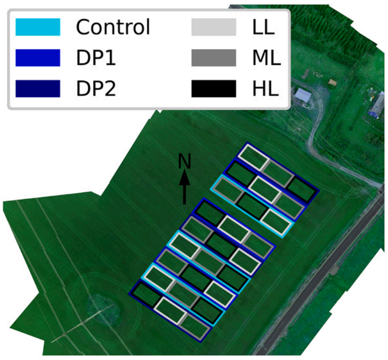

Fig. 1. Experimental site imaged 14th of July 2022. Rectangles with shades of blue show the main plots with different tillage treatments (control and two deep plough treatments) and rectangles with shades of grey the split plots with different liming levels. The sampling points were in the centres of the 27 split plots.

For X-ray tomography imaging, intact soil cores were sampled from the sampling points in aluminium cylinders with an inner diameter of 46 mm and a height of 70 mm. From each sampling point, one sample was taken from topsoil and one from subsoil. The sampling depths were approximately 10–15 cm and 25–30 cm, respectively. For both sampling depths, three samples from each tillage plot were sampled such that one sample was taken from each liming plot. Thus, in total 54 soil cores for imaging were collected. The collected soil samples were wrapped with plastic film to preserve their natural soil moisture and stored at +5 °C until imaging. In addition, subsoil samples for water retention measurements were taken from ca. 25–30 cm soil depth to cylinders with an inner diameter of 72 mm and a height of 60 mm. Sampling locations were the same as for imaging samples, i.e., in total 27 samples for water retention measurements were collected. The sampling times for topsoil and subsoil samples were 29th June and 26th September 2022, respectively. Water retention samples were also covered and stored at +5 °C before measurements.

To assess possible differences in crop growth between the previous tillage treatments, a remote sensing dataset of the field site was collected on 14th July 2022 with an unmanned aerial vehicle (UAV) DJI Matrice RTK V2 quadcopter equipped with a Micasense Altum radiometric multispectral camera. The flight altitude was 80 m and after orthomosaicing, the pixel size of the image was 5.3 cm. In addition, whole aboveground biomass samples of ripe barley (Hordeum vulgare) were collected from each sampling point on 1st September 2022, by cutting the crop at 4-cm height within a 50 cm × 50 cm frame.

2.3. *Laboratory analyses*

The soil core samples were dried at 40 ℃ and weighed for bulk density. Thereafter, the samples were ground to pass a 2-mm sieve and analysed for total C via dry combustion (Leco 628 CHN Determinator), which in the acidic soil can be taken to represent organic C (Nelson and Sommers, 1996). C stocks in soil profiles were calculated using the equivalent soil mass method with the C concentrations determined for the 10-cm soil layers. Stocks were calculated to represent a 600 kg m^{-2} mineral soil layer, which corresponded to soil depths between 43 and 50 cm. Calculations were done as described by Heikkinen et al. (2021). Concentrations of SOC were considered in 0–20 cm and 20–40 cm topsoil and subsoil layers. For this purpose, an average weighted by bulk density was calculated over the SOC concentrations determined in the 10-cm segments.

For analyses of pH and electrical conductivity (1:2.5 water suspension) samples representing 0–20 cm and 20–40 cm depths were constructed from the core samples taken in 10-cm segments by mixing equal volumes of samples from the two layers. For the analysis of soil particle size distribution (texture) by the pipette method of Elonen (1971), samples from the three sampling points in each plot were further combined to form one representative sample for each plot from both 0–20 cm and 20–40 cm layers.

The composite soil samples taken from each plot were size and density fractionated for assessing the soil C reserves in free particulate form (POC) and mineral-associated form (MOC) following slightly modified procedure of Keskinen et al. (2024). In brief, 50 g of fresh soil was dispersed by shaking (18 h) in deionized water, and thereafter wet sieved on sieves of 2 mm, 0.25 mm, and 0.063 mm mesh in succession. The size fractions were oven-dried at 80 ℃. The fractions of 0.25–2 mm and 0.063–0.25 mm were further density separated in sodium polytungstate adjusted to 1.8 g cm^{-3} density to recover lighter POC and heavier MOC. The total C concentration of all five fractions was analysed via dry combustion (Leco 628 CHN Determinator). Further, the POCs and MOCs in 0.25–2 mm and 0.063–0.25 mm size fractions were summed up resulting in three SOC fractions: POC, MOC>0.063 mm and MOC<0.063 mm.

