Received: 16 November 2023 | Revised: 15 February 2024 | Accepted: 23 February 2024

DOI: 10.1111/sum.13040

RESEARCH ARTICLE

Soil Use and Management | WILEY

# Comparing structural soil properties of boreal clay fields under contrasting soil management

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**Abstract**

Soil management significantly affects soil structure. Tillage and grassland renovation may have destructive influences, while conversion of arable land to grassland can improve pore structure and related soil functions. In crop rotations including perennial grasses, soil structure is affected by these counteracting processes. This work aimed to quantify the impacts of different soil management practices on the structure of boreal clay soils. We studied intact topsoil samples taken from two locations by X-ray computed microtomography, image-based flow simulations and water retention measurements. At both locations, adjacent field areas with two contrasting soil management histories were compared. Both locations had at least a 30-year-old grassland site, which was compared to arable soils either under no-till management with annual crop rotation or conventional tillage with crop rotation including perennial grasses. Both imaging and water retention measurements showed significant differences in the soil macropore structure between the long-term grassland and arable no-till soil such that macroporosity and hydraulic conductivity of the long-term grassland were higher than those of soil under agricultural production. On the contrary, at the second study location, differences between long-term grassland and cultivated fields were minor and the long-term grassland exhibited lower macroporosity. Our results confirm that soil management affects the macropore structure of boreal clay soil and that no-till annual cropping and periodically tilled crop rotation including perennial phases exert different effects on the soil structure as compared with long-term grassland.

**KEYWORDS**

porosity, soil management, soil structure, water retention, X-ray tomography

## 1 | INTRODUCTION

Soil structure or architecture refers to the organization of solid particles (mineral and organic matter) of soil into a solid matrix and thereby the arrangement of the soil pore system within this matrix across different length scales (Vogel et al., 2022). Soil structure controls a wide range of physical, chemical and biological processes occurring in soil including transport and storage of water, solutes, gases and heat, microbial activity, root penetration and decomposition and stabilization of soil organic matter, which, in turn, affect soil productivity and environmental loading (Ghezzehei, 2011; Rabot et al., 2018). Well-functioning soil requires soil structure with a continuous pore system consisting of pores of different sizes (Nimmo, 2013). Regarding a 'good' soil macropore structure, macroporosity (i.e., pore sizes >30 μm) positively contributes to water infiltration, gas exchange and root growth (Hernandez-Ramirez et al., 2014; Kuncoro et al., 2014), whereas very large pores (pore size >300 μm) may lead to non-equilibrium water and solute transport and thus negative water quality impacts (Jarvis, 2007).

Soil management is known to significantly impact soil structure (Bronick & Lal, 2005; Pagliai et al., 2004). Tillage mode and intensity influence pore structure and thus soil functions such as water retention properties, hydraulic conductivity and aeration (Keskinen et al., 2019; Kreiselmeier et al., 2020; Schlüter et al., 2020). For example, Jarvis et al. (2013) collected and analysed a global dataset of hydraulic conductivity measurements and concluded that arable soils have 2–3 times smaller hydraulic conductivity than soils under natural vegetation or perennial agriculture. Generally, reduced tillage intensity has been considered to have positive effects on soil structural properties but results on the structural differences between no-tillage and conventional tillage are partly incoherent (Abdollahi & Munkholm, 2017; Blanco-Canqui & Ruis, 2018; Strudley et al., 2008). After a new management system has been taken into use, soil structural properties change both within the growing season (Keskinen et al., 2019; Sandin et al., 2017), and over longer time scales (Reichert et al., 2016). Influences of earlier reduced tillage on soil physical properties have been observed to persist over occasional ploughing events (Kuhwald et al., 2017) even though the impacts of such occasional tillage are controversial (Blanco-Canqui & Wortmann, 2020). In addition to tillage, other management options such as long-term fertilization (Zhou et al., 2016) or residue management (Abdollahi et al., 2017; Abdollahi & Munkholm, 2017) and associated variation in organic matter inputs, affect the physical properties of soil.

Grasslands have been found to have profound effects on soil structure and functions (Bodhinayake & Si, 2004; Kodesova et al., 2011; Schwartz et al., 2003). For example, the absence of tillage in perennial grasslands leads to the formation of continuous biopores by roots and earthworms (Schlüter et al., 2022). Converting degraded soil to grassland has been shown to stimulate improvements in soil structure (Ajayi & Horn, 2016). While tillage due to grass renovation is expected to deteriorate soil structure and soil carbon stocks (Necpálová et al., 2014; Reinsch et al., 2018), notable improvement of soil structure has been reported already 2 years after renovation even though structural recovery continues for a longer time, especially in deeper soil layers (Ajayi et al., 2021). Also, the introduction of grassland into crop rotation has been shown to improve soil structure through the so-called legacy effect, which refers to changes in soil properties that are passed to the following crops after the grass phase (Hoeffner et al., 2021).

There are still considerable gaps in understanding how long-term grasslands and crop rotations including perennial grasses affect the soil structure in comparison with arable soils with less diverse crop rotations and varying tillage intensity. The purpose of the present study was to evaluate the effects of different soil management practices on the macropore structure of boreal clay soil. To this end, we collected intact topsoil samples from two study locations and studied them by X-ray computed microtomography, image-based flow simulations and water retention measurements. The adjacent field areas with two contrasting soil management histories were compared at both locations. One study area at both locations was a long-term (at least 30 years old) grassland, which was compared to arable soil under annual cropping with no-till management or crop rotation frequently including perennial grass phases. Our study hypothesis was that the long-term grassland has positive influences on the soil structure in comparison with both no-till and crop rotation including periodical tillage and perennial grass phases.

