**The effects of long-term fertilizations on soil hydraulic properties vary with scales**

Xiaoxian Zhang1, Andrew L. Neal2, John W. Crawford3, Aurelie Bacq-Labreuil4, Elsy Akkari1, William Richard1

1 Department of Sustainable Agricultural Sciences, Rothamsted Research, Harpenden, AL5 2JQ, UK.

2 Sustainable Agriculture Sciences, Rothamsted Research, North Wyke, EX20 2SB, UK

3 Adam Smith Business School, University of Glasgow, West Quadrangle, Glasgow. G12 8QQ. UK

4 Division of Agriculture & Environmental Sciences, School of Biosciences, University of Nottingham, Sutton Bonington Campus, Leicestershire LE12 5RD, UK

**Abstract**

Soil structural alterations instigated by cropping system conversion and fertilization change have been well documented, but how such alterations vary with scale remains elusive. We investigated this based on the Rothamsted long-term wheat experiment (since 1843) in the UK. Triplicate cores 7cm high and 10cm in diameter were taken from plots that have been under different fertilizations and returned to natural woodland for more than one century for imaging with X-ray computed tomography at resolution of 40µm. We then broke each core and sampled three aggregates from it to scan them at resolution of 1.5µm. For each core or aggregate sample, we calculated its pore size distribution, as well as permeability and tortuosity from pore-scale simulations. The results showed that the fertilization change more than 170 years ago reshaped the soil structure but differently between the core scale and the aggregate scale. Macro-porosity of the pores (>40µm) in the cores unfertilized or fertilized with inorganic fertilizers were low and poorly connected in the top 10cm of soil, compared to the cores given farmyard manure or in the woodland. In all treatments, the large macropores in the cores were hydraulically anisotropic with their permeability being higher in the horizontal direction than in the vertical direction, whereas the aggregates were comparatively isotropic. The fertilization affected porosity and permeability of macropores at core scale more significantly than those at aggregate scale, and the aggregates fertilized with farmyard manure and in the woodland were more permeable than aggregates in other treatments. It is also found that, compared to no-fertilization or fertilization with complete fertilizers, fertilizing without phosphorus over the past 20 years increased the porosity and permeability of the aggregates but not of the cores. Fertilization with inorganic fertilizers increased tortuosity of the macropores in the cores but not of the intra-aggregates micropores, compared to no-fertilization. Porosity-permeability relationship for aggregates unfertilized or fertilized with inorganic fertilisers follows a power law with *R*2 > 0.8. In contrast, the permeability of aggregates in farmyard manure and in the woodland trended differently with the porosity. Aggregates and cores responded differently to carbon in that, with soil carbon increasing, the permeability of the aggregates increased asymptotically while the permeability of the cores increased approximately exponentially. Since soil structure is indicators of soil quality and evolves slowly, our results have important implications for understanding how agronomical practice changes reshape soil structure at different scales as well as the long-term consequence for hydrological and biochemical processes.

***Key words****: Rothamsted long-term experiment*; *hierarchical soil structural change*; *pore-scale simulations*; *X-ray computed tomography*.

1. **Introduction**

Most soils in natural and managed terrestrial ecosystems are hierarchically structured with pores ranging from less than one micron to several millimetres in diameter (Young and Crawford, 2004). Such structures are a result of the interplay of a variety of abiotic and biotic processes operating across a wide range of scales, and are the foundation of all life in terrestrial ecosystems as they keep the soil moist and oxygenated (Young et al., 2008). Macropores in soil are formed mainly by actions of plant roots, earthworms, aggregations, and swelling and shrinkage (Bronick and Lal, 2005), providing preferential pathways for water and nutrients to flow (Beven and Germann, 2013). In contrast, micropores formed biotically and abiotically function as storage for water and nutrients (Feeney et al., 2006; Kallenbach et al., 2016; Totsche et al., 2018). Microorganisms play a critical role in soil genesis and their feedback reactions with soil structure are mediated by organic matters in complex ways (Young et al., 2008). However, it is generally accepted that boosting microbial activities increases soil porosity due to the enhanced soil aggregation. For example, Crawford et al (2012) found that incubating repacked fine-textured soil for three weeks resulted in a 17% increase in porosity. The importance of soil structure in physical and biogeochemical processes is fairly understood. In addition to its well-documented role in controlling water flow and solute transport, however, soil structure also plays a critical role in soil functions (Kravchenko and Guber, 2017) as recent findings revealed that enzymatic activities were strongly associated with a specific range of pores, implying that the associated carbon and nutrient cycling is pore-dependant (Kravchenko et al., 2019)

Soil reorganizes its structure following agronomical practice change (Caplan et al., 2017). Tillage and root growth could instantly reshape soil structure, while the change induced by microbial activities could be a slow process (Crawford et al., 2012; Kallenbach et al., 2016). For example, Neal et al (2020) recently found that following a conversion from a fallowed land to arable or grassland, the change in intra-aggregate structure did not reach equilibrium in10 years; the Rothamsted long-term wheat experiment revealed that soil carbon took about one century to stabilize after changing fertilization to farmyard manure (Poulton et al., 2018). As the dynamics of soil carbon is determined by its accessibility to microbes (Dungait et al., 2012) which in turn is modulated by soil structure, it is rational to conjecture that the change in soil structure following the fertilization change could not reach equilibrium before soil carbon stabilized. This is also corroborated by recent findings that soil physical properties affected soil carbon and nitrogen more than soil enzymes and microbial communities (Li et al., 2020). Understanding multiscale soil structural alteration instigated by agricultural practice change is hence important as pores at different scales play different roles in hydrological and biogeochemical functions (Wang et al., 2019; Yudina and Kuzyakov, 2019).

