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Karin Muller, Sheela Katuwal, Iain M. Young, Malcolm Mcleod, Per Moldrup, et al.. Characterising and linking X-ray CT derived macroporosity parameters to infiltration in soils with contrasting structures. *Geoderma*, 2018, 313, pp.82-91. <10.1016/j.geoderma.2017.10.020>. <hal-02047865>

HAL Id: hal-02047865

<https://hal.science/hal-02047865v1>

Submitted on 25 Feb 2019

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HAL Authorization

Pre-print; published in Geoderma as Müller K, Katuwal S, Young I, McLeod M, Moldrup P, de Jonge LW, Clothier B 2018. Characterising and linking X-ray CT derived macroporosity parameters to infiltration in soils with contrasting structures. Geoderma 313: 82-91.
<https://doi.org/10.1016/j.geoderma.2017.10.020>

**Characterising and linking X-ray CT derived macroporosity parameters to infiltration in
soils with contrasting structures**

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Abstract

Soils deliver the regulating ecosystem services of water infiltration and distribution, which can be controlled by macropores. Parameterizing macropore hydraulic properties is challenging due to the lack of direct measurement methods. With tension-disc infiltrometry hydraulic properties near saturation can be measured. Differentiating between hydrologically active and non-active pores, at a given water potential, indirectly assesses macropore continuity. Water flow through macropores is controlled by macropore size distribution, tortuosity, and connectivity, which can be directly derived by X-ray computed tomography (CT). Our objective was to parameterize macropore hydraulic properties based on the imaged macropore network of three horizons of an Andosol and a Gleysol. Hydraulic conductivity K_{unsat} was derived from infiltration measurements. Soil cores from the infiltration areas were scanned with X-ray CT. K_{unsat} was significantly higher in the Andosol than in the Gleysol at all water potentials, and decreased significantly with depth in both soils. The *in situ* measurements guided the definition of new macroporosity parameters from the X-ray CT reconstructions. For the Andosol, K_{unsat} was best predicted using the imaged-limited macroporosity. A low total macroporosity, coupled with a high macropore density, indicated the abundance of smaller macropores, leading to homogeneous matrix flux. Imaged macropores were not well connected. In contrast, the Gleysol had a bi-modal macropore system with few very-large, but well-connected macropores. K_{unsat} was best predicted using the imaged macroporosity consisting only of macropores with diameters between 0.75 and 3 mm. Our research demonstrates that linking traditional soil physical measurements with soil-visualization techniques has a huge potential to improve parameterizing macropore hydraulic properties. The relevance of the relationships found in this study for larger scales and other

soil types still needs to be tested, for example by a multi-scale investigation including a much wider range of different soils.

Keywords: Soil structure; Pore network; Image analysis; Hydraulic parameters; Tension disc infiltrometry.

1. Introduction

Macropores are pores with a diameter larger than 0.3 mm (Jarvis, 2007) which are arranged in a complex and connected network intermixed with unconnected matrix elements. They are made of earthworm channels, fissures, channels from decaying roots, and inter-aggregate voids. The importance of macropores as preferential pathways of water, air, and chemicals in the soil has long been recognized (Clothier et al., 2008; Jarvis et al., 2007). Some 30 years ago, Watson and Luxmore (1986) reported that water flux through macropores can be as high as 70% of the total flux and thus are the governing process, even though macropores form only a small fraction of the total soil volume. Despite intensive research over many decades, macropores still constitute a major challenge for modelling flow and transport processes due to their high spatio-temporal variability (Jury et al., 2011). In addition, there is a lack of methods to parameterise hydraulic properties of macropores in order to account adequately for their contribution to fluxes.

Recent advances in 3-D X-ray computed tomography (CT) and image analysis technologies, as well as the increasing availability of X-ray CT, have rekindled the interest in modelling preferential flow processes at the pore scale (Jarvis et al., 2016). The X-ray CT has been applied to characterize *inter alia*, pore networks, biomass distribution, root architectures, bulk density, organic matter distribution and transport parameters (Hamamoto et al., 2016; Naveed et al., 2013; Nunan et al., 2006; Pierret et al., 2002; Tracy et al., 2010; Wang et al., 2012). In fact, a number of reviews have been published on the successful application and the potential of applying X-ray CT in soil science (Cnudde et al., 2006; Helliwell et al., 2013; Schlüter et al., 2014; Wildenschild et al., 2002). One reason for applying X-ray CT in soil science is to link the geometrical features analyzed, applying X-ray CT to soil functions such as water flow, gas exchange, and solute transport (Deurer et al., 2009; Katuwal et al., 2015; Larsbo et

al., 2014; Paradelo et al., 2016; Rabbi et al., 2016). The outcome of such a linkage could be that the prediction of properties and processes that cannot be easily measured and observed might be improved and facilitated with structural parameters (Vogel et al., 2010). Vogel et al. (2010) concluded that there are basically two alternative approaches. The first method is to use the structural parameters derived from X-ray CT and use them directly as realistic boundary conditions for the simulation of soil functions (Naveed et al., 2016; Vogel et al., 2005). A problem with this approach is the large computational power required which dictates the scale of the simulations. Scheibe et al. (2015) discussed the problem associated with pore-scale modelling at a smaller scale than the representative elementary volume (REV) of the macroscopic behaviour of the processes. They successfully demonstrated pore-scale modelling at the decimetre scale integrating structural parameters measured with X-ray CT. The aim of the second approach is to establish a quantitative, statistically based relationship between measured structural parameters and hydraulic properties (Samouëlian et al., 2007). The direct quantification, reconstruction, and visualization of 3-D macropore networks allow correlating macropore characteristics to the water and solute transport, as well as gas exchanges in soils. Here we have applied this indirect approach to link structural parameters to the hydraulic parameters of macropores derived with tension-disc infiltrometry.