## 2 | MATERIALS AND METHODS

### 2.1 | Study sites

Soil sampling was conducted in autumn 2021 at two locations. The first study site was the Kotkanoja (K) experimental field located in Jokioinen, southwest Finland (60°49′ N, 23°30′ E). The second study site was located at the Mustiala (M) research and educational farm in Tammela, southwest Finland (60°49′ N, 23°47′ E). The distance between the two sites is approximately 15 km, whereby the weather conditions in both locations can safely be assumed to be similar.

Management histories of the study areas for the 12-year period before sampling are presented in Figure 1. At both locations, one study area was a long-term extensively managed grassland (K1 and M1) which had not been tilled for at least 30 years before sampling and these areas were compared with adjacent fields under cultivation. At Kotkanoja, except for a single ploughing event in the year 2018, the second study area had been under

| | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| K1 | Grass | | | | | | | | | | | |
| K2 (no-till) | Oats | Barley | | | Spring wheat | | Oats | | Barley | Canola | | Oats |
| M1 | Grass | | | | | | | | | | | |
| M2 (crop rotation) | Oats | Barley | Grass | | | | | Oats | | | Grass | |

**FIGURE 1** Management of the study sites for years preceding the sampling. K1 and M1 are the permanent grasslands at Kotkanoja and Mustiala. K2 is the no-till annual cropping at Kotkanoja and M2 periodically ploughed crop rotation at Mustiala. Red cell borders indicate the timing of moldboard ploughing events. Sampling was conducted in autumn 2021.

**TABLE 1** Texture and carbon (C) content of the soils at the study sites.

| Site | C [%] | Clay [%] | Silt [%] | Sand [%] |
|---|---|---|---|---|
| K1 | 3.3 | 45 | 36 | 19 |
| K2 | 2.1 | 41 | 39 | 20 |
| M1 | 5.1 | 60 | 31 | 9 |
| M2 | 4.5 | 52 | 43 | 5 |

*Note*: The textural classification is <2 μm for clay, 2–63 μm for silt and 63 μm – 2 mm for sand. K1 and M1 are the permanent grasslands at Kotkanoja and Mustiala. K2 is the no-till annual cropping at Kotkanoja and M2 periodically ploughed crop rotation at Mustiala.

no-till management for 13 years prior to sampling (K2). Five years before introducing the no-till, K2 was managed as perennial green set-aside and before this period stubble cultivated. Regular moldboard ploughing at K2 was discontinued already 30 years before sampling. At Mustiala, the second study area (M2) had been under crop rotation with altering cereal and perennial grass phases and tilled by moldboard ploughing. At the sampling time, the M2 area had been under grass for 2 years after a three-year cereal period. Mustiala is a dairy farm and manure had been regularly spread in the M2 area. Mustiala Farm has been under organic farming since 2018.

## 2.2 | Climate

The study sites are located in the boreal climate zone. According to the long-term averages for the meteorological normal period 1991–2020 (Jokinen et al., 2021), the annual mean precipitation in the area is 621 mm and the annual mean temperature is 5.2°C. The absolute maximum and minimum temperatures in this period were 32.3°C and −31.5°C, respectively. The average monthly maximum and minimum temperatures were 22.1°C (July) and −8.3°C (February), respectively. The average snow depth was the highest at the end of February (20 cm). Weather data was obtained from the Finnish Meteorological Institute's observation station located at Jokioinen near the Kotkanoja site.

## 2.3 | Soil properties

To analyse the soil texture, ca. 10 subsamples were collected from each study area and bulked into one composite sample. The sampling depth was 0–15 cm. The samples were air-dried and ground and passed through a 2-mm sieve. The mass fractions of sand, silt and clay were determined by the pipette method described by Elonen (1971). Sieved samples were also analysed for total C content (Leco TruMac CN, Leco Corporation, Michigan, USA). Soil characteristics of the study sites are given in Table 1.

## 2.4 | Soil sampling

Intact soil samples for water retention measurements and X-ray tomography were collected at ca. 5–10 cm depth. For water retention measurements, six replicate samples from each sampling site were taken in sample rings with an inner diameter of 72 mm and a height of 60 mm. For imaging, five replicate samples from each sampling site were taken in aluminium cylinders with a height of 70 mm and an inner diameter of 46 mm. The collected samples were preserved in their moisture status at the time of sampling and stored at +5°C until measurements or imaging.

## 2.5 | Water retention measurements

The soil water retention properties were measured with a UGT MP10 ku-pF apparatus (Umwelt-Geräte-Technik GmbH, Germany). Before the measurements, soil samples were saturated with water from below. Two microtensiometers were inserted in the samples 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 recorded automatically in 10-min intervals until reaching the air-entry tension (ca. 85 kPa). Samples were covered with 3D-printed perforated lids during the measurements to restrain the evaporation rate and to reduce the tension difference between the top and bottom of the samples. After air-entry pressure was reached, samples were oven-dried at 105°C and the weight losses in the samples were converted to volumetric water contents. Water tensions (Ψ) were converted to pore diameters (d) using the Young-Laplace equation and capillary bundle model, $d=4\gamma/\Psi$, where $\gamma$ is the surface tension of the water-air interface (Bachmann & van der Ploeg, 2002).

## 2.6 | Imaging and image analysis

The tomographic images of soil samples were acquired using an in-house built JTomo tomograph. It is based on an L12161-07 X-ray tube (Hamamatsu Photonics, 40–150 kV, 75 W) and Shad-o-Box 6 K HS flat panel detector (Teledyne) in cone-beam geometry. The soil samples were imaged using 150 kV acceleration voltage and 30 W tube power in medium focus mode. X-rays were filtered with a 6 mm thick glass filter. Each sample was imaged over 360 degrees with 5880 projections using 500 ms exposure time with 20 μm image pixel size. Projections were reconstructed into 3D volumes using the Filtered Backprojection algorithm (Feldkamp et al., 1984). To acquire an image of the entire sample, images at two partially overlapping vertical positions were taken and after the reconstruction, the images were stitched together into one continuous panoramic image using the NRStitcher software (Miettinen et al., 2019).