Most measurable macroscopic phenomena in soil and hydrology emerge from biogeochemical and physical processes occurring at the microscopic scale (Baveye et al., 2018; Zhang et al., 2016), and it has been increasingly recognized that it is impossible to reliably predict physical and biochemical processes by studying the bulk soils alone (Wilpiszeski et al., 2019). As such, there has been a surge in study of soil structure and its impact on water and solute transport over the past two decades largely due to the development in X-ray computed tomography (CT) and its application in various fields (Helliwell et al., 2013; Huang et al., 2015; Schlüter et al., 2014). One application of X-ray CT in soil is to quantify soil structural change induced by agronomical management (Lucas et al., 2019; Piccoli et al., 2019; Soto-Gomez et al., 2020) as well as its consequence for hydrological process (Armenise et al., 2018; Baveye et al., 2018; Gharedaghloo et al., 2018; Luo et al., 2010; Zhang et al., 2019; Zhou et al., 2019).

Modelling water flow and solute transport in hierarchically structured soils often separates their macropores and micropores into two hydraulically linked domains, with flow and transport in each domain represented by a set of equations while the mass exchange between them is described by empirical formulae (Gerke and van Genuchten, 1993; Larsson and Jarvis, 1999; Simunek et al., 2003; Vogel et al., 2000). Separating the pores into two domains improves the model but it also increases the numbers of parameters which have to be determined empirically by calibration against observed data (Frey et al., 2016; Haas et al., 2020; Lamy et al., 2009). The X-ray CT has potential to plug this gap but needs to scan the soil at multiscale so as to characterize the geometry of the matrix between the macropores at a macro-scale and the pore geometry inside the matrix at a micro-scale (Li et al., 2018b; Zhang et al., 2016). Linking soil hydraulic conductivity to pore geometry obtained from X-ray images is available, but most of them integrated the macropores and micropores (Koestel et al., 2018; Pohlitz et al., 2019; Schlüter et al., 2020; Zhang et al., 2019). There are also studies on geometrical change in both intra-aggregate pores and macropores (Borges et al., 2019; Galdos et al., 2019; Koestel and Schluter, 2019; Pires et al., 2019; Schlüter et al., 2018), as well as their temporal evolution under different managements (Lucas et al., 2019; Schlüter et al., 2011). However, soil structure change is a slow process (Lohse and Dietrich, 2005) and could take decades to reach equilibrium (Lucas et al., 2019; Neal et al., 2020). Therefore, for experiments with repacked soil that did not last long enough (Crawford et al., 2012; Kallenbach et al., 2016; Menon et al., 2020; Rabbi et al., 2018), the observed soil structure could be just temporary rather than what the soil would evolve to.

The hierarchical soil structure is formed by a multitude of biotic and abiotic processes operating at different scales and how this multiscale structure responds to management practice change is poorly understood. Apart from this, another issue that has been overlooked is hydraulic anisotropy. Soil anisotropy is important not only in hillslope hydrology for lateral water flow but also in plant uptake of water as vertically-dominant 3D root architectures drive water flowing mainly in the horizontal direction from distant soil towards root surfaces (Zhang et al., 2020). This paper aims to investigate these based on the Rothamsted long-term experiment in the UK that has been in operation since 1843. Triplicate cores 7cm high and 10cm in diameter were taken from plots under different fertilizations for centuries and were scanned using X-ray CT at resolution of 40μm. We then broke each core and sampled three aggregates to scan them in X-ray CT at resolution of 1.5μm. The permeability in three directions of each sample was calculated using pore-scale simulation to elucidate how the change in fertilization centuries ago reshaped the soil structure at both core and aggregate scales. Since soil structural change at microscopic scale was driven by carbon-mediated processes, we also analysed how the permeability responds to soil carbon at aggregate and core scales respectively.

1. **Materials and methods** 
   1. **Site description**

The Rothamsted long-term experiment at Broadbalk (Latitude 51° 48’ 34.44” N; Longitude 0° 21’ 22.76” W) started in1843 to test the effects of various combinations of inorganic fertilizers (N, P, K and Mg) and organic manures on the yield of winter wheat, with a unfertilized strip as the control. The mean annual temperature and rainfall on the site is 10.1oC and 701mm respectively (<http://www.era.rothamsted.ac.uk>). The soil on the site is predominantly clay loam classified as Chromic Luvisol (FAO classification). The plough layer (0-23cm) contains 25% of sand, 25% of silt and 50% of clay with an average particle density of 2.56g/ cm3 (Gregory et al., 2010). The pH is maintained at 7-7.5 by liming. Since its inception the experiment was made a few changes aimed to make it representative to the changes in farming in the UK. Detailed description of the experiment is available online (<http://www.era.rothamsted.ac.uk>) and in the literature (Blair et al., 2006; Watts et al., 2006). We provide in the supplementary materials the fertilization history and layout of the experimental site. In short, the site consists of 19 strips each associated with a specific fertilization ranging from farmyard manure to different combinations of nitrogen, phosphorus, potassium and magnesium minerals. Initially, all 19 strips were for continuous wheat and they all were made into 10 sections later aimed to compare the impact of other agronomical managements under the same fertilization, including a straw incorporation since1986. In 1882, a part on west edge of the site was withdrawn from cultivation leading to development of a small area of woodland colonised by various grass species and trees mostly Ash (Fraxinus excelsior), Sycamore (Acer pseudoplatanus) and Hawthorn (Craetagus monogyna) (Poulton et al., 2003).