Tension-disc infiltrometry enables measuring near-saturated hydraulic properties *in situ* (Reynolds and Elrick, 2005). Soil macropores are only hydraulically active in this water pressure head range close to saturation (Ankeny et al., 1990). Macroporosity, the number of macropores, pore length, their pore size distribution, and also their 3-D geometry and topology including continuity, tortuosity, and connectivity are important characteristics impacting on water and solute flow through macropores (Bastardie et al., 2005; Luo et al., 2010a). However, these 3-D characteristics are difficult to quantify with traditional

methodologies such as the analysis of thin sections (Prado et al., 2007). While tension-disc infiltrometry allows to differentiate between hydrologically active and non-active pores at a given tension, but the continuity of macropores can only indirectly derived from these measurements.

To link soil structure and function, relevant soil macropore features need to be identified and quantified. Our objective was to investigate the role of macropore topological features on the hydraulic properties derived with *in situ* infiltration measurements of soils with different parent materials and textures.

2. Material and methods

2.1. Soils studied

The sites represent two soil orders with contrasting soil texture and structure that were known for differing filtering behavior for bacteria and viruses (Aislabie et al., 2001; McLeod et al., 2001). The first soil was classified as a Typic Orthic Allophanic Soil ((Hewitt, 1998); Andosol (IUSS Working Group WRB, 2006); Typic Hapludand (US)) and the second soil was classified as a Typic Orthic Gley Soil ((Hewitt, 1998); Gleysol (IUSS Working Group WRB, 2006); Typic Endoaquept (US)). Both sites were under permanent pasture and grazed by cattle and are located in Waikato, North Island, New Zealand.

2.2. Tension-disc infiltration measurements

In March 2011, we measured infiltration rates at four different tension heads ($h = -10, -20, -40, -70$ mm) over three depths of both soils. The depths were chosen to represent three distinct soil genetic horizons: the topsoil (Ah), the upper (Bw1 or Bg1), and lower subsoil (Bw2 or Bg2) layers of the two soils (Table 1). All measurements were conducted in triplicate with

a tension-disc infiltrometer with a 100-mm radius base. To ensure good contact between the disc and the topsoil, the grass was cut to the ground, and a thin layer of acid-washed sand was evenly spread across the soil surface. Flow measurements were stopped when steady-state flow was reached, as defined in Deurer et al. (2008). The theoretical basis for using tension infiltrometry to derive hydraulic properties has been detailed elsewhere (e.g., Ankeny et al., 1991; Perroux and White, 1988; Reynolds and Elrick, 1991; Reynolds and Elrick, 2005; Vandervaere et al., 2000). We derived the unsaturated hydraulic conductivity at several tensions, following Reynolds and Elrick (2005) who adapted the theory of infiltration from a shallow circular pond (Wooding, 1968).

Applying the capillary-rise equation allows calculating the maximum water filled pore size r (m) at a specific height h (m):

$$r = 2\sigma \cos(\alpha) / \rho g h \quad (1)$$

where σ is the surface tension of water (N m^{-1}), α the contact angle between water and the pore wall, which is assumed to be zero, ρ the specific density of water (kg m^{-3}), and g the acceleration due to gravity (g m^{-2}). According to the capillary rise equation, infiltration at tension heads of -10 mm, -20 mm, -40 mm and -70 mm will exclude pores from flow processes, which have equivalent pore radii greater than 1.48, 0.74, 0.37 and 0.21 mm, respectively.

2.3. Basic soil properties

Intact soil-cores for determining bulk density and bulk soil for measuring texture and organic carbon contents were collected close to all measurement points. The bulk soil was air dried, sieved to 2 mm prior to further analysis. The texture was determined by a combined sieve and hydrometer method (Gee and Or, 2002). Total soil organic carbon (SOC) was analysed by

the Dumas method for %C using a 'Leco TruMac' instrument (Blakemore et al., 1987). Bulk density was determined following standard procedures on intact soil cores of 100 cm³, which were also used for measuring the total porosity and macroporosity at $h = -10$ mm (Blakemore et al., 1987).