A bilateral filter was applied to the reconstructed and stitched images to reduce noise (spatial sigma = 40 μm, radiometric sigma = 3500) and after the filtering images were scaled to 40 μm voxel size. Segmentation of the images into soil and void was done by manual thresholding. The threshold was selected so that it yielded the best and most accurate segmentation of void and soil. The same threshold value was applied for every image and the proper segmentation was visually confirmed. Images were examined for sampling perturbations and perturbed parts were excluded from the region of interest in subsequent analysis. Total porosity was calculated from the segmented binary image by dividing the total number of void voxels by the total number of voxels (void and solid) in the entire sample.

To estimate pore diameter, the local thickness map (Hildebrand & Ruegsegger, 1997) was calculated from the segmented images. The local thickness value for a voxel is the diameter of the largest possible sphere that fits inside the void phase and contains the voxel. Effectively, each voxel in the pore space is associated with the diameter of the pore it is contained in. The local thickness map was then used to calculate the pore size distribution in each sample by statistical binning.

Critical pore size, i.e., the diameter of the largest spherical particle that can penetrate through the entire sample through the voids (Katz & Thompson, 1986; Koestel et al., 2018) was calculated by studying the local thickness map in an iterative process. First, the local thickness map was thresholded by a selected pore diameter value, resulting in an image containing only the pores whose diameter is greater than or equal to the selected value. A flood fill process was initiated from the top of the sample and it was observed whether the fill can progress from the top side of the sample to the bottom side through the thresholded region. If it could, the selected pore diameter was assigned as the critical pore size, and if not, the process was repeated with a smaller pore diameter. The iteration started with the largest pore diameter value in the local thickness map and proceeded with 1 voxel decrements until the critical pore size was found.

Tomographic reconstruction and image analysis were performed using Python scripts and the pi2 package (available at https://github.com/arttumiettinen/pi2).

## 2.7 | Flow simulations

Saturated water flow through the macropore system was simulated using the lattice Boltzmann method and the segmented X-ray tomographic images (e.g., Liu et al., 2016). The grid spacing of 40 μm was used in the simulations such that the largest possible cuboid fitting in the imaged cylinder was used as the simulation domain. In our simulations, we used the D3Q19 lattice Boltzmann model with the two-relation-time collision operator (Ginzburg et al., 2008) and the bounce-back no-slip boundary conditions at the pore walls. The flow through the sample was driven by using a forcing term in the vertical direction and hydraulic conductivity was determined using the Darcy law. Details of the used implementation are given, e.g., by Hyväluoma et al. (2018).

## 2.8 | Statistical analysis

Statistical assessment of possible differences in the determined quantities was done with the independent *t*-test at the significance level of $p < .05$. The normality of data was tested with the Shapiro–Wilk's test, and homoscedasticity with Levene's test, both at the significance level of $p > .05$. Structural parameters derived from X-ray tomography and water retention fulfilled the normality and homoscedasticity assumptions, but simulated hydraulic conductivity and critical pore diameter were not normally distributed whereby the logarithms of these quantities were used in statistical analyses. All statistical analyses were carried out with Python using the Stats module in the SciPy library (Virtanen et al., 2020). Note that the study design did not allow for replicates and the comparisons are based on pseudoreplicate samples.

## 3 | RESULTS

### 3.1 | Water retention measurements

Water retention curves determined for each study site are shown in Figure 2. Visual inspection of curves indicated that at the Kotkanoja study location, there was a clear difference between the pore size distribution (which can be obtained from water retention curves through differentiation) at the two contrasting managements. At Mustiala differences between the two managements were less obvious although the water retention of M2 was systematically higher than that of M1.

The total porosities obtained from water retention measurements are shown in Figure 3 and the pore size distributions derived from water retention curves for selected pore-size classes are presented in Table 2. Statistical analyses of these results show that concerning total porosity, there were statistically significant differences between K1 and K2 as well as M1 and M2 ($p = .0098$ in both comparisons). At Kotkanoja, the total porosity of grassland soil (K1) was higher than that of arable no-till soil (K2) with porosities being 0.55 and 0.48, respectively. Mustiala soils M1 (grassland) and M2 (cultivated crop rotation) had a smaller difference between the managements with porosities of 0.51 and 0.55, and in this case, the porosity of long-term grassland was lower than that in the field soil. Similar trends were observed in pore size distributions (Table 2). At Kotkanoja, grassland management (K1) had greater porosity than arable no-till (K2) for pore diameters greater than 30 μm and the differences were statistically significant for all considered pore size classes. For pore sizes below 30 μm, no statistical difference between managements K1 and K2 was observed. Porosities of M2 were in all size classes greater than those of M1, and the observed difference was statistically significant for pore diameters below 200 μm. Nevertheless, the porosity differences between M1 and M2 were smaller in magnitude as compared with K1 and K2.

### 3.2 | Imaging

Visual examples of four X-ray-imaged soil samples are shown in Figure 4. Visualizations show that there are differences in soil macropore systems due to contrasting land use. According to visual inspection, at Kotkanoja the samples from the long-term grassland had higher macroporosity than those from the no-till soil (Figure 4a vs. 4b). At Mustiala the differences between long-term grassland and crop rotation were minor (Figure 4c vs. 4d).