* 1. **Acquisition of soil images**

Triplicate cores 7cm high and 10cm in diameter were taken in October 2015 from each of the following four plots (marked in the supplementary materials) that have been under different fertilizations since 1843: An unfertilized plot (referred to as CK), a plot given farmyard manure (referred to as FYM), and two other plots that have been fertilized with different combinations of inorganic minerals. There were some changes in fertilization after its inception and the details are given in the supplementary materials. In what follows we will refer the plot that is currently receiving 144kg of N, 90kg of K and 35kg of P and 12kg of Mg as N3, and the plot that has not received P since 2001 as No P. As a comparison, triplicate cores were also taken from the woodland. Each sample was taken by gently hammering a PVC core into the topsoil with the core-top 1-2cm below the soil surface; we then dug the core out after removing the soil surrounding the core using a trowel. We the peeled the loose and extra soil at the two ends using a sharp knife before tightly wrapping it with plastic films prior to x-ray imaging.

All cores were scanned using X-ray CT and details of the procedure were given in previous work (Bacq-Labreuil et al., 2018). In short, we used the Phoenix v∣tome∣x M scanner (GE Measurement and Control solution, Wunstorf, Germany) at the Hounsfield Facility of University of Nottingham to scan the cores under 160kV and 180μA at a pixel resolution of 40μm. After the scanning, each core was manually broken to pass through a series of sieves of 4, 2 and 0.71mm by horizontally shaking at 300 rotations/min for 3minutes; and three aggregates retained in the sieves of 2mm and 0.71mm were randomly selected and scanned using a Phoenix Nanotom® (GE Measurement and Control solution, Wunstorf, Germany) under 90kV and 65μA at a pixel resolution of 1.51μm. The sizes of all aggregates were thus approximately 0.8 mm to 4mm. The scanned images were reconstructed using the software provided by the manufacturer with an optimisation to correct any possible sample-movement during the scanning process. To avoid internal collapse in the cores, all cores were scanned at prevailing water content approximately the field capacity, while the aggregates were scanned after an overnight of air-drying.

We firstly analysed the images using Image J with a region of interest (ROI) cropped out from each image for ease of analysis. The ROIs of the core images (1000x1000x1000) were positioned centrally to exclude the gaps between the soil and the wall of the core, while for the irregular aggregates we cropped a cuboid ROI (64x480x400) out of each image. The cropped ROIs were grey-scale and they were segmented using the bin bi-level threshold method presented in Vogel and Kretzschmar (1996). Details of the segmentation method were given previously (Bacq-Labreuil et al., 2018). In short, 20 slices were randomly selected from each stack and each slice had a single threshold value that was calculated from the Li-threshold algorithm in Image J. The values of the two thresholds used in the bin bi-level method for segmenting the stack were calculated from the extreme values obtained from the 20 slices.

**2.3. Permeability**

The permeability of all cores and aggregates was calculated from pore-scale simulation of water flow in their pore space using the lattice Boltzmann (LB) model we developed previously (Zhang et al., 2010). Most early LB models used for pore-scale simulation were based on the single-relaxation time (SRT) approach (Qian et al., 1992), but it was later found that the commonly used bounce-back method associated with the SRT model was erroneous for solving the fluid-wall boundary (Pan et al., 2006). The multiple relaxation time (MRT) LB method can resolve this problem (d'Humières et al., 2002) and we hence used it in this paper. Details of the method and its implementation are given in the supplementary materials.

Water flow in each sample was driven by a pressure gradient in one direction generated by imposing a high pressure on one side and a low pressure on the opposite side of the sample. Other four sides were treated as periodic boundaries. We selected three pressure gradients to ensure that water flow was laminar and that the flow rate was proportional to the pressure gradient. In all simulations, the initial velocity was zero and we simulated the flow to steady state, deemed to have reached when the relative difference in average flow rate at two moments spanning 100 time-steps was less than 10-7. We then sampled the velocity and pressure at all voxels and volumetrically averaged them over each cross-section perpendicular to the pressure gradient direction to calculate the permeability. We sampled the pressure aimed to check pore homogeneity as our previous work showed that the average pressure distribution could become non-linear in highly heterogenous soils (Li et al., 2018a). To test hydraulic anisotropy, we calculated the permeability in the three directions of each sample.

For simulation under each pressure gradient, the volumetric average water flow was assumed to follow the Darcy’s law. Taking the pressure gradient generated in the z direction as an example, that means

 (1)

where *qz*(*z*) is the average flow rate over the cross-section perpendicular to the *z* direction, *k* is permeability, *u* is kinetic viscosity of water, *P* is the averaged pressure over the cross-section, and ρ is water density. The averaged water flow rate and pressure were calculated from pore-scale simulation as follows:

 (2)

where *Nz* and *Nzw* are the number of all voxels and the number of water-filled voxels in the cross section located at *z* respectively,and are the pressure and water velocity component in the *z* direction at voxel centred on respectively.

At steady stateis independent of z because of the mass balance constraint, and the permeability of the sample was calculated from

 (3)

where *L* is the length of the sample in the *z* direction. Once the permeability *k* was calculated, its associated hydraulic conductivity *K* can be calculated from K=kg/μ,

where *g* is the gravitational acceleration. Since water density and viscosity depend on temperature and the chemical composition of the water, the hydraulic conductivity is not a constant but varies with soil environment. In what follows, we hence use permeability rather than convert it to hydraulic conductivity.

* 1. **Pore size distribution and tortuosity**

We calculated the pore size distribution for both aggregates and cores using the Plug-in CT-image Analysis & Manipulation (SCAMP) (Houston et al., 2017) and Bone J in Image J finding that the difference between the two was less than 5%. In what follows we only present the results obtained from Bone J. We expressed the pore size distribution as volumetric fraction of pores of different sizes.