The water retention properties of subsoil samples were determined by using the UGT MP10 ku-pF apparatus (Umwelt-Geräte-Technik GmbH, Germany). Before measurement, soil cylinders were saturated with water from below and after this, two micro-tensiometers were inserted horizontally in drilled holes at a height difference of 3 cm. After being placed in the apparatus, the samples were weighed and the tensiometer readings were read automatically in 10-min intervals until the air-entry tension of the tensiometers was reached (ca. 85 kPa). During the measurement, samples were covered with 3D-printed perforated lids to restrain the evaporation rate and thus the tension difference between the top and bottom of the samples. Thereafter the samples were oven-dried at 105 °C and the weight losses in the samples were converted to volumetric water content values at each time. The pore volumes above and below 30 μm pore diameter (field capacity) were considered, which also approximately corresponds to the porosity visible and invisible in the X-ray tomography images, respectively.

Normalized difference vegetation index (NDVI) was calculated from the remote sensing data to estimate the growth in different field plots. NDVI index is defined as NDVI = (NIR-Red)/(NIR+Red), where NIR and Red stand for the calibrated reflectance values for near-infrared and red bands, respectively. Further details of the UAV imaging approach can be found in Niemitalo et al. (2021). The above-ground cereal biomass was oven-dried at 60 °C for 6 days and thereafter weighed.

2.4. *Image analysis*

Soil porosity, critical pore size and pore size distribution were determined using an in-house built JTomo X-ray tomograph. X-rays were generated with an L12161 X-ray tube (Hamamatsu Photonics, 40–150 kV, 75 W) and source voltage and power were set to 150 kV and 30 W, respectively, in medium focus mode. Incident X-rays were filtered with a 6 mm thick glass filter. Radiographs were acquired with a Shad-o-Box 6k HS flat panel detector (Teledyne) in cone-beam geometry. In each scan either 5880 or 2940 projections over 360 degrees were captured with 500 ms exposure time and 20 μm pixel size. Each sample was imaged at two vertical positions to cover it in its entirety.

Reconstruction of tomographs (Fig. 2a) and image analysis was done with pi2 software (available at github.com/arttumiettinen/pi2) Reconstruction of tomographs was performed using the Feldkamp-Davis-Kress Filtered Backprojection algorithm (Feldkamp et al., 1984). After reconstruction, the two tomographs were stitched to a single 3D volume using NRStitcher software (Miettinen et al., 2019).

The imaging noise was reduced (Fig. 2b) from the stitched images with bilateral filter (spatial sigma = 40 μm, radiometric sigma = 3500) and images were scaled to 40 μm pixel size. Segmentation of images was then done by thresholding all samples with the same threshold value. The threshold value was manually selected so that it yielded the visually most accurate separation of void and solid phases.

Porosity was calculated from the segmented binary images (Fig. 2c). In the porosity analysis, the top and bottom parts of the sample were excluded to avoid analysing possible damaged parts of the sample due to