To quantify the differences in the pore system, we calculated porosities for the imaged samples and the results are shown in Figure 5. There was a statistically significant ($p = 3.5 \times 10^{-5}$) difference in the porosities from the two Kotkanoja sites K1 and K2 such that porosity was higher in the long-term grassland (mean porosity 0.14) than in the arable no-till soil (0.050). Contrariwise, Mustiala sites had statistically significant ($p = .041$) but much smaller difference between the two management practices and the porosity of long-term grassland was lower than that of crop rotation in the grass phase (mean porosities 0.047 and 0.076, respectively). Considering the differences between different pore size classes, comparisons of the two management histories at both study locations are presented in Table 3. In all pore size classes, porosities of K1 exceeded those of K2 and the differences were statistically significant up to 2 mm pore diameter. On the contrary, the comparison of M1 and M2

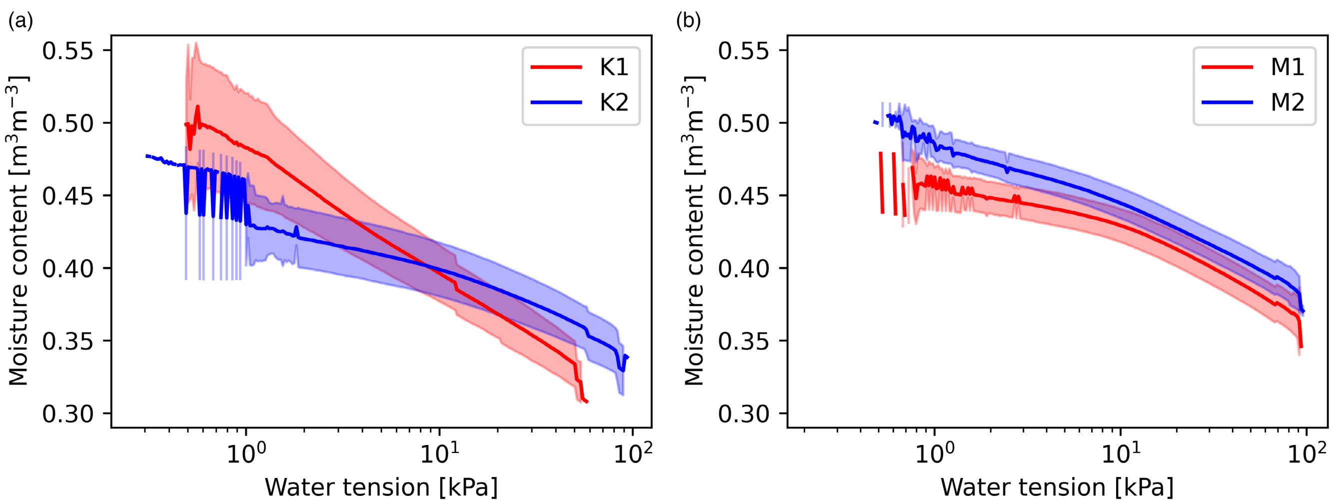


FIGURE 2 Water retention curves for the four study areas. The solid lines are the means of the measured values of six replicate samples and shaded areas denote the moisture range at a given water tension. Red curves are for long-term grassland sites and blue ones are for sites under cultivation. Results are shown for (a) Kotkanoja and (b) Mustiala study locations.

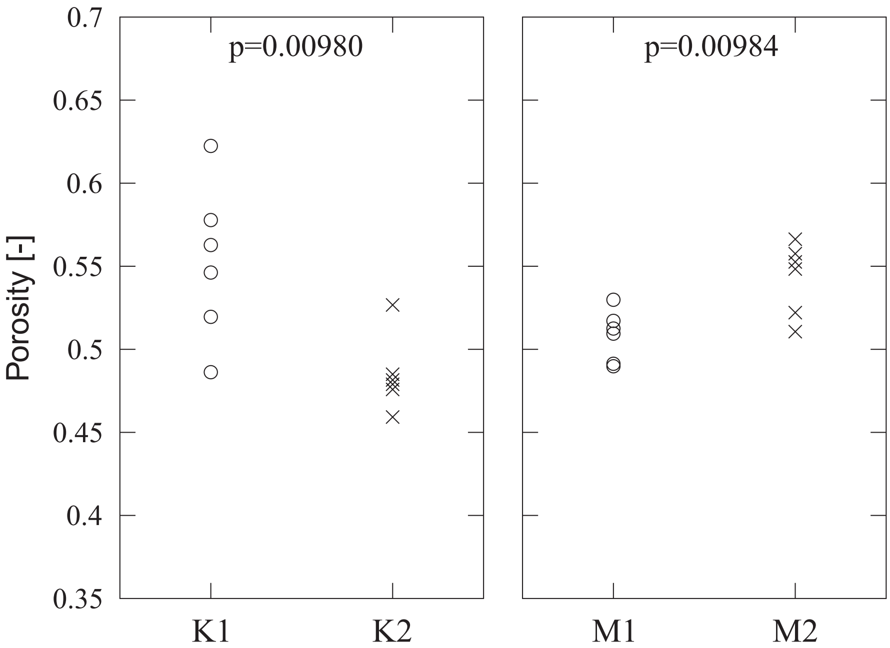


FIGURE 3 Total porosities for the four sampling areas (K1, K2, M1, M2). Statistical comparisons were done separately for both study locations and the resulting *p*-values are shown in the corresponding figure panels.

TABLE 2 Soil porosities derived from water retention measurements for selected pore diameter classes.

| Pore size class [μm] | Mean porosities | | | | | |
|---|---|---|---|---|---|---|
| | K1 | K2 | *p*-Value | M1 | M2 | *p*-Value |
| <30 | 0.396 | 0.399 | .822 | 0.429 | 0.444 | **.035** |
| 30–100 | 0.044 | 0.016 | $\mathbf{3.01 \times 10^{-5}}$ | 0.015 | 0.021 | **.014** |
| 100–200 | 0.029 | 0.010 | $\mathbf{3.47 \times 10^{-4}}$ | 0.007 | 0.012 | $\mathbf{1.20 \times 10^{-3}}$ |
| >200 | 0.083 | 0.059 | **.020** | 0.057 | 0.065 | .374 |

*Note*: Statistical comparisons were performed between the two management practices at both locations. Statistically significant differences are shown as bolded.