There are different ways to calculate tortuosity and we calculated it in this paper as the ratio between the bulk diffusion coefficient of a solute in free water and its effective diffusion coefficient in the soil sample. The effective diffusion coefficient was calculated using the lattice Boltzmann model we developed for pore-scale simulation of solute transport in soil (Hu et al., 2014; Zhang et al., 2016).

1. **Results**

We took one grey-scale core image from each of the five treatments as an illustration to qualitatively show the impact of fertilizations (Figure 1). We also took a grey-scale aggregate image and its segmentation from each of the five treatments to qualitatively illustrate the impact of the treatments on aggregate structure and the accuracy of the segmentation method (Figure 2).

* 1. **Permeability of the aggregates**

We calculated the permeability components in the three directions in each cuboid aggregate image as shown in Figure 2, finding that the difference between the highest and lowest components varied between 5% to 25%. As it was impossible to keep the orientation of the aggregates, the permeability we analyse and discuss in the following is the average of the three permeability components calculated for each sample.

Table 1 compares the average permeability of the aggregates for the five treatments. Fertilization with inorganic fertilizers did not result in a significant change in aggregate porosity and permeability, compared to the CK. Fertilization with farmyard manure made the aggregates as permeable as returning the soil to natural woodland for more than a century although the former is slightly more porous than the latter. On average, increasing carbon input to the soil through farmyard manure or perennial vegetation coverage as in the woodland improved aggregate permeability approximately fivefold from about 0.10 μm2 for treatments without exogenous carbon input to approximately 0.59μm2 due to the increase in porosity and volumetric fraction of large intra-aggregate pores (Figure 3A), as well as the reduced tortuosity (Figure 3B). Applying N, P, K and Mg fertilizers did not appear to have altered the aggregate porosity and permeability noticeably compared to no-fertilization because of their similarity in pore-size distribution, porosity and tortuosity (Table 1, Figures 3A and 3B). However, Table 1 shows that fertilization without phosphorus since 2001 appeared to have increased aggregate porosity and permeability compared to CK and fertilization with N, K, P and Mg, although the increase was minor.

The porosity and permeability of the aggregates sampled from the cores taken from the same treatment varied. Figure 3C compares the change in permeability with the porosity for all aggregates. For aggregates sampled from cores taken from soils unfertilized or fertilized with inorganic fertilizers, their porosity-permeability relationship follows roughly a same power law with *R*2>0.8 (Figure 3C). In contrast, the permeability of the aggregates taken from cores fertilized with farmyard manure and in the woodland trended differently with porosity (Figure 3C) because of the difference in their pore-size distribution and tortuosity (Figures 3A, B).

Increasing carbon input to soil through farmyard manure or perennial vegetation coverage appeared to have made the aggregates more homogenous in terms of porosity and permeability. Table 1 shows the coefficient of variation (CV) - the ratio of standard deviation to the mean - for both porosity and permeability. The aggregates taken from the cores fertilized with farmyard manure and in the woodland have approximately the same CV for porosity but different CV for permeability, although they are all smaller than the CVs of the aggregates taken from other treatments. Compared to no-fertilization or fertilization with N, K, P and Mg, fertilization without phosphorus since 2001 appeared to have made the aggregates more heterogenous, with its CV for porosity and permeability being 0.405 and 1.145 respectively, larger than the associated CVs for other treatments.

* 1. **Permeability of the cores**

Table 2 compares the average porosity and permeability in both vertical and horizontal direction for all cores taken from the five treatments. We did not keep horizontal orientation of the cores, and the horizontal permeability in all tables and figures are thus the average of the two horizontal components calculated for each core. The porosity of the macropores (>40μm) in soil received farmyard manure and in the woodland was higher than that in other treatments, and their permeability in both vertical and horizonal directions was two to three orders higher in magnitude than that of the cores taken from other treatments. Fertilization with inorganic fertilizers appeared to have affected the macropores more significantly than the intra-aggregate micropores. At aggregate scale the tortuosity of the aggregates in soils unfertilized or fertilized with inorganic fertilizations was comparable (Figure 3B), while the tortuosity of cores under inorganic fertilizations was substantially higher than that under other treatments (Figure 4A). This is partly due to that increased volumetric fractions of small pores in the two inorganic fertilizer treatments as shown in Figure 4B. Fertilization without phosphorus since 2001 reduced the macropores and their permeability compared to those unfertilized or fertilized with N, K P and Mg (Table 2). The porosity and permeability of the cores taken from the woodland are much higher than that of the cores fertilized with farmyard manure, while at the aggregate scale their values in the two treatments are close.

All cores are hydraulically anisotropic with their permeability in the horizontal direction higher than in the vertical direction, although the difference varies between treatments (Table 2). Compared with other treatments, the cores in the woodland are more hydraulically homogenous and isotropic, with the ratio of its permeability in the horizontal direction to the vertical direction being 1.3. Fertilization with farmyard manure made soil most anisotropic, with its horizontal permeability fivefold its vertical permeability. Table 2 reveals that no-fertilization or fertilization with inorganic fertilizers made soil more spatially heterogenous at core scale, with the CVs of their porosity and permeability being both higher than that of other treatments.

Figure 5 plots the relationship between macro-porosity and permeability in both vertical and horizontal directions for the cores taken from different treatments. Although they both roughly follow a power law, their *R*2 is smaller than the *R*2 for the aggregates (Figure 3C). As there were only three replicate cores for each treatment, we did not separately fit the core results for each treatment as we did for the aggregates.