2.4. X-ray computed tomography

We extracted undisturbed soil cores (40 mm diameter and 50 mm length) with PVC-sleeves from the centre of each of the infiltration areas immediately after completion of the experiments to relate the macropore architecture — as determined by X-ray CT analysis — to the results of the tension infiltrometry. The soil cores were stored at 4°C until analysis. The scanning of the soil cores in the PVC sleeves was performed with the 160 kV X-ray source at 150 μ A. In each scan 1250 angular projections images were collected and each radiograph was averaged over 32 frames. Ring artefacts were minimized during data acquisition and a 0.5 mm copper filter was used to reduce beam hardening. The software package CT-Pro v.1.0 (Metris X-tek Systems Ltd., Hertfordshire, United Kingdom), which employs the filtered back-projection algorithm for CT reconstruction, was used to obtain the three-dimensional maps of attenuation coefficients from the two-dimensional angular projections. The three-dimensional images of attenuation coefficients with the isotropic voxel size of 0.0734 mm were then translated into a continuous stack of two-dimensional 16-bit TIFF images using the software VGStudio MAX 1.2.1 (Volume Graphics GmbH, Heidelberg, Germany). Each image slice of the stack had the thickness of 73.4 μ m and an in-plane resolution of 0.0734 x 0.0734 mm.

The images were analysed using ImageJ v1.51p software (Schneider et al., 2012). The images were pre-processed to adjust the brightness and contrast using enhance contrast command

in ImageJ and cropped to remove the cylinder wall. Segmentation of the images was achieved by combining two different methods. First a local threshold method of Sauvola and Pietikäinen (2000) was applied. The local segmentation algorithm calculates a threshold value for each pixel $T(x,y)$ based on the mean $m(x,y)$ and standard deviation $s(x,y)$ of the intensity values of pixels within a specified neighbourhood w about the pixel as:

$$T(x, y) = m(x, y) \left[1 + k \left(\frac{s(x, y)}{R} - 1 \right) \right] \quad (2)$$

where R is the dynamic range of standard deviation and k is a constant with values between 0.2 and 0.5 (Phansalkar et al., 2011). The best segmentation results were obtained with $w = 5$, $R = 200$ and by adjusting the value of the parameter k between 0.2 – 0.3 for the different soils. The algorithm generally worked well for segmenting the air-filled pore spaces. However, for large pores the boundaries of the pores were well delineated but pixels close to the centre of the pores were not correctly segmented. To eliminate this problem, the pre-processed gray-scale images were segmented again using an image histogram based algorithm. The minimum method in ImageJ was applied, which iteratively smoothes the image histogram until two clear peaks are obtained and then chooses the local minima between these two peaks as the threshold. The segmentation results obtained from the two methods were combined to obtain the final segmentation results. As a post-processing step, features with diameter less than twice the image resolution (i.e. 0.147 mm) were removed from the segmented images, thus the analysed pore properties refer to pores greater than or equal to 0.147 mm in diameter. These are also referred to as macropores in the study, unless otherwise stated.

Using the post-processed segmented images the macroporosity density, the number of macropores in a unit soil volume (MPD , number mm^{-3}), total macroporosity (TMP , $\text{mm}^3 \text{mm}^{-3}$)

³), volume of macropores connected from the top to the bottom per unit soil volume (*CTMP*, mm³ mm⁻³), and the macroporosity distribution along the soil depth were determined. The minimum value of macroporosity along the soil depth at depth interval corresponding to one voxel depth was determined and referred to as limiting total macroporosity. The connectivity of the macropores and their average diameter were determined using Particle Analyser plugin within the BoneJ plugin (Doubé et al., 2010) in ImageJ. The connectivity of macropores in a soil core was calculated by obtaining the Euler characteristics of the pore networks using BoneJ plugin and quantified as the Genus density, i.e. the total number of redundant connections per unit soil volume (Vogel et al., 2010). The mean diameter of macropores (*MPDIA*) in mm in a soil core was calculated as the volume weighted average of the average macropore thickness of each macropore within a soil column as:

$$MPDIA = \sum_{i=1}^n V_i d_i / \sum_{i=1}^n V_i \quad (3)$$

where n is the number of macropores, V_i is the volume of i^{th} macropore (mm³), and d_i its average thickness/diameter (mm) determined using the algorithm by Dougherty and Kunzelmann (2007) and implemented within the BoneJ plugin in ImageJ. This algorithm is based on determining the diameter of the largest sphere which completely fits within the pore structure at each point along its centreline. The average thickness of a single pore structure within a soil column is then calculated as the volume weighted average of the largest spheres at each point along the centreline of the pore structure. The vertical tortuosity of the macropores was determined as an average value of the ratio of the actual length of a macropore to the vertical distance between the ends of the macropore. This was achieved by obtaining the skeletons of the macropores, namely the centreline of the macropores using Skeletonize 3D and Analyze Skeletons plugin within BoneJ. The effect of uneven surface of the

macropore wall on the quantification of vertical tortuosity was eliminated by removing features less or equal to 0.147 mm from the skeletons of the macropores.

Linking the infiltration experiments with the flow-active pores was further facilitated by dividing the macropores into different size classes corresponding to the water potentials used in the infiltration experiments. The plugin 'Shape Filter' (Wagner and Lipinski, 2013) in ImageJ was used for filtering macropores based on the diameter (minimum Feret's diameter) into different size classes (< 0.43 mm, 0.43 – 3 mm, 0.75 – 3 mm and 1.5 – 3 mm).