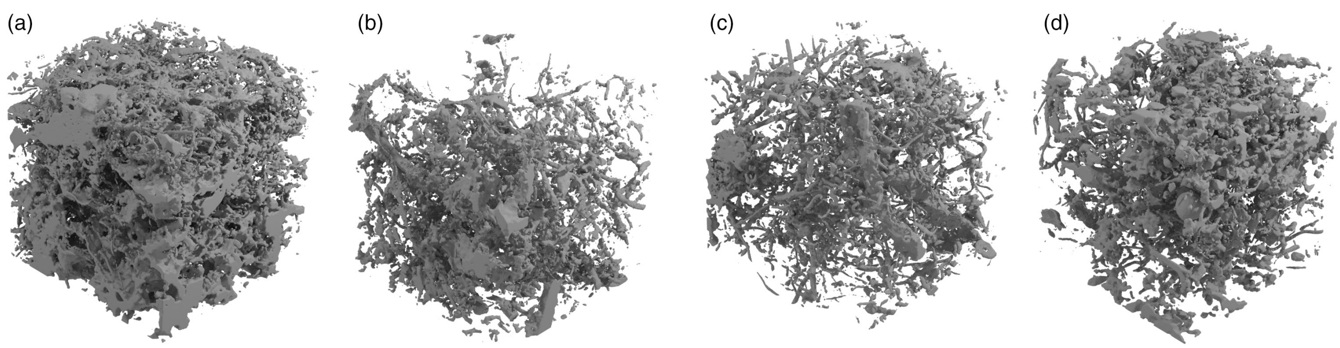


FIGURE 4 Examples of macropore systems that are visible in the X-ray tomography images. Visualized cubical domains are subsamples of the analysed images and have an edge length of 2 cm. Sampling areas for the shown soils are as follows: (a) K1 (long-term grassland), (b) K2 (arable no-till), (c) M1 (long-term grassland) and (d) M2 (cultivated crop rotation).

did not show statistically significant differences in any pore size class despite that a difference was found for the total porosity. Critical pore diameters calculated for the samples are shown in Figure 6 for the four sampling sites. While no statistically significant differences between the managements were observed ($p = .059$ for K1 vs. K2 and $p = .34$ for M1 vs. M2), the trends appear to be similar to those observed for other pore structure attributes.

## 3.3 | Flow simulations

Possible functional implications of the differences between the macropore systems were investigated by pore-scale flow simulations. Saturated hydraulic conductivities for all imaged samples are shown in Figure 7. At Kotkanoja sites K1 and K2, there was a statistically significant ($p = .021$) difference between the logarithms of

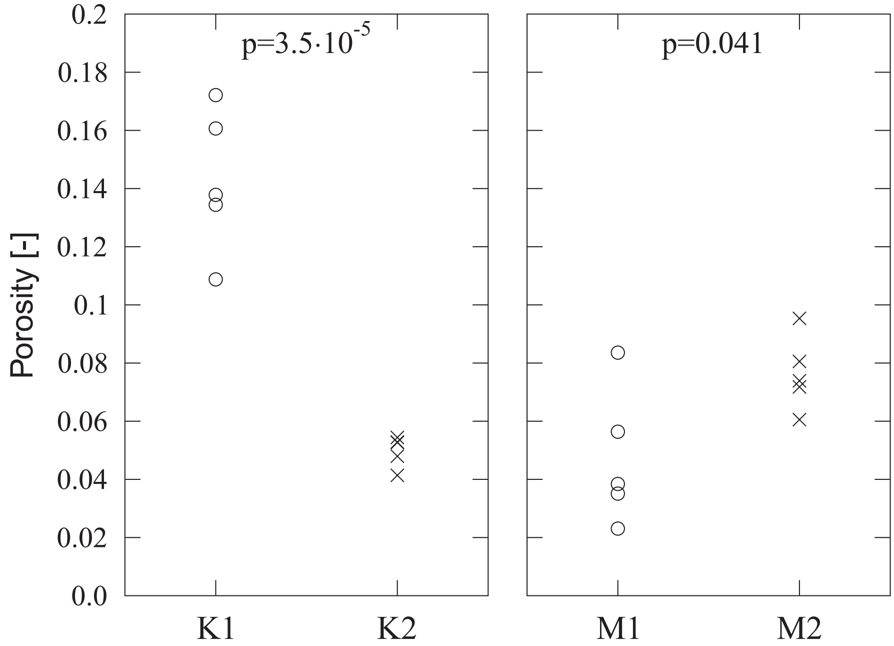


**FIGURE 5** X-ray visible porosities of all imaged samples shown for the four sampling areas (K1, K2, M1, M2). Statistical comparisons were done separately for both study locations and resulting *p*-values are shown in corresponding figure panels.

**TABLE 3** Porosity results from X-ray tomography.

| Pore size class [μm] | Mean porosity | | | | | |
|---|---|---|---|---|---|---|
| | K1 | K2 | *p*-Value | M1 | M2 | *p*-Value |
| <200 | 0.020 | 0.006 | $\mathbf{2.73 \times 10^{-6}}$ | 0.007 | 0.007 | .682 |
| 200–400 | 0.034 | 0.010 | $\mathbf{3.07 \times 10^{-8}}$ | 0.011 | 0.011 | .951 |
| 400–600 | 0.023 | 0.008 | $\mathbf{3.52 \times 10^{-6}}$ | 0.007 | 0.008 | .501 |
| 600–1000 | 0.025 | 0.010 | $\mathbf{2.66 \times 10^{-4}}$ | 0.008 | 0.010 | .498 |
| 1000–1500 | 0.019 | 0.009 | $\mathbf{2.45 \times 10^{-3}}$ | 0.006 | 0.008 | .316 |
| 1500–2000 | 0.012 | 0.004 | $\mathbf{6.14 \times 10^{-3}}$ | 0.004 | 0.007 | .128 |
| >2000 | 0.010 | 0.002 | .134 | 0.005 | 0.025 | .057 |

*Note*: The mean porosities for different sampling areas are given in different pore size classes. Statistical comparisons were performed between the two management practices within locations. Statistically significant differences are shown as bolded.

simulated hydraulic conductivities such that hydraulic conductivity was over an order of magnitude higher at long-term grassland in comparison to arable no-till soil. At Mustiala sites M1 and M2 no statistically significant difference ($p = .32$) was detected. At both study locations, within-site variation was greater at cultivated sites than at long-term grassland. Finally, in Figure 8, we relate the critical pore diameter with the simulated hydraulic conductivity. The simulated hydraulic conductivities were found to relate to the critical pore diameter with a power law dependence $K_s \propto D_c^{1.76}$.