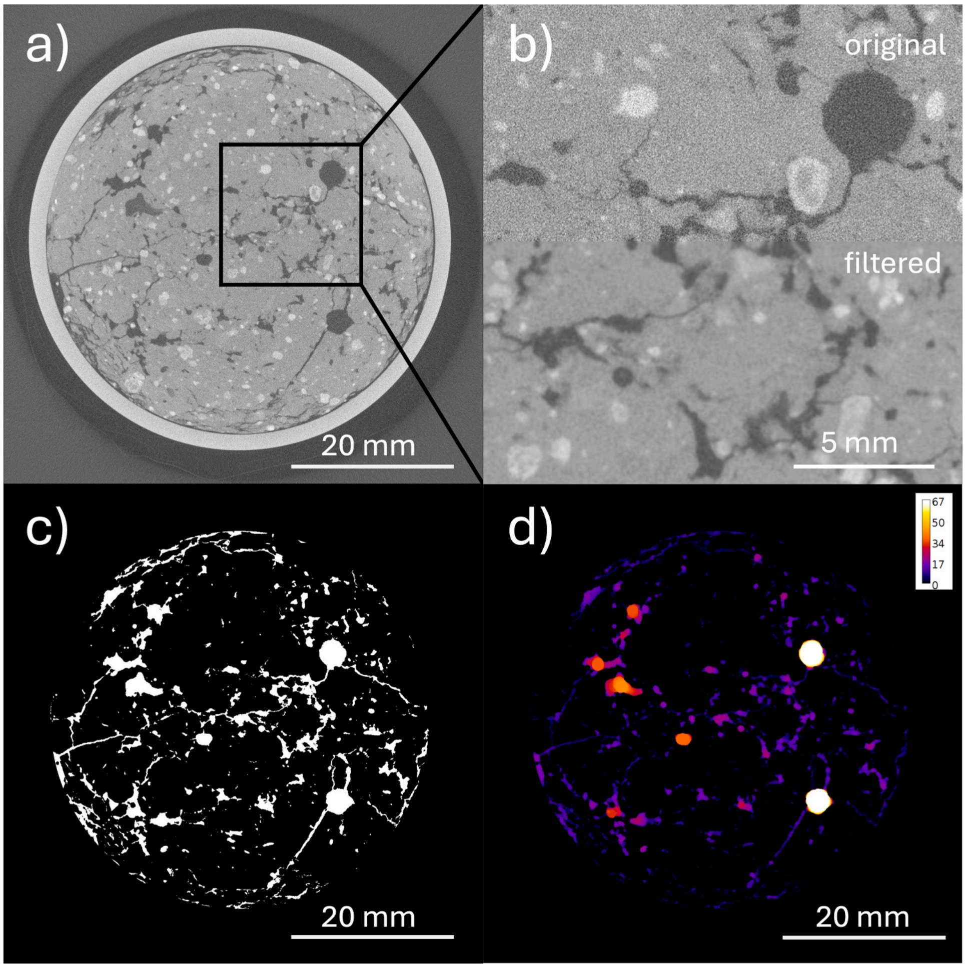

Fig. 2. a) Reconstructed cross-section of a soil sample. b) A smaller region before and after bilateral filtering. c) Segmentation of the same cross-section, where voids are shown as white and d) local thickness map of the segmentation. The colour bar in d) shows pore diameter values in pixels.

sample collection. Pore diameter distribution was calculated from local thickness maps (Fig. 2d) of void space with statistical binning (Hildebrand and Ruegsegger, 1997).

The largest sphere that can travel through the voids in the sample is called critical pore size (Koestel et al., 2018; Katz and Thompson, 1986). The critical pore size was calculated through an iterative flood-fill process. First, the local thickness map was thresholded by the largest pore size, dividing the image into space consisting of voids larger than the threshold value, and everything else. If a flood fill process started at the void space above the sample could not progress to the void space below it through the large voids, the thresholding pore size value was decreased by 1 pixel and the process was repeated. The critical pore size was defined as the first threshold value that resulted in the flood fill being able to propagate through the sample.

2.5. Statistical analyses

The experimental design was a randomized split-plot experiment with three blocks, where plough treatment was used as the whole plot and lime treatment as the subplot. In addition, measurements were taken from two depths from each plot.

The analyses of response variables measured at two depths were performed with, generalized linear mixed models (GLMM) with plough treatment (CT, DP1, DP2), lime treatment (LL, ML, and HL), depth (0–20 cm, 20–40 cm) and all their interactions were denoted as fixed effects. The random effects of block, block × plough treatment, and block × depth were assumed to be independent and normally distributed. For those response variables having measurements only from the one soil layer, the model was simplified omitting the effect of depth from the models.

Correlations between depths were taken into account using a heterogeneous or homogeneous compound symmetry (CSH or CS) covariance structure. Heterogenous structures also allow non-constant variance. The Akaike's Information Criterion (AICc) was used to choose the most suitable covariance structure for each model.

An identity link was used for the Gaussian-distributed models. Due to skewed response variables, the assumption of gamma distribution with a log link was used for C concentration, equal soil mass-based SOC stocks, and imaged porosities for topsoil and subsoil. The residual pseudo-likelihood (RSPL) estimation method for the models having the gamma distribution assumption, and the residual maximum likelihood (REML) method for the Gaussian-distributed models were used. Degrees of freedom were calculated using the Kenward-Roger method. The normality of the residuals was found adequate using boxplots. Deep plough treatments and depths were compared to the control treatment (CT) and to the topsoil layer (0–20 cm), and thus the method of Dunnett-Hsu was used for all pairwise comparisons of means with a significance level of 0.05. Due to the small study size, also results trending towards statistical significance ($0.05<p<0.10$) are presented and denoted as 'marginally significant'. The analyses were performed using the GLIMMIX procedure in the SAS Enterprise Guide 8.3 (SAS Institute Inc., Cary, NC, USA).