2.5. Statistical analysis

A general analysis of variance with two fixed effects (soil type, horizon) was used to determine if the mean values of the macropore properties of the soils were significantly different. We interpreted the differences between averages of macroporosity characteristics and hydraulic properties to be significant if they were larger than their respective least significant differences (LSD) at the 95% confidence level ($P \leq 0.05$). Pairwise Multiple Comparison Procedures (Holm-Sidak method) was used as a *post hoc* test. Parameters that did not follow the normal distribution were log transformed prior to the analysis. Additionally, Pearson correlation and linear regression analyses were performed. All statistical tests were conducted at the 95% confidence level using the software Sigma Plot 12.05 (Systat Software Inc.).

3. Results and discussion

3.1. General description of soils

Selected soil properties for the two soils are provided in Table 1. The Andosol had greater silt and sand contents than the Gleysol, which was characterized as a clay loam. The Andosol's

texture was described as a gritty silt loam. The topsoil structure of the Gleysol was strongly developed and medium or coarse polyhedral. The subsoil structure was coarse prismatic with a low porosity within the prism structure. The prismatic structures in the subsoil showed large cracks which were often coated with translocated organic matter, silt, or clay (McLeod et al., 2008). In contrast, the Andosol had a weakly developed fine polyhedral structure with single grains and a high porosity. Both soils had clay contents above 20% and a clay to organic carbon ratio larger than 3 in all horizons (Table 1), and, hence, were expected to exhibit a potential for preferential flow (Koestel and Jorda, 2014). Bulk density of the Andosol did not change with depth, while the bulk density of the Gleysol increased with depth in line with increasing clay contents and decreasing organic carbon contents (Table 1).

3.2. Visualization and quantification of macropore networks

Macropore networks were reconstructed using the binary images acquired with X-ray CT. The six macropore networks shown in Figure 1 are representative of the three horizons of both soils. In total 18 soil cores were scanned. The red colour represents macropores larger than 0.147 mm, the resolution of the X-ray CT images. The macroporosity was based on pores with a diameter larger than 0.147 mm and is referred to as total macroporosity ($TMP_{(> 0.147)}$).

It has to be noted that the macropore networks in our soils developed under permanent grassland and thus have not been disturbed through cultivation for at least a decade. The macropore networks were distinctly different for the two soils. The average macropore diameter was 0.244 ± 0.008 mm in the Andosol as compared to 0.315 ± 0.015 mm in the Gleysol (Table 2). In particular, in the lower subsoil of the Andosol (Figure 1, bottom), the macropores were of small diameter and tubular. Relatively narrow and round macropores are typical for macropores formed by roots, which decrease in size with depth (Luo et al., 2010b).

In the Gleysol, the macropores were shaped differently, as they were more tortuous and more randomly organized. They might have been formed in wetting and drying cycles through the swelling and shrinkage of the abundant clay minerals in the Gleysol. Significant ($P \leq 0.05$) differences were observed between the average tortuosity values among both horizons and soils. Maximum and minimum tortuosity was 2.585 and 2.84 for the Andosol and 2.986 and 3.5 for the Gleysol, respectively. The average tortuosity for each horizon and soil type (Table 2) was much higher than those reported in the literature for arable soils (Katuwal et al., 2015) and grassland soils (Peth et al., 2008) reflecting the high biological activity of the two permanent grassland soils included in our study, which have not been disturbed through cultivation for at least a decade.

The macropore density was significantly ($P \leq 0.001$) higher in the Andosol than in the Gleysol. Moreover, it tended to increase ($P = 0.05$) with depth (Table 2). The differences between the average macropore diameters of the two soils were significant ($P \leq 0.001$). The average mean macropore diameter of the two soils decreased significantly ($P \leq 0.001$) with depth (Table 2). The average mean macropore diameter of the Ah-, Bg1-, and Bg2-horizons was $0.378 (\pm 0.013)$ mm, $0.278 (\pm 0.005)$ mm, and $0.288 (\pm 0.002)$ mm, respectively. The average mean macropore diameter of the three horizons Ah, Bw1, and Bw2 of the Andosol were $0.272 (\pm 0.004)$ mm, $0.237 (\pm 0.002)$ mm, and $0.222 (\pm 0.004)$ mm, respectively (Table 2).

The total macroporosity determined for the three horizons of the two soils ranged between 0.192 and 0.029 mm³ mm⁻³, with an average of 0.06 mm³ mm⁻³ (Table 2). These are in the range of those reported for soils under permanent pasture in the literature. For example, in the top 0.1 m of silt loam soils under apple orchards in New Zealand, Deurer et al. (2009) found an average macroporosity of 0.025 and 0.075 mm³ mm⁻³ under integrated and organic orchard management, respectively. Luo et al. (2010b) analysed CT-images of cores taken from

the top 0.35 m of a fine-textured silt loam soil and a fine-loamy soil and reported average macroporosities of 0.061 and 0.031 mm³ mm⁻³, respectively. They defined macropores as pores with a diameter greater than 0.75 mm. Perret et al. (1999) determined macroporosities between 0.022 and 0.038 mm³ mm⁻³ for 800 mm long undisturbed soil cores extracted from a sandy loam soil under grassed field borders. In our study, the total macroporosity of the Gleysol was 0.141 ± 0.027 mm³ mm⁻³ and was significantly ($P \leq 0.001$) larger than in the Andosol, which had an average total macroporosity of 0.065 ± 0.004 mm³ mm⁻³; it varied greatly with depth, and decreased significantly ($P \leq 0.001$) from the topsoil to the two subsoil horizons. In both soils, the macroporosities of the two subsoil horizons were comparable. Decreasing macroporosities with depth have been observed in previous studies (Katuwal et al., 2015; Naveed et al., 2013).