* 1. **Pore size distribution and tortuosity**

Figure 3A and Figure 4A compare the pore-size distribution of the aggregates and cores under different treatments, respectively. The pore-size distribution was expressed as volumetric fraction of pores of different sizes rather than their absolute values aimed to elucidate that it is the porosity or pore sizes that rendered the permeability of the cores and aggregates differing between the treatments. Figure 4A reveals that the volumetric fraction of large macropores at core scale in the CK is higher than that in other treatments, implying that its low permeability compared to the farmyard and woodland was due to the reduced porosity rather than the change in pore sizes. In contrast, the volumetric fraction of large macropores in the cores fertilized with farmyard manure and in the woodland is higher than that unfertilized or fertilized with inorganic fertilizers, and their increased permeability was thus due to the combined impact of increased porosity and pore sizes. The pore-size distribution of the aggregates between different treatments was similar to that between the cores. The volumetric fraction of large intra-aggregate pores in 10-25μm was higher in soil given farmyard manure or in the woodland than that in other treatments, and not applying P since 2001 increased the volumetric fraction of small intra-aggregate pores (5-10μm).

Figure 3B and Figure 4B compare the tortuosity of both aggregates and cores. Consistent with the permeability results, the tortuosity of aggregates unfertilized or fertilized with organic fertilizers was comparable and higher than the tortuosity of aggregates fertilized with farmyard manure or in the woodland. In contrast, the macropores at core scale in soils fertilized with inorganic fertilizers were more tortuous than the macropores in other treatments including CK. On average, the macropores in the woodland was least tortuous while the macropores in soil fertilized without P since 2001 was most tortuous.

1. **Discussion**

Management change could lead to an instant response in soil structure (Crawford et al., 2012; Rabbi et al., 2016), but because soil is hierarchically structured formed by numerous biotic and abiotic processes, such structural change could take decades or even centuries to reach equilibrium (Lohse and Dietrich, 2005; Lucas et al., 2019). Long-term experiments are thus invaluable to assess how an agronomical management change reshapes soil structure and its long-term impact on hydrological and biogeochemical processes at different scales. The results obtained from the Rothamsted long-term experiment showed substantial difference in hydraulic properties of soils at both core and aggregate scales between different fertilizations that have been in operation for more than 170 years.

In all treatments but fertilization without P since 2001, the permeability of the cores is one to three orders in magnitude higher than that of the aggregates. The ability of the soils to infiltrate water is hence overwhelmingly dominated by pores larger than 40μm at saturation as found at this experimental site in 1882 (Beven and Germann, 1982), and corroborated by recent results obtained by others based on X-ray tomography (Katuwal et al., 2015; Paradelo et al., 2016; Zhang et al., 2019). The reduced permeability of macropores in cores fertilized without P since 2001 was due to the decrease in porosity rather than the numbers of large pores as the pore-size distribution (Figure 4A) showed that the volumetric fraction of pores of different sizes in cores fertilized without P was comparable to that fertilized with P. The volumetric fraction of large macropores in the cores taken from CK was higher than those in other treatments, while its permeability was lower than the cores fertilized with farmyard manure and in the woodland due to the reduced porosity (Table 2).

Existing studies on impact of cropping on soil anisotropy are inconsistent, with some showing isotropy while others showing anisotropy (Gharedaghloo et al., 2018). But there is a consensus that soil anisotropy depends on scale, weaker at small scale than at large scale (Beckwith et al., 2003). The woodland has grown naturally since 1882 and because of the accrual of rooting activity and other biotic and abiotic processes, both cores and aggregates have become relatively isotropic and homogeneous (Tables 1, 2). This is consistent with some study on peat soils which were found to be more isotropic although the underlying mechanisms remains obscure (Gharedaghloo et al., 2018).

The experimental site is ploughed annually after harvest using a mouldboard plow. While different abiotic and biotic processes might have combined to make the macropores hydraulically anisotropic, earthworm burrowing could be an important one. Field survey since 1922 has consistently showed that the number of earthworms in the plots continuously receiving farmyard manure is significantly higher than in other treatments. For example, a 2014 survey found that the total earthworm biomass in plots given farmyard manure was 109g/m2, compared to 6g/m2 in plots never receiving farmyard manure (Sizmur et al., 2017). In all treatments, the endogeic earthworm was found to be the dominant species (Sizmur et al., 2017) which is known to make horizontal burrows (Le Couteulx et al., 2015).

The permeability of cores varied significantly between treatments due to their difference in porosity, volumetric fraction of large macropores (Table 2, Figure 4A) and connectivity of these pores (Figure 4B). The long-term experiment did not measure roots, but if the biomass of roots are assumed to be positively related to yield and an increased root biomass improves soil porosity, the average yield of the plots given farmyard manure, inorganic fertilizer and the CK is 11 t/ha, 5.5t/ha and 1.2t/ha, respectively. The yield is hence positively related to the porosity and permeability of their associated soil cores (Tables 1 and 2) except for the treatment without phosphorus fertilization since 2001. Fertilization without phosphorus, however, had increased the averaged porosity and permeability of the aggregates compared to other inorganic fertilization treatments (Table 1). It has been known that plant under phosphorus deficit proliferates root hairs and arbuscular mycorrhiza to enhance its phosphorus mining in soil (Lazarevic et al., 2018), which could be one of mechanisms underlying the increased porosity and permeability of the aggregates.