3. Results and discussion

3.1. General features

The experimental area proved to be overall rather uniform in texture. However, according to the main plot soil samples (n=9), clay content was significantly higher in the 0–20 cm soil layer of the deep ploughed plots (DP1 and DP2) than in the control plots (p=0.025 and p=0.0087, respectively, Table 1). In the 20–40 cm soil layer, there were no significant textural differences. The small effect of the DP treatments on the textural composition of the topsoil is explained by the subsoil richer in clay being mixed in the topsoil due to deep inverting of the soil profile. The lack of effect in the subsoil may derive from a smaller relative effect or a steep textural depth gradient within the 20–40 cm subsoil since although mouldboard ploughing buries the topmost soil efficiently, redistribution of the layer at the very bottom has been shown to be less efficient (Scanlan and Davies, 2019).

Table 1
Clay (< 0.002 mm), silt (0.002–0.02 mm) and sand (0.02–2 mm) contents in 0–20 cm and 20–40 cm soil layers in control (CT) and deep-ploughed plots (DP1 and DP2). Tillage treatments differing significantly ($p<0.05$) from the control treatment are marked with an asterisk (*).

		CT	DP1	DP2
0–20 cm	Clay	44.9	46.4*	46.8*
	Silt	30.8	30.2	30.3
	Sand	24.3	23.4	22.9
20–40 cm	Clay	59.1	58.3	60.0
	Silt	26.2	26.1	26.0
	Sand	14.7	15.7	14.0

The previous liming treatments carried out on split-plots still showed a significant effect on soil pH ($p < 0.001$) the mean pH increasing with an increase in lime application rate. Overall, pH was lower in the topsoil (5.9 LL; 6.4 ML; 6.5 HL), than in the subsoil (6.3 LL; 6.5 ML; 6.6 HL). The tillage treatments showed no effect on soil pH ($p = 0.127$). Regarding the long-term effects of liming, Holland et al. (2019) considered two long-term liming experiments and reported that the deviating pH following the lime application persisted over a decade. Bennett et al. (2014), on the other hand, did not find statistically significant differences between liming and non-limed control in a sampling performed 12 years after lime application but observed significant differences in hydraulic conductivity and aggregate stability. Although the effects of liming are known to depend on the soil properties such as texture and organic matter content (Holland et al., 2018), these studies demonstrate that liming can have effects on soil properties persisting on a decadal time scale as also observed in the present study. Manure application has been reported to have a liming effect on soil (Eghball, 1999; Whalen et al., 2000), which may also affect the observed results, as manure has been spread to the study field frequently. The detectable effects of the liming history can also be taken to confirm that the positioning of the field experiment was successful despite the lack of exact coordinates.

Similarly to pH, a significant effect on soil electrical conductivity (EC) was recorded for depth (96 $\mu S\ cm^{-1}$ at 0–20 cm and 63 $\mu S\ cm^{-1}$ at 20–40 cm; $p < 0.001$) but not for tillage ($p = 0.794$). Differences in the liming history were neither reflected in the present EC values ($p = 0.303$). The EC value reflects the presence of soluble salts in soil (Hardie and Doyle, 2012), and higher EC at the topsoil in comparison to the subsoil can be attributed to inputs of mineral fertilizers and manure.

3.2. Soil carbon

3.2.1. Soil carbon concentration and stock

Only a marginally significant main effect on SOC concentration was found for the tillage treatment ($p = 0.079$) but the tillage and plough depth had a significant interaction effect ($p = 0.016$; Fig. 3a). This was manifested as a slightly lower SOC concentration in the topsoil of DP2 in comparison to the topsoil of CT (2.63 % vs. 2.80 %; marginally significant, $p = 0.058$) and secondly as a higher SOC concentration in the subsoil of DP1 in comparison to the subsoil of CT (1.31 % vs. 1.01 %; $p = 0.048$). A marginally significant difference between DP1 and CT could also be seen in carbon stock when calculated to the equivalent depth of 20–40 cm (DP1 3.83 $kg\ C\ m^{-2}$, CT 2.89 $kg\ C\ m^{-2}$; $p = 0.053$). However, in equal mass-based SOC stocks to 600 $kg\ m^{-2}$, no significant differences between the tillage treatments occurred (CT 10.0 $kg\ C\ m^{-2}$, DP1 10.6 $kg\ C\ m^{-2}$, DP2 9.7 $kg\ C\ m^{-2}$; $p = 0.215$, Fig. 3b). No significant effect on SOC was observed either for lime treatment ($p = 0.382$) but overall, SOC decreased with depth ($p < 0.001$).