The connected total macroporosity ($CTMP_{(> 0.147)}$), which only considers macropores that are connected from the top to the bottom of a core ranged from 0.185 to 0.005 mm³ mm⁻³ with an average of 0.049 mm³ mm⁻³. The total connected macroporosity of the Andosol (0.022 ± 0.007 mm³ mm⁻³) was significantly ($P \leq 0.001$) smaller than in the Gleysol (0.075 ± 0.017 mm³ mm⁻³). Similar to the $TMP_{(> 0.147)}$ it decreased significantly ($P \leq 0.001$) from the topsoil to the subsoil. In the Andosol, the $CTMP_{(> 0.147)}$ contributed 74, 31 and 20% to the $TMP_{(> 0.147)}$ in the topsoil, upper, and lower subsoil, respectively, while in the three horizons of the Gleysol it exceeded 75% for all horizons ranging between 79 and 94% (Table 2). The largest number of connected macropores was five in the upper subsoil of the Andosol for all horizons. Generally only 1 or 2 macropores were found that connected the top to the bottom of a core. This indicates a strong connectivity of the macropores in both the horizontal and vertical directions. In addition, genus density was also calculated to account for the connectivity of the pores. It ranged from 0.309 to 2.276 mm⁻³ for the Gleysol and from 0.144 to 1.057 mm⁻³

for the Andosol, respectively, and the differences between soils and horizons were significant ($P \leq 0.05$). The higher connectivity of the macropores in the Gleysol than in the Andosol corroborates the findings of Luo et al. (2010) and Katuwal et al. (2015), who reported more connected macropore networks in soils with larger macroporosities.

3.3. Tension-disc infiltrometry

Results of the tension-disc infiltrometry are presented in Figure 2. The highest unsaturated hydraulic conductivity was measured in the Andosol at the water potential nearest to saturation $K_{unsat}(-10 \text{ mm})$ at $8.15 \pm 3.86 \text{ mm h}^{-1}$. The comparable average unsaturated hydraulic conductivity in the Gleysol was $6.6 \pm 2.68 \text{ mm h}^{-1}$, while the average unsaturated hydraulic conductivities were generally higher in the Andosol than in the Gleysol for all three horizons (Figure 2). The difference between the two soils was not significant ($P > 0.05$) for the water potential $h = -10 \text{ mm}$ ($K_{unsat}(-10 \text{ mm})$). Unsaturated hydraulic conductivities displayed a high spatial variability with coefficients of variation ranging between 1 and 113% for the Andosol and between 12 and 93% for the Gleysol, respectively. For the topsoil and upper subsoil of the Andosol, the highest variability was observed close to saturation, probably associated with high biological activities and the resulting biopores. Generally, the highest variability, however, was observed in the lower subsoil possibly. Shoji et al. (1993) reported greater unsaturated hydraulic conductivities in Andosols than other mineral soils in the water potential range of 0 to -100 mm. They attributed this to the higher 'ratio of the cross-sectional area for unsaturated flow to the total soil cross sectional area'.

In the water potential range from -70 to -10 mm, the unsaturated hydraulic conductivity increased by one order of magnitude in the topsoil of the Andosol and by two orders of magnitude in the topsoil of the Gleysol, respectively. A larger increase was expected for the

finer textured and structured clay in comparison with the coarser, single-grain, poorly structured silt loam (Jarvis and Messing, 1995). In the structured Gleysol, surface-vented macropores were of greater importance for unsaturated flow than in the Andosol. The hydraulic conductivities at different water potentials suggest at least a bimodal pore system for the topsoil of the Gleysol with one or two break-points dividing the pore systems between -20 and -40 mm. In contrast, a linear regression fitted the hydraulic conductivity — tension pairs ($R^2 = 0.98$) of the Andosol's topsoil — indicating a homogeneous pore distribution (Figure 2). In the subsoils, in particular in the lower subsoil of the Andosol, the unsaturated hydraulic conductivity was low and varied little with water potential (Figure 2).

The near-saturated hydraulic conductivity decreased with depth in both soils at the water potentials $K_{unsat}(-10 \text{ mm})$ and $K_{unsat}(-20 \text{ mm})$ (Figure 2). The hydraulic conductivities were significantly ($P < 0.05$) higher in the topsoil and the upper subsoil than in the lower subsoil at these two water potentials which is related to the higher clay content of the subsoil and the higher consolidation of the subsoil compared with the topsoil. At the water potentials $K_{unsat}(-70 \text{ mm})$ and $K_{unsat}(-40 \text{ mm})$, the unsaturated hydraulic conductivity of the upper subsoil was significantly ($P < 0.05$) higher than those in the topsoil and the lower subsoil. Generally, greater hydraulic conductivities can be attributed to better pore continuity.