Increasing carbon input to soil in farmyard manure or perennial vegetation coverage increased porosity and permeability of the soil at both aggregate and core scales, as anticipated for fine textured soils like the clay loam on the experimental site. The comparatively isotropic aggregates suggested that the genesis of the aggregate structure was less impacted by root growth than by microbially-mediated processes such as root exudations and fungus. Adding carbon boosts microbial activities thereby enhancing soil aggregation and increasing porosity of fine textured soil (Helliwell et al., 2014), especially the volumetric fraction of large intra-aggregate pores (Figure 3A). The experimental site was rich in fungus and the total bacterial community in the woodland was twofold that in the arable soil (Hargreaves et al., 2003).These could be an important mechanism underlying the increased soil porosity, pore connectivity (Figures 3A, B) and permeability of the aggregates in soil given farmyard manure and in the woodland (Crawford et al., 2012).

Aggregates in soils are formed largely through binding of minerals by fungus and decomposed organic matter and its runover is much slower than macropores (Rabbi et al., 2020). It is hence interesting to see how permeability of the aggregates and cores responded to soil carbon change. The total carbon in the top 23cm of soil in the plots given farmyard manure has increased from 30t/ha in1843 to 75t/ha, while in the woodland it has increased to 160t/ha. In contrast, the carbon in the plots fertilized only with mineral fertilizers remained almost unchanged and the carbon in the top 23cm of soil not receiving any inputs reduced to 25t/ha. Figure 6A shows that with soil carbon increasing, the permeability of the aggregates increased asymptotically plateauing when the carbon exceeded 75t/ha, while the permeability of the cores, especially the vertical permeability, increased exponentially (Figure 7B). Permeability of the aggregates in soil given farmyard manure is slightly higher than that of the aggregates in the woodland, consistent with the experimental measurement (Blair et al., 2006) but differing in magnitude as what we calculated from X-ray images were the permeability of the top 12cm soil while the permeability measured in the field was the average of the soil profile. At steady state, the permeability measured at field is the geometrical average of the permeability of all stratified layers along the soil profile (Li et al., 2018a). This increase was due to the increase in porosity and volumetric fraction of large pores (Figures 3A, 4A), which combined to reduce the tortuosity and resistance for water to flow in soil (Figures 3, 4). Figure 6 also hints that as soil carbon increased, the impact of carbon on macropores (>40μm) was more significant than on intra-aggregate micropores, consistent with recent findings that soil enzymatic activities, which modulate soil carbon distribution, are not randomly distributed but closely associated with pores in a specific range (Kravchenko et al., 2019). Given the increasing interest in sequestrating carbon into soil, understanding how soil at different scales hydraulically responds to carbon input is important but appears to have been overlooked (Poulton et al., 2018).

1. **Conclusions**

We investigated the long-term impact of fertilizations on multiscale soil structural change using intact cores taken from soils under different combinations of inorganic fertilizers and farmyard manure for more than 170 years at the Rothamsted long-term wheat experiment. The cores were scanned using X-ray CT at resolution of 40μm first and we then sampled triple aggregates from each core and scanned them with X-ray CT at resolution of 1.5μm. The permeability of each core and aggregate sample was calculated from pore-scale simulation of water flow in its pore space using the lattice Boltzmann model. For testing hydraulic anisotropy, we calculated the permeability in both vertical and horizontal direction of each core sample.

Soil structure at both core and aggregate scales had evolved after more than 170 years of the fertilization change, but the structural change at core scale is more significant than at aggregate scale. Overall, increasing carbon input to the soil increased porosity and permeability at both aggregate and core scales although the increase at core scale is more significant than at aggregate scale. The aggregates in all treatments are approximately hydraulically isotropic, but the cores are anisotropic with their permeability in the horizontal direction higher than in the vertical direction, although the anisotropy varies between treatments. The cores taken from the woodland was most homogenous and isotropic, while the cores taken from the soils fertilized with farmyard manure was most anisotropic with its permeability in the horizontal direction more than fivefold its permeability in the vertical direction. The porosity-permeability relationship for aggregates in soils unfertilized or fertilized with inorganic fertilizers follows the same trend indicating geometrically similar pores, while the permeability of aggregates in soils fertilized with farmyard manure and in the woodland trended differently with porosity.

The multiscale soil structural alteration instigated by management practice change is a slow process and varies with scales. Long-term experiments are thus invaluable to assess how the multiscale soil structure eventually evolves after centuries of fertilization change or cropping conversion. The Rothamsted long-term experiments, having been running for more 170 years, provide unparallel opportunity to examine this. The results presented in this paper thus have important implications for understanding the long-term impact of fertilization on soil structural change and its consequence for hydrological and biogeochemical functions.

**Acknowledgements**

This work is part of the Soil to Nutrition (S2N) strategic programme (BBS/E/C/000I0310) funded by the Biotechnology and Biological Sciences Research Council (BBSRC) of the UK.

**References**

Armenise, E. et al., 2018. Soil seal development under simulated rainfall: Structural, physical and hydrological dynamics. J. Hydrol., 556: 211-219. DOI:10.1016/j.jhydrol.2017.10.073

Bacq-Labreuil, A. et al., 2018. Effects of cropping systems upon the three-dimensional architecture of soil systems are modulated by texture. Geoderma, 332: 73-83. DOI:10.1016/j.geoderma.2018.07.002

Baveye, P.C. et al., 2018. Emergent Properties of Microbial Activity in Heterogeneous Soil Microenvironments: Different Research Approaches Are Slowly Converging, Yet Major Challenges Remain. Front. Microbiol., 9: 48. DOI:10.3389/fmicb.2018.01929

Beckwith, C.W., Baird, A.J., Heathwaite, A.L., 2003. Anisotropy and depth-related heterogeneity of hydraulic conductivity in a bog peat. II: modelling the effects on groundwater flow. Hydrol. Process., 17(1): 103-113. DOI:10.1002/hyp.1117

Beven, K., Germann, P., 1982. Macropores and water flow in soil Water Resour. Res., 18(5): 1311-1325. DOI:10.1029/WR018i005p01311