The lack of systematic effect of deep tillage on SOC concentrations or stocks likely partly originates from the sampling design. The sampling

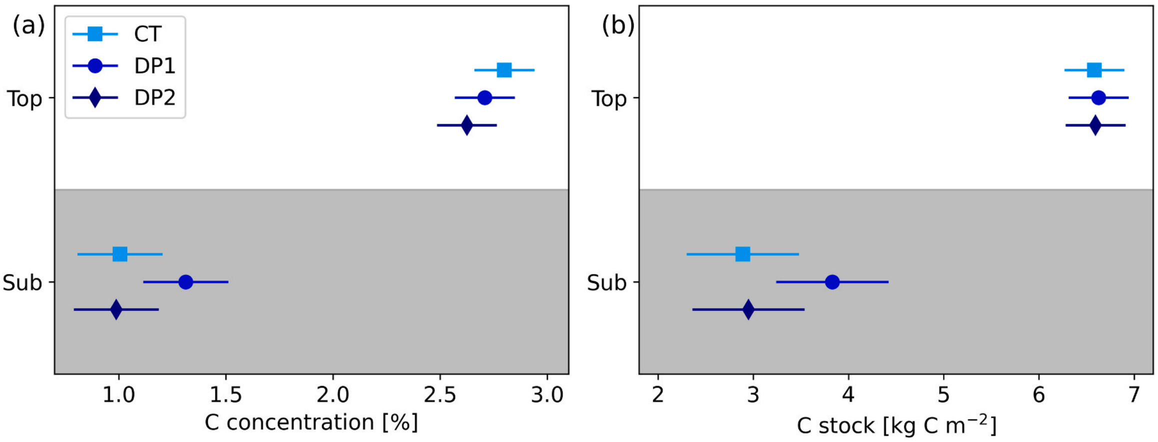

Fig. 3. (a) Carbon concentrations and their 95 % confidence intervals in topsoil (0–20 cm) and subsoil (20–40 cm) layers for the tillage treatments (control CT and two deep plough treatments DP1 and DP2). (b) Carbon stock in the topsoil and subsoil layers.

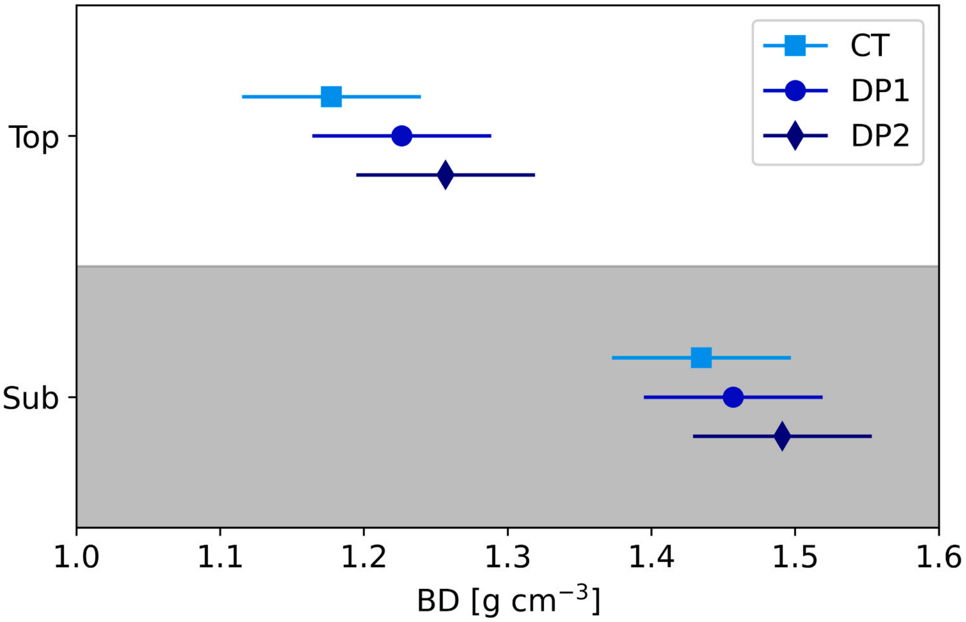

Fig. 4. Bulk densities and their 95 % confidence intervals of topsoil (0–20 cm) and subsoil (20–40 cm) layers for the tillage treatments (control CT and two deep plough treatments DP1 and DP2).