3.4. Correlation analysis of macropore network characteristics

Significant strong correlations were found between most of the macropore characteristics assessed by CT-images (Table 3). The joint correlation analyses for the two soils required that the parameters macroporosity, mean macropore diameter, genus density and the hydraulic conductivities needed to be log transformed to fulfill the requirement of normal distributed data. The analysis showed that $\log(\text{macroporosity})$, $\log(\text{mean macropore diameter})$, and

connectivity (genus density) were positively correlated (Table 3), indicating that larger macroporosities were associated with a more-connected macropore network with on average larger macropores. Vertical tortuosity was the only structural parameter derived from X-ray CT that was not correlated with the other structural parameters analysed, with the exception of the macropore density.

The log-values of the unsaturated hydraulic conductivity determined at a water potential of -70 mm were highly correlated with all structural parameters, except the log values of connectivity. Soils with higher flow rates had a larger proportion of smaller pores (< 0.75 mm) than soils with low flow rates. In comparison, the log-values of the unsaturated hydraulic conductivity determined at a water potential of -10 mm diameter were only significantly ($P < 0.05$) correlated to tortuosity and the log values of connectivity, but not to the log values of total macroporosity (Table 3). In contrast, Larsbo et al. (2014) reported significant correlations between the X-ray CT macroporosity and $K_{unsat}(-10 \text{ mm})$, measured with tension-disc infiltrometer, but not with $K_{unsat}(-50 \text{ mm})$. They explained their findings by noting that the pores conducting at a water potential of -50 mm would have been mostly smaller than the resolution of their images (0.485 mm). The resolution of our images with 0.0734 mm was about 3-times higher than the maximum macropore diameter of pores active (0.430 mm) at a water potential of -10 mm. This resolution cannot explain the lack of correlation between total macroporosity and near-saturated hydraulic conductivities. Others have found significant positive correlations between saturated hydraulic conductivities and macroporosities (e.g., Luo et al., 2010b). The macroporosity determined at $h = -10 \text{ kPa}$ (Table 1) was not correlated to the total macroporosity assessed by X-ray CT ($P = 0.347$), indicating that different pore sizes dominated the different measures of macroporosities. This can be

explained by the fact that smaller macropores that are not captured by X-ray CT are integrated in this measure.

3.5. Relationship between X-ray computed tomography macroporosity and unsaturated conductivity

Figure 3 shows the relationships between unsaturated conductivity, derived from *in situ* tension-disc infiltrometer measurements, and different measures of macroporosity, derived from the X-ray CT images separately for the Andosol and the Gleysol. The macroporosities derived include the total macroporosity ($TMP_{(> 0.147)}$) and connected total macroporosity ($CTMP_{(> 0.147)}$). In a linear regression, 76 and 62% of the variability in the unsaturated hydraulic conductivity measured *in situ* at a tension of -10 mm were explained in all horizons of the Gleysol and the Andosol with the total macroporosity ($TMP_{(> 0.147)}$), respectively (Figure 3a and b). The results were similar when $K_{unsat}(-10 \text{ mm})$ was regressed with the connected total macroporosity ($CTMP_{(> 0.147)}$) (Figures 3c and d). The results of the *in situ* infiltration measurements suggest a bimodal pore system for the Gleysol, with a break-point dividing the pore systems in all horizons somewhere around a pore diameter of 0.74 mm, equivalent to a water potential of -40 mm. At and below this water potential, infiltration rates dropped to insignificant rates (Figure 2). Considering this information from the field measurements, a new macroporosity, the macroporosity consisting only of macropores with diameters between 0.75 and 3 mm ($MP_{(3-0.75)}$) was extracted from the X-ray CT images. The new structural parameter $MP_{(3-0.75)}$ limits the total macroporosity to the pores, theoretically conducting flow in the respective water potential range -10 to -40 mm, and isolates the macropores that conducted the majority of the flux in the tension-disc infiltrometer measurements. About 78% of the variability in the unsaturated hydraulic conductivity for the

tension range between - 40 and -10 mm was explained in all horizons of the Gleysol with $MP_{(3-0.75)}$ (Figure 3e). In the next step, the macroporosity was further reduced by excluding all macropores that were not connected from the top to the bottom of the cores. So, only the active macropores are included in the new macroporosity parameter $CTMP_{(3-0.75)}$. The relationship between macroporosity and the unsaturated conductivity for the Gleysol was further improved. The resulting regression coefficient increased to 86% (Figure 3g). As expected from the results of the infiltration measurements with the Andosol, regressing the measured unsaturated conductivities with the same macroporosity parameters for the Andosol did not improve the results. In fact, the goodness of the fit of the linear regression decreased (Figures 3f and h), supporting the findings of the infiltration measurements, which predicted a homogeneous pore system for the Andosol (Figure 2).