## 4 | DISCUSSION

Our initial study hypothesis was that long-term grassland positively influences the soil structure of boreal high-clay soils. At Kotkanoja sites, where grassland was compared with soil that had been under no-till management and annual crop production for a long time, differences in macroporosity and hydraulic conductivity between the two contrasting managements were clear. These soil properties were less distinct in the grassland and cereal–grass crop rotation managements at Mustiala and the values of porosity-related quantities were higher in the cultivated soil than in the long-term grassland. All structural quantities determined for the studied soils showed coherent results, even though there were differences in the statistical significance between different properties. At Kotkanoja, the long-term grassland had higher values in comparison with the arable no-till soil. In both areas, mechanical disturbance on the soil had been minimal due to minimal tillage which suggests that the influence of grassland had been positive on the formation of macroporosity. There are concerns that reduced tillage may increase the risk of soil consolidation and compaction due to reduced

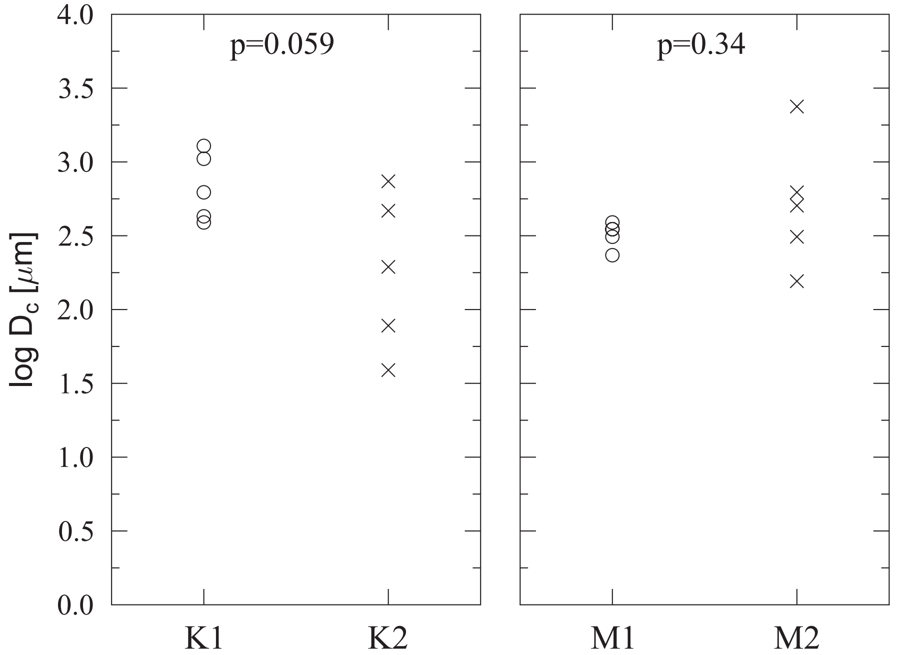


**FIGURE 6** Critical pore diameters determined for all imaged samples shown for the four sampling areas (K1, K2, M1, M2). Statistical comparisons were done separately for both study locations and resulting *p*-values are shown in corresponding figure panels.

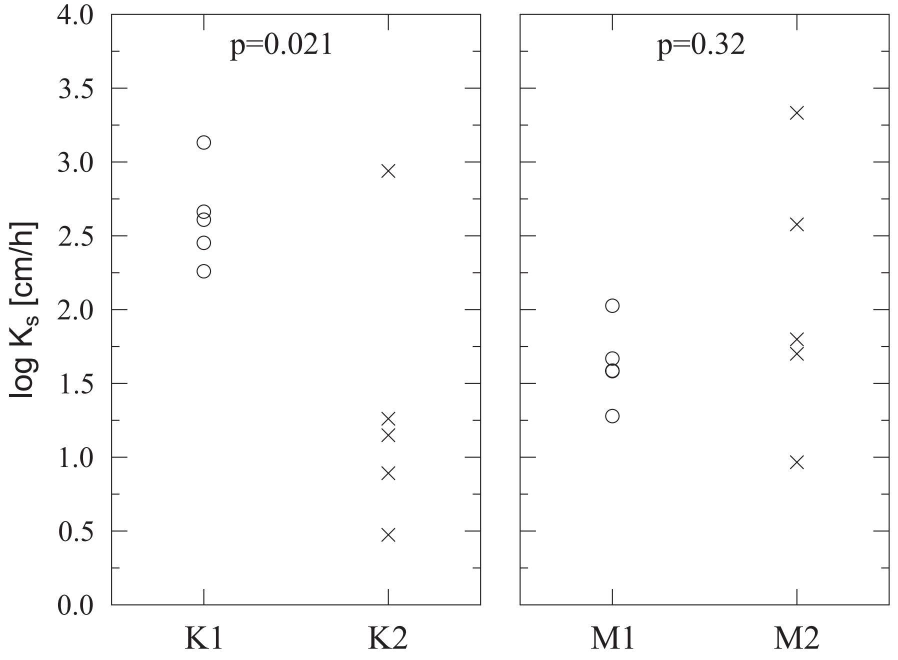


**FIGURE 7** Saturated hydraulic conductivities derived from the simulated flow fields in the imaged macropore systems for all samples from the four sampling areas (K1, K2, M1, M2). Statistical comparisons were done separately for both study locations and resulting *p*-values are shown in corresponding figure panels.