pattern consisting of single sample points on the centre line of each plot could not capture the variation or heterogeneity in the subsoil derived from the furrow slices (Scanlan and Davies, 2019). The sampling was thus rather non-sensitive to small changes. In case of more resources, increasing the sample number to, e.g., three parallel points in each sampling location to cover the width of the furrow would be recommendable (e.g., Alcántara et al., 2016). However, the lack of a clear significant increase in SOC stocks after nearly 30 years from the tillage operations does not in this case support the hypothesis of enhanced SOC accrual via the less C-saturated mineral surfaces of the subsoil in comparison to topsoil. The plough depth (ca. 35 cm) used in the study site was shallower here than those considered in some other studies focusing on the impacts of deep ploughing. For example, Alcántara et al. (2016) studied deep plough sites where the plough depth varied between 55 and 90 cm. While the plough depth may partly explain the milder results, the plough depth nevertheless was clearly deeper than the conventional ploughing depth (ca. 20 cm) used in the region (Turtola et al., 2007). Deep ploughing may also have adverse effects on SOC accrual through the so-called priming effect. The introduction of easily decomposable organic matter to subsoil may trigger the mineralization of old stabilized SOC stored in the deeper soil layers (Fontaine et al., 2007). However, the results of the priming effect in subsoil are inconclusive. For example, in microcosm incubations by Wordell-Dietrich et al. (2017), the same organic matter addition decomposed slower in the subsoil than in topsoil and the added organic matter did not lead to accelerated mineralization of native SOC. Dai et al. (2022), in turn, found that organic matter addition resulted in a positive priming effect both in topsoil and subsoil, but the effect was stronger in topsoil.

3.2.2. Soil carbon in mass and density fractions

Of the total OC in the composite soil samples, 13 % was recovered in the POC fraction in the 0–20 cm soil layer and 7.7 % in the 20–40 cm layer. Of the total OC, 11 % (both layers) were larger-sized MOC (>0.063 mm), and 75 % (0–20 cm) and 81 % (20–40 cm) MOC smaller than 0.063 mm. The shares of POC and MOC fall within shares reported for similar soil (Salonen et al., 2023). The mean POC concentration was clearly higher in the 0–20 cm layer (0.34 mg C (100 g)$^{-1}$ soil) than in the 20–40 cm depth (0.12 mg C (100 g)$^{-1}$ soil) ($p<0.0001$). There were no statistically significant differences between the tillage treatments in the MOC or POC concentrations in the 0–20 cm layer but in the 20–40 cm layer, the POC concentration in DP2 was marginally higher than in CT ($p=0.064$) (Table 2), which may reflect the presence of former topsoil material. Below 20 cm, the sum of all C fractions resulted in higher SOC concentration that measured from the profile cores sampled down to 40 cm depth. This may suggest that the soil sample from 20 to 40 cm taken with the thinner 2-cm auger was contaminated with the surface soil while sampling.

The results thus indicated, that during the years following partial mixing of the soil layers differing in SOC contents, the MOC fraction in the surface soil (0–20 cm) of the deep-ploughed plots likely approached the SOC content levels of the control treatment, responding similarly to the same management practices applied across the field. Despite expectations that deep ploughing would increase MOC content in deeper soil layers, this was not observed. Though the MOC fraction is overall more stable and resistant to changes in management and environment than the POC fraction, it is nevertheless diverse and to some extent cycling (Sokol et al., 2022). More research on the pathways of MOC formation and its retention in the subsoil conditions is needed.

3.3. *Soil structural properties*

The effect of tillage treatment on topsoil bulk density was significant ($p=0.017$) and pairwise comparisons showed difference between CT and DP1 treatments ($p=0.043$). Lime treatment did not show statistically significant effects ($p=0.85$).