The depth distributions of the total macroporosity ($TMP_{(> 0.147)}$), and the connected total macroporosity ($CTMP_{(> 0.147)}$), are shown in Figures 4a and 4c for the Gleysol, and in Figures 4b and 4d for the Andosol, respectively. The general patterns observed in the two soils were similar. Total macroporosity exhibited a high variability in the topsoils, but in both soils there was typically an increase of the total macroporosity from the soil surface to about 20 or 25 mm depth, followed by a gradual decrease of the total macroporosity. The low total macroporosity at the soil surface for the two soils was likely associated with compaction caused by grazing. The higher total macroporosity at 25 mm depth might be explained by earthworm activities and ramification by roots. In the upper subsoil of the two soils (Bw1 and Bg1), total macroporosity was generally less variable, and about half of the average total macroporosity determined in the topsoils. The total macroporosity further decreased with depth, and reached its minimum in the lower subsoil for both soils. The lower subsoil of the Andosol had the lowest average total macroporosity of all horizons. Over the 30 mm of each

of the two subsoil layers analyzed, $TMP_{(> 0.147)}$ remained more or less constant. A decline in macroporosity with depth has been observed by others (Ersahin et al., 2002) and been attributed to changes in structure and bulk density. The decrease in organic carbon contents in the subsoils would have further contributed to lower macroporosities at depth in our study. The connected total macroporosity of the Gleysol followed the trend of $TMP_{(> 0.147)}$, but for the Andosol the $CTMP_{(> 0.147)}$ was much lower in the two subsoils than the $TMP_{(> 0.147)}$.

The macroporosity of a soil is composed of clusters of highly connected pores of different diameters and isolated features. Not the entire macroporosity is conductive due to dead-end macropores, bottleneck situations, and restrictions in the pore diameters. Flow might be restricted for parts of the macroporosity because of changing pore widths, but also air inclusions might cut off parts of the macropore network from flux (Jarvis, 2007). This has been shown in previous studies applying X-ray CT while conducting solute transport experiments (Sammartino et al., 2015). In our study, the much lower connected total macroporosity of the Andosol clearly indicated that many of the macropores of the Andosol determined by X-ray CT were not conductive because they were not connected from the top to the bottom of a soil core (Figures 4c and d; Table 2). In contrast, most of the measured macroporosity of the Gleysol was connected and thus conductive. Therefore, regressing the limited macroporosity with the unsaturated hydraulic conductivity improved the relationship for the Andosol considerably while the relationship between limited macroporosity and unsaturated hydraulic conductivity was similar to previous relationships for the Gleysol (Figures 4e and f). The regression coefficients were 83 and 69% for the Gleysol and the Andosol, respectively. Larsbo et al. (2014) found that soil cores with smaller macroporosity determined by X-ray CT had smaller near-saturated conductivities. In contrast, in our study the Andosol, which had the smaller imaged macroporosity, had significantly higher near-saturated conductivities than

the Gleysol. The macropore network of the andosol was more homogeneous, with a significantly higher macropore density and significantly smaller average mean macropore diameter than those of the Gleysol. This suggests that for the Andosol, pores that are not visible at the resolution of the X-ray CT images, were important for unsaturated hydraulic conductivity.

4. Conclusions

Our linking of *in situ* measurements of unsaturated conductivities guided the definition of new macroporosity parameters from X-ray CT reconstructions of the two contrasting soils. Our measurements discerned different flow mechanisms for the two soils. A comparatively low total macroporosity, coupled with a high macropore density, indicated the abundance of many smaller macropores, which leads to homogeneous matrix flux in the Andosol. The relatively small macroporosity of this soil was not well connected. Thus, the near saturated hydraulic conductivity was best predicted for this soil using the imaged-limited macroporosity. In contrast, the Gleysol had a bi-modal macropore system with a few very large, but well-connected, macropores. This results in preferential flow. In this soil, the near-saturated hydraulic conductivity was best predicted using the imaged macroporosity consisting only of macropores with diameters between 0.75 and 3 mm, which were the conductive pores confirmed by the *in situ* measurements.

In a further perspective, the research presented here demonstrates that linking traditional soil physical measurements with rapidly evolving soil visualization techniques at the small scale is a powerful tool towards better parameterization of simulation models. This will lead to an improved understanding and quantification of essential ecosystem services of soils, such as the regulation of water and gas fluxes and contaminant filtering. More soil types need to

be analysed to draw firmer conclusions on the dependence between structural parameters and near-saturated hydraulic conductivity. It also needs to be confirmed that the relationships found in this study are relevant for larger scales. This could be achieved by a multi-scale investigation, which should also include a much wider range of different soils.

Acknowledgement

This research was funded through Landcare Research and the Ministry for Business, Innovation and Employment (Contract 1314-32-001K). Parts of the work were supported by the European Union's Horizon 2020 Research and Innovation Project under grant agreement No. 645717 (PROTINUS project). We thank Drs Markus Deurer and John Scott for initiating this research.

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Figures

Fig. 1. 3-D renderings of macropores (> 0.147 mm) obtained from X-ray Computed Tomography of the two soils for the three horizons.

Fig. 2. Unsaturated hydraulic conductivities of the two soils for (top) the topsoils, (middle) the upper subsoils, and (bottom) the lower subsoils. The bars denote the standard deviation of three replicates.

Fig. 3. Relationships of macroporosities (total macroporosity ($TMP_{(> 0.147)}$), connected total macroporosity ($CTMP_{(> 0.147)}$), macroporosity between 0.75 and 3 mm ($MP_{(3-0.75)}$), and connected macroporosity between 0.75 and 3 mm ($CMP_{(3-0.75)}$)) derived with X-ray Computed Tomography and the unsaturated hydraulic conductivity determined in situ at -10 mm ($K_{unsat}(-10\text{ mm})$) and -40 mm ($K_{unsat}(-40\text{ mm})$) using tension-disc infiltrometry for the Andosol (a, c, e, g) and the Gleysol (b, d, f, g). Solid lines represent linear relationships. The R^2 and P -values for the regressions are provided.