Beven, K., Germann, P., 2013. Macropores and water flow in soils revisited. Water Resour. Res., 49(6): 3071-3092. DOI:10.1002/wrcr.20156

Blair, N., Faulkner, R.D., Till, A.R., Poulton, P.R., 2006. Long-term management impacts on soil C, N and physical fertility - Part 1: Broadbalk experiment. Soil Tillage Res., 91(1-2): 30-38. DOI:10.1016/j.still.2005.11.002

Borges, J.A.R. et al., 2019. X-ray computed tomography for assessing the effect of tillage systems on topsoil morphological attributes. Soil Tillage Res., 189: 25-35. DOI:10.1016/j.still.2018.12.019

Bronick, C.J., Lal, R., 2005. Soil structure and management: a review. Geoderma, 124(1-2): 3-22. DOI:10.1016/j.geoderma.2004.03.005

Caplan, J.S. et al., 2017. Nitrogen-mediated effects of elevated CO2 on intra-aggregate soil pore structure. Glob. Change Biol., 23(4): 1585-1597. DOI:10.1111/gcb.13496

Crawford, J.W. et al., 2012. Microbial diversity affects self-organization of the soil-microbe system with consequences for function. J. R. Soc. Interface, 9(71): 1302-1310. DOI:10.1098/rsif.2011.0679

d'Humières, D., Ginzburg, I., Krafczyk, M., Lallemand, P., Luo, L.S., 2002. Multiple-relaxation-time lattice Boltzmann models in three dimensions. Philos. Trans. R. Soc. Lond. Ser. A-Math. Phys. Eng. Sci., 360(1792): 437-451. DOI:10.1098/rsta.2001.0955

Dungait, J.A.J., Hopkins, D.W., Gregory, A.S., Whitmore, A.P., 2012. Soil organic matter turnover is governed by accessibility not recalcitrance. Glob. Change Biol., 18(6): 1781-1796. DOI:10.1111/j.1365-2486.2012.02665.x

Feeney, D.S. et al., 2006. Three-dimensional microorganization of the soil-root-microbe system. Microb. Ecol., 52(1): 151-158. DOI:10.1007/s00248-006-9062-8

Frey, S.K. et al., 2016. Dual permeability modeling of tile drain management influences on hydrologic and nutrient transport characteristics in macroporous soil. J. Hydrol., 535: 392-406. DOI:10.1016/j.jhydrol.2016.01.073

Galdos, M.V. et al., 2019. Assessing the long-term effects of zero-tillage on the macroporosity of Brazilian soils using X-ray Computed Tomography. Geoderma, 337: 1126-1135. DOI:10.1016/j.geoderma.2018.11.031

Gerke, H.H., van Genuchten, M.T., 1993. A dual-porosity model for simulating preferential movement of water and solutes in structured porous media. Water Resour. Res., 29(2): 305-319. DOI:10.1029/92wr02339

Gharedaghloo, B., Price, J.S., Rezanezhad, F., Quinton, W.L., 2018. Evaluating the hydraulic and transport properties of peat soil using pore network modeling and X-ray micro computed tomography. J. Hydrol., 561: 494-508. DOI:10.1016/j.jhydrol.2018.04.007

Gregory, A.S., Bird, N.R.A., Whalley, W.R., Matthews, G.P., Young, I.M., 2010. Deformation and Shrinkage Effects on the Soil Water Release Characteristic. Soil Sci. Soc. Am. J., 74(4): 1104-1112. DOI:10.2136/sssaj2009.0278

Haas, C., Horn, R., Ellerbrock, R.H., Gerke, H.H., 2020. Fluorescence imaging for mm-scale observation of macropore-matrix mass transfer: Calibration experiments. Geoderma, 360: 9. DOI:10.1016/j.geoderma.2019.114002

Hargreaves, P.R., Brookes, P.C., Ross, G.J.S., Poulton, P.R., 2003. Evaluating soil microbial biomass carbon as an indicator of long-term environmental change. Soil Biol. Biochem., 35(3): 401-407. DOI:10.1016/s0038-0717(02)00291-2

Helliwell, J.R., Miller, A.J., Whalley, W.R., Mooney, S.J., Sturrock, C.J., 2014. Quantifying the impact of microbes on soil structural development and behaviour in wet soils. Soil Biol. Biochem., 74: 138-147. DOI:10.1016/j.soilbio.2014.03.009

Helliwell, J.R. et al., 2013. Applications of X-ray computed tomography for examining biophysical interactions and structural development in soil systems: a review. Eur. J. Soil Sci., 64(3): 279-297. DOI:10.1111/ejss.12028

Houston, A.N. et al., 2017. Quantification of the pore size distribution of soils: Assessment of existing software using tomographic and synthetic 3D images. Geoderma, 299: 73-82. DOI:10.1016/j.geoderma.2017.03.025

Hu, W.L., Huang, N., Zhang, X.X., 2014. Impact of saturation on mass transfer rate between mobile and immobile waters in solute transport within aggregated soils. J. Hydrol., 519: 3557-3565. DOI:10.1016/j.jhydrol.2014.10.057

Huang, Y.J., Yang, Z.J., Ren, W.Y., Liu, G.H., Zhang, C.Z., 2015. 3D meso-scale fracture modelling and validation of concrete based on in-situ X-ray Computed Tomography images using damage plasticity model. Int. J. Solids Struct., 67-68: 340-352. DOI:10.1016/j.ijsolstr.2015.05.002

Kallenbach, C.M., Frey, S.D., Grandy, A.S., 2016. Direct evidence for microbial-derived soil organic matter formation and its ecophysiological controls. Nat. Commun., 7: 10. DOI:10.1038/ncomms13630