mechanical disturbance (Blanco-Canqui & Ruis, 2018; Guan et al., 2015). At Mustiala, the differences between the two soil managements were lesser, which indicates that the inclusion of tillage and longer-term perennial grass phases in the crop rotation had positive impacts on soil macroporosity. However, the impact of tillage is only directed to topsoil and the effect is likely lost or reversed below the plough layer due to direct wheeling on subsoil during in-furrow ploughing, although subsoil was not studied here. It would also be interesting to consider how much inclusion of, e.g., cover crops or deep-rooted plants in no-till management could enhance soil macroporosity. For example, a recent review concluded that the combination of cover crops with no-till improved water infiltration more than when with tilled soils (Blanco-Canqui & Ruis, 2020), which suggests that these approaches could be beneficial also in the studied soil type to reduce the disadvantages of no-till management on soil structure.

While at both locations the two managements were sampled from neighbouring fields and the distance between the sampling areas was small, soil characterizations showed some differences in texture and C contents

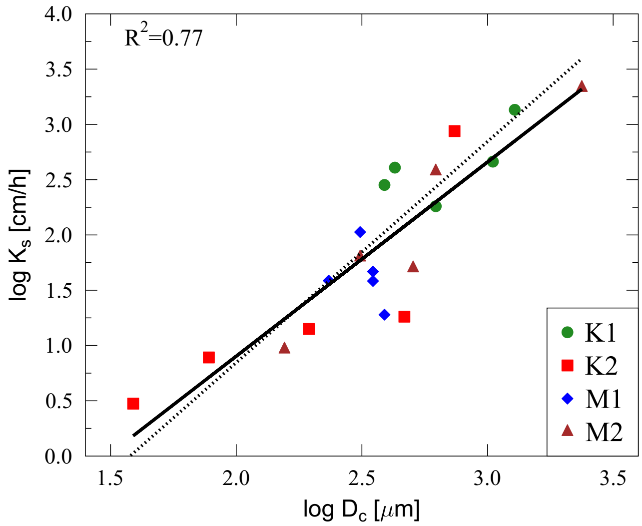


**FIGURE 8** Simulated hydraulic conductivity as a function of critical pore diameter on log–log scale. Different sampling sites are denoted with different symbols and colours. The solid line is a linear fit to all data points which has a slope of 1.76 ($R^2$ = 0.77). For comparison, a line with slope 2 (percolation theory) is also shown as a dotted line.

between the sites. At both locations, the higher C content at grassland sites can be understood based on the long-lasting contrasting management practices. Perennial vegetation is known to be efficient in accumulating soil C due to high and persistent root-derived C input (Anderson-Teixeira et al., 2013; Rasse et al., 2005). The slightly deviating texture between the two study areas at both locations suggests that all observed differences do not necessarily solely result from differences in management practices. Recently, Soinne et al. (2023) studied the impacts of C and clay contents on the structural properties of Finnish high-clay soils and reported that clay correlated negatively with macroporosity and hydraulic conductivity. Thus, the slightly higher clay contents at the grassland sites at both study locations could have a minor negative impact on the studied porosity-related soil properties. Regarding the differences between the two study locations, the Mustiala sites had higher C and clay contents than the Kotkanoja sites. Concerning the two similarly managed grassland sites K1 and M1, the structure-related quantities were systematically larger in K1. These differences can be understood based on texture differences between the sites as the Mustiala sites had higher clay contents than Kotkanoja (cf. Soinne et al., 2023). Other structure-forming factors may also affect the observed structural differences between the two grassland sites. For example, differences in soil fauna (Ma et al., 2021), field traffic (Keller et al., 2021) or drainage (Shipitalo et al., 2004) can also be responsible for the observed differences. The present measurements do not allow further speculation about their role, whereby our comparisons were mainly made between the managements within the study locations.

Water retention measurements and X-ray tomography probed partly different pore size regimes. However, when comparing the regime joint for both methods the results were consistent even though not fully identical. For example, considering macroporosity in pores exceeding 200 μm in diameter, a greater difference between the two managements at both study locations was attained by X-ray tomography than from the water retention curves. It is unlikely that full similarity between the two used methods could be obtained as by imaging pore size distribution is determined directly from the imaged pore system, whereas water retention measurement relies on an indirect approach through the capillary bundle model (Bachmann & van der Ploeg, 2002). The total porosities and macroporosities derived from water retention measurements and imaging were in line with previous results determined for similar boreal clay soils. For example, Turtola et al. (2007) determined macroporosities (>300 μm) for tilled soil at the Kotkanoja field and their reported values ranged between 1.2% and 6.8%. Rasa et al. (2012), in turn, determined the total porosities of vegetated buffer zones in the same region and similar soil type to our study sites and their reported values were between 58% and 65%.