Fig. 4. Depth distribution of the limiting macroporosity ($TMP_{(> 0.147)}$) and the connected limiting macroporosity ($CTMP_{(> 0.147)}$) for all soil cores of (a, c) the Andosol and (b, d) the Gleysol. Relationship of limiting $TMP_{(> 0.147)}$ and the unsaturated hydraulic conductivity determined in situ at -10 mm ($K_{unsat}(-10\text{ mm})$) using tension-disc infiltrometry for the Andosol (e) and the Gleysol (f). Solid lines represent linear relationships. The R^2 and P -values for the regressions are provided.

Tables

Table 1 Selected physical and chemical properties of the two soils and for the three horizons studied.

Soil Horizon Depth (cm)	Andosol			Gleysol		
	Ah 0-15	Bw1 15-31	Bw2 31-64	Ah 0-20	Bg1 20-38	Bg2 >38
Sand (%)	24	19	n.d. ^a	10	0	n.d.
Silt (%)	50	47	n.d.	38	31	n.d.
Clay (%)	26	34	n.d.	52	69	n.d.
Organic Carbon (%)	6.8	1.7	n.d.	5.4	0.8	n.d.
Bulk density (g cm ⁻³)	0.8	0.8	0.8	0.9	1.1	1.0
Total porosity (%)	65.5	70.7	71.8	63.8	60.8	61.5
Macroporosity -10 kPa (% vol.)	11.8	22.8	25.4	1.7	6.7	1.8

^an.d. not determined

Table 2 The average macropore density (*MPD*), macropore diameter (*MPDIA*, diameter of the connected macropores (*CMPDIA*), total X-ray CT Macroporosity ($TMP_{(>0.147)}$), the connected total macroporosity ($CTMP_{(>0.147)}$), the number of connected macropores, the genus density, and the vertical tortuosity for the two soils and three horizons. Standard error of three replicates in parentheses.

Soil	Andosol			Gleysol		
Horizon	Ah	Bw1	Bw2	Ah	Bg1	Bg2
<i>MPD</i> (number mm ⁻³)	1.129 (0.112)	1.487 (0.056)	1.568 (0.136)	0.679 (0.046)	0.769 (0.045)	0.433 (0.054)
<i>MPDIA</i> (mm)	0.272 (0.004)	0.237 (0.002)	0.222 (0.004)	0.378 (0.013)	0.278 (0.005)	0.288 (0.002)
<i>CMPDIA</i> (mm)	0.300 (0.010)	0.301 (0.008)	0.266 (0.013)	0.390 (0.019)	0.297 (0.008)	0.306 (0.003)
$TMP_{(>0.147)}$ (mm ³ mm ⁻³)	0.065 (0.004)	0.035 (0.003)	0.034 (0.002)	0.141 (0.027)	0.069 (0.004)	0.049 (0.005)
$CTMP_{(>0.147)}$ (mm ³ mm ⁻³)	0.048 (0.006)	0.011 (0.002)	0.007 (0.002)	0.133 (0.027)	0.054 (0.006)	0.039 (0.004)
$CTMP_{(>0.147)}$ of $TMP_{(>0.147)}$ (%)	74	31	20	94	79	80
Number of connected macropores (-)	1	5	3	1	1	2
Genus density (mm ⁻³)	1.022 (0.018)	0.200 (0.030)	0.223 (0.031)	1.507 (0.393)	0.548 (0.051)	0.353 (0.026)
Vertical tortuosity (-)	2.615 (0.024)	2.815 (0.014)	2.709 (0.016)	2.996 (0.020)	3.098 (0.025)	3.366 (0.112)

Table 3 Pearson correlation coefficients among different macropore characteristics

(log(macroporosity) C1; log(mean macropore diameter) C2; log(genus density) C3; vertical tortuosity C4; macropore density C5), as determined from X-ray computed tomography-images and hydraulic parameters ($\log(K_{unsat}(-10\text{ mm}))$ C6; and $\log(K_{unsat}(-70\text{ mm}))$ C7) for all horizons of the two soils studied. Probability values in parentheses are indicated by two significance levels (** <0.01; * <0.05).

	C1	C2	C3	C4	C5	C6
C2	0.919 (<0.001)**					
C3	0.934 (<0.001)**	0.818 (<0.001)**				
C4	0.161 (<0.523)	0.410 (0.091)	-0.0219 (0.931)			
C5	-0.578 (0.0119)*	-0.754 (0.0003)**	-0.490 (0.039)*	-0.790 (<0.001)**		
C6	0.462 (0.053)	0.202 (0.422)	0.505 (0.0325)*	-0.625 (<0.001)**	0.248 (0.322)	
C7	-0.594 (0.009)**	-0.808 (<0.001)**	-0.429 (0.075)	-0.640 (0.004)*	0.777 (<0.001)**	0.216 (0.390)