Regarding the image analysis results, no significant effect between tillage treatments was detected for topsoil macroporosity (CT 0.12, DP1 0.11, DP2 0.10; $p=0.61$) or critical pore diameter (553 μm, 536 μm, 514 μm; $p=0.945$). Similarly to tillage, neither did liming treatment show a significant effect on these quantities ($p=0.496$ and 0.457, respectively). However, macroporosity had a marginally significant interaction effect between tillage and liming treatments ($p=0.082$). For subsoil macroporosity, no significant differences were detected (CT 0.023, DP1 0.041; DP2 0.023; $p=0.29$). The effect of tillage treatment on subsoil critical pore diameter was significant (CT 259 μm, DP1 415 μm, DP2 190 μm; $p=0.0281$). Pairwise comparison showed no significant difference between CT and DP treatments, even though the subsoil critical pore diameter of DP1 was clearly larger than in CT.

Water retention measurements were only done for subsoil samples. Tillage treatment showed no significant effect on the total subsoil porosity determined from the water retention measurements (CT 0.48, DP1 0.47, DP2 0.48; $p=0.607$), whereas liming treatment had a significant effect (HL 0.48, ML 0.49, LL 0.47; $p=0.0015$) and a marginally significant interaction effect was detected between tillage and lime treatment ($p=0.0839$). Pairwise comparisons showed significant differences between HL and ML ($p=0.04$) as well as ML and LL ($p=0.001$) treatments. Porosities for two pore size classes were considered from the water retention curves namely pores with a diameter less or greater than 30 μm, which corresponds to the field capacity and approximately also the resolution of X-ray tomography. For pore sizes less than 30 μm, lime treatment had a marginally significant effect on porosity (HL 0.42, ML 0.43, LL 0.41; $p=0.089$) whereas tillage treatment showed no significant effect (0.42 for all tillage treatments; $p=0.98$). Pairwise comparisons showed a marginally significant difference between LL and ML treatments ($p=0.078$). For the larger pore size class, no significant effect due to tillage (CT 0.059, DP1 0.054, DP2 0.062; $p=0.609$) or liming (HL 0.058, ML 0.061, LL 0.056; $p=0.743$) was observed.

Table 2
Particulate organic carbon (POC) and mineral-associated organic carbon (MOC) in <0.063 mm and >0.063 mm size fractions. Tillage treatments that differ marginally significantly ($p<0.10$) from the control are marked with a circle (°).

		CT	DP1	DP2
		mg C $(100\ \text{g})^{-1}$ soil		
0–20 cm	POC	0.35	0.32	0.35
	MOC >0.063 mm	0.30	0.31	0.27
	MOC <0.063 mm	1.92	1.96	1.90
20–40 cm	POC	0.10	0.09	0.17°
	MOC >0.063 mm	0.16	0.20	0.16
	MOC <0.063 mm	1.18	1.16	1.32

In general, our results show that deepened ploughing has had only minor and scattered effects on soil structural properties. Neither water retention measurement nor X-ray tomography showed differences in microporosity between the tillage treatments. Water retention measurements indicated differences between liming treatments, but the differences are minor as compared to, e.g., differences observed between different soil management practices in the topsoil of similar boreal clay soils (Hyväluoma et al., 2024). It should be noted, however, that both measurement techniques used focused on the macropore regime, whereby there may be differences in micropore and mesopore regimes which comprise most of the total porosity. Image analysis showed differences in the subsoil critical pore diameter between tillage treatments. Therefore, despite comparable macroporosities, the macropore connectivity differs between the treatments which can lead to differences in soil functioning as percolation theory links the saturated hydraulic conductivity to critical pore diameter via a power law (Katz and Thompson, 1986). Percolation theory has been found to describe the hydraulic conductivity of soils in several studies (Ghanbarian et al., 2017; Koestel et al., 2018; Soinne et al., 2023; Hyväluoma et al., 2024). Thus, our results suggest that deep ploughing can lead to long-term effects on subsoil hydraulic functions. In total, the results do not reassert the concerns about the harmful effects of deep ploughing on the soil structure and functions (e.g., Baveye et al., 2020) at least at the time scale and ploughing depth considered here. The structural effects of deep ploughing have been found to be site-specific and especially soil texture can be assumed to be a key factor. For example, Burger et al. (2023) studied the effects of deep ploughing on several soil properties 50 years after the deep ploughing event at three sites and concluded that deep ploughing had site-specific legacy effects on the soils. Deep ploughing on sandy soils had led to reduced subsoil bulk density whereas the effect on silty soil was the opposite. The study by Baumhardt et al. (2008) considered bulk density on deep-ploughed clay loam and found that the lowered subsoil bulk density observed four years after deep ploughing was still present but diminished when determined 31 years after ploughing.