To evaluate the connection between soil structure and hydraulic properties, the imaged soil macropore systems were used as simulation geometries in pore-scale flow simulation. The comparison between arable no-till soil and long-term grassland resulted in statistically significant differences between these managements similar to those observed with water-retention measurements and structural analyses by imaging. On the contrary, the comparison between cultivated crop rotation and long-term grassland did not lead to a clear deviation between the managements. It is known that porosity alone does not define the soil hydraulic properties, but other pore space characteristics such as pore continuity and pore size distribution can also have a significant effect (e.g., Dörner & Horn, 2006). Especially, the critical pore diameter (the diameter of the largest sphere that can pass through the pore system in the vertical direction) is an important structural parameter determining the hydraulic conductivity of soils as it represents the smallest bottleneck that resists the flow (Ghanbarian et al., 2017; Koestel et al., 2018; Schlüter et al., 2020; Soinne et al., 2023). Percolation theory links the saturated hydraulic conductivity to critical pore diameter with a power law with exponent 2 (Katz & Thompson, 1986), which highlights the effect of a single feature of the soil macropore system on the obtained hydraulic conductivity. Therefore, differences in hydraulic conductivity within and between the managements appear on the order-of-magnitude scale in contrast with the structural attributes. Due to differences in pore size distribution, macroporosity has been found to have a large effect on the hydraulic conductivity of clay soils as compared to coarse-textured soils (Jarvis et al., 2013) and our results show that soil management practices promoting the formation of macroporosity can have a significant impact on the hydraulic conductivity of clay soils. Our samples showed a power-law dependence with an exponent of 1.76, but as shown in Figure 8, the difference between this behaviour and prediction by percolation theory is small as compared with the variance in the data. Recently Schlüter et al. (2020) studied the effects of tillage practices on hydraulic conductivity in a long-term field experiment with silt loam texture. They used finite-volume simulations on pore systems segmented from X-ray tomography images and observed that critical pore diameter predicted very well the simulated hydraulic conductivity for samples from no-till soil but much worse for samples from conventionally tilled soils. Our dataset did not contain enough samples for each studied management to make a similar analysis reasonable.

Several studies have focused on structural differences between no-till and conventionally tilled soils, but less is known about differences between long-term grasslands and no-till soils. In our work, we compared the structure of two management practices, annual cropping under no-till and cereal-grass crop rotation under conventional tillage, both of which have been considered to be beneficial for soil structure stability as compared with conventionally tilled cereal monoculture (Loaiza Puerta et al., 2018; Mondal & Chakraborty, 2022). However, no-till management is also known to lead to increasing bulk density (Moraru & Rusu, 2013; Schlüter et al., 2020). In the no-till site considered in the present study, there had been a one-time ploughing event in the field 3 years before the sampling. Apart from that event, the field had not been ploughed for 30 years. According to the review by Blanco-Canqui and Ruis (2018), single tillage events appear to have only a small or negligible influence on the properties of no-till soil, even in the case of inversion tillage.

While soil management is known to impact soil structural properties (Bronick & Lal, 2005; Pagliai et al., 2004; Skaalsveen et al., 2019), it is challenging to obtain general information about the direct effects of management as several additional interrelated factors influence the structure of soil as well. These factors include for example soil type and climatic conditions but also study setup and especially the sampling time due to temporal variation of soil structural quantities especially in tilled soils where consolidation occurring during the growing season may affect the results (Keskinen et al., 2019; Sandin et al., 2017). Therefore, it is perhaps not surprising that results for the impacts of soil management reported in the literature are partly controversial (Blanco-Canqui & Ruis, 2018).

While the structural differences between grassland and tilled soil can be directed to the disruptive effects of tillage operations, our results show that grass management has positive impacts also when compared with soil under no-till management. Furthermore, our results from the comparison between long-term grassland and crop rotation suggest that tillage done a couple of times during the ca. 5-year rotation did not have a negative impact on soil pore structure. According to Watts and Dexter (1997), soils with low C content are more sensitive to mechanical disturbance than high C soils. This suggests that the relatively high C content in M2 soil under crop rotation could have protected soil structure from the destructive effect of tillage. Instead, occasional tillage together with longer grass periods appeared to increase the porosity. Considering previous research focusing on management effects on structure in comparable climatic conditions, Jarvis et al. (2017) studied the effects of grass leys on soil structure and considered four different long-term crop rotations with varying numbers of grass years included in a six-year rotation. They imaged soil samples with 65 μm resolution but found no treatment effects on the imaged pore space and thus concluded that the effects of crop rotation were limited to porosity smaller than imaging resolution. Hellner et al. (2018), in turn, investigated tillage effects on soil macropore structures and considered four different treatments, i.e., conventional tillage, conventional tillage and liming, reduced tillage and green fallow. They could not find any significant difference between the tillage treatments. However, the fallow treatment had more continuous macropore characteristics compared with conventional and reduced tillage.

Our results show that soil management can significantly affect the soil structural properties which was especially evident when comparing the arable no-till soil with long-term grassland. Large within-treatment variation is common in soil structural studies, which may hide the treatment effects from analyses (Hellner et al., 2018; Houston et al., 2017; Sandin et al., 2017). In our results, the within-field variation was greater in soil under arable no-till and conventionally tilled crop rotation as compared with the long-term grasslands. Since our results show significant differences in soil structure between treatments despite the reasonably small number of replicate samples, it can be inferred that altered soil management practices can lead to reasonable changes in soil structural properties of boreal clay soils. Further research is needed to quantify the effects of a wider range of management practices and soil types.

## 5 | CONCLUSION

We considered the structural properties of boreal clay soils through water retention measurements and 3D imaging with X-ray microtomography. The impacts of different soil management practices on the structure were quantified and the results showed that soil management can lead to considerable differences in soil macropore structure. Significant differences were observed between long-term grasslands and arable no-till soil such that all studied attributes indicated greater macroporosity in grassland soil. The differences were much smaller in another study site where long-term grassland was compared with soil under conventional tillage with crop rotation containing perennial phases. Our results show that soil management impacts the macropore structure of boreal clay soil and that no-till and periodic tillage combined with partial perenniality have clearly different effects on the soil structure as compared with long-term grassland.

### ACKNOWLEDGEMENTS

The work was part of the HiiletIn project funded by the Ministry of Agriculture and Forestry of Finland through the Catch the Carbon research and innovation programme. CSC – IT Center for Science is acknowledged for computing time through project #2005253.

### DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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**How to cite this article:** Hyväluoma, J., Niemi, P., Kinnunen, S., Brobbey, K., Miettinen, A., Keskinen, R., & Soinne, H. (2024). Comparing structural soil properties of boreal clay fields under contrasting soil management. *Soil Use and Management*, *40*, e13040. https://doi.org/10.1111/sum.13040