3.4. *Crop growth*

The NDVI indices indicated no differences in the greenness of the vegetation between tillage plots but a statistically significant ($p = 0.0006$) increase in NDVI was found with an increase in previous liming rate. This effect was, however, practically insignificant as all mean NDVI values exceeded 0.9 (see Fig. 1). The mean total aboveground biomass of ripe crops was higher in CT (8252 kg ha^{-1}) than in the deep ploughed plots (DP1 7267 kg ha^{-1}; DP2 7847 kg ha^{-1}), but the main effect of the tillage treatment was merely marginally significant ($p = 0.0881$). Consistently, in pairwise comparisons CT differed marginally from DP1 ($p = 0.0551$). The residual effect of liming on crop growth was also only marginally significant ($p = 0.0869$) although the lowest liming level resulted in the lowest mean yield.

Our results showed a slight negative crop response trend as yields were 12 % and 5 % lower in DP1 and DP2 as compared to CT. Recently, Burger et al. (2023) studied three German sites (two sandy and one silty soil) five decades after the deep ploughing and observed positive yield effects due to deep ploughing at one sandy soil in dry conditions while the effects were minor and not significant for the two other sites. A meta-analysis based on a large number of yield comparisons showed that on average deep tillage had a slightly positive effect on crop yield (+6 %) (Schneider et al., 2017). Regarding the crop response of deep tillage, soil texture was recognized as a key variable, whereby the success of deep tillage depends on site-specific soil properties (Schneider et al., 2017). In particular, the effects of deep ploughing were considered negative on silty soils. Håkansson et al. (1998) attributed the negative yield effect on high-silt soils to deteriorated surface structure and consequent surface layer hardening due to the dilution of SOM. In clay and sandy soils, the main reasons behind positive yield effects to deepened tillage were deeper loosening and more efficient weed control than in shallow treatment.

4. Conclusions

A deep ploughing and liming experiment that was established ca. 30 years earlier was revisited to investigate the legacy effects of these management practices on SOC stocks, soil structure and yield. We found minor differences in topsoil texture due to deep ploughing and some indications of lowered SOC concentration in the topsoil and increased subsoil SOC concentration, which may indicate a transfer of the topsoil SOC to deeper layers and dilution of the SOC in the topsoil due to deep ploughing. However, we did not observe significant differences in SOC stocks between the tillage treatments. Thus, our results did not indicate major SOC sequestration effects due to deep ploughing reported in some previous studies. Compared with other studies where the effects of deep ploughing have been considered, the plough depth in the field experiment considered here was shallower, which may partly explain the milder results. The plough depth (35 cm) was nevertheless deeper than that typically used for these soils (20–25 cm). We also studied the soil structural properties and found only minor and scattered impacts between tillage treatments, whereby the deepened plough had not caused long-lasting extensive structural damage to the soil structure but neither any benefits for the subsoil layer. Regarding the liming treatments, we still found that increasing liming rates consistently induced differences in soil pH after three decades. To summarize, our results do not support the possibility of remarkably increasing SOC stocks in the subsoil layer with deep ploughing, but neither could we find signs of severe structural damages that would remain after three decades, whereas liming appeared to have the clearest long-term impacts on the soil properties. Since the impacts of soil management operations carried out three decades before the sampling were still detectable, our results highlight the importance of studying the long-term consequences of soil management practices. For an enhanced understanding of the effects of site-specific conditions and e.g. ploughing depth, further studies on the impacts of deep tillage on subsoil properties and SOC accrual are still necessary.

CRediT authorship contribution statement

Viktoriia Hetmanenko: Writing – review & editing, Investigation. **Riikka Keskinen:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Arttu Miettinen:** Writing – review & editing, Software, Methodology. **Sami Kinnunen:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis. **Jari Hyväluoma:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Conceptualization. **Janne Kaseva:** Writing – review & editing, Writing – original draft, Formal analysis. **Petri Niemi:** Writing – review & editing, Investigation. **Helena Soinne:** Writing – review & editing, Writing – original draft, Project administration, Investigation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.still.2024.106323.

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