Katuwal, S. et al., 2015. Linking air and water transport in intact soils to macropore characteristics inferred from X-ray computed tomography. Geoderma, 237: 9-20. DOI:10.1016/j.geoderma.2014.08.006

Koestel, J. et al., 2018. Estimating the Permeability of Naturally Structured Soil From Percolation Theory and Pore Space Characteristics Imaged by X-Ray. Water Resour. Res., 54(11): 9255-9263. DOI:10.1029/2018wr023609

Koestel, J., Schluter, S., 2019. Quantification of the structure evolution in a garden soil over the course of two years. Geoderma, 338: 597-609. DOI:10.1016/j.geoderma.2018.12.030

Kravchenko, A.N., Guber, A.K., 2017. Soil pores and their contributions to soil carbon processes. Geoderma, 287: 31-39. DOI:10.1016/j.geoderma.2016.06.027

Kravchenko, A.N. et al., 2019. Microbial spatial footprint as a driver of soil carbon stabilization. Nat. Commun., 10: 10. DOI:10.1038/s41467-019-11057-4

Lamy, E., Lassabatere, L., Bechet, B., Andrieu, H., 2009. Modeling the influence of an artificial macropore in sandy columns on flow and solute transfer. J. Hydrol., 376(3-4): 392-402. DOI:10.1016/j.jhydrol.2009.07.048

Larsson, M.H., Jarvis, N.J., 1999. Evaluation of a dual-porosity model to predict field-scale solute transport in a macroporous soil. J. Hydrol., 215(1-4): 153-171. DOI:10.1016/s0022-1694(98)00267-4

Lazarevic, B., Losak, T., Manschadi, A.M., 2018. Arbuscular mycorrhizae modify winter wheat root morphology and alleviate phosphorus deficit stress. Plant Soil Environ., 64(1): 47-52. DOI:10.17221/678/2016-pse

Le Couteulx, A., Wolf, C., Hallaire, V., Peres, G., 2015. Burrowing and casting activities of three endogeic earthworm species affected by organic matter location. Pedobiologia, 58(2-3): 97-103. DOI:10.1016/j.pedobi.2015.04.004

Li, J., Nie, M., Pendall, E., 2020. Soil physico-chemical properties are more important than microbial diversity and enzyme activity in controlling carbon and nitrogen stocks near Sydney, Australia. Geoderma, 366: 114201. DOI:<https://doi.org/10.1016/j.geoderma.2020.114201>

Li, Z.Y., Wang, D., Zhang, X.X., Crawford, J.W., 2018a. Water flow across the interface of contrasting materials: Pressure discontinuity and its implications. J. Hydrol., 566: 435-440. DOI:10.1016/j.jhydrol.2018.09.029

Li, Z.Y., Zhang, X.X., Wang, D., Liu, Y., 2018b. Direct methods to calculate the mass exchange between solutes inside and outside aggregates in macroscopic model for solute transport in aggregated soil. Geoderma, 320: 126-135. DOI:10.1016/j.geoderma.2018.01.021

Lohse, K.A., Dietrich, W.E., 2005. Contrasting effects of soil development on hydrological properties and flow paths. Water Resour. Res., 41(12): 17. DOI:10.1029/2004wr003403

Lucas, M., Schlüter, S., Vogel, H.J., Vetterlein, D., 2019. Soil structure formation along an agricultural chronosequence. Geoderma, 350: 61-72. DOI:10.1016/j.geoderma.2019.04.041

Luo, L.F., Lin, H., Li, S.C., 2010. Quantification of 3-D soil macropore networks in different soil types and land uses using computed tomography. J. Hydrol., 393(1-2): 53-64. DOI:10.1016/j.jhydrol.2010.03.031

Menon, M. et al., 2020. Pore system characteristics of soil aggregates and their relevance to aggregate stability. Geoderma, 366: 114259. DOI:<https://doi.org/10.1016/j.geoderma.2020.114259>

Neal, A.L. et al., 2020. Soil as an extended composite phenotype of the microbial metagenome. Sci Rep, (In press). DOI:10.1038/s41598-019-43937-6

Pan, C.X., Luo, L.S., Miller, C.T., 2006. An evaluation of lattice Boltzmann schemes for porous medium flow simulation. Computers & Fluids, 35(8-9): 898-909. DOI:10.1016/j.compfluid.2005.03.008

Paradelo, M. et al., 2016. X-ray CT-Derived Soil Characteristics Explain Varying Air, Water, and Solute Transport Properties across a Loamy Field. Vadose Zone J., 15(4). DOI:10.2136/vzj2015.07.0104

Piccoli, I., Schjonning, P., Lamande, M., Zanini, F., Morari, F., 2019. Coupling gas transport measurements and X-ray tomography scans for multiscale analysis in silty soils. Geoderma, 338: 576-584. DOI:10.1016/j.geoderma.2018.09.029

Pires, L.F., Roque, W.L., Rosa, J.A., Mooney, S.J., 2019. 3D analysis of the soil porous architecture under long term contrasting management systems by X-ray computed tomography. Soil Tillage Res., 191: 197-206. DOI:10.1016/j.still.2019.02.018

Pohlitz, J., Rucknagel, J., Schluter, S., Vogel, H.J., Christen, O., 2019. Computed tomography as an extension of classical methods in the analysis of soil compaction, exemplified on samples from two tillage treatments and at two moisture tensions. Geoderma, 346: 52-62. DOI:10.1016/j.geoderma.2019.03.023

Poulton, P., Johnston, J., Macdonald, A., White, R., Powlson, D., 2018. Major limitations to achieving "4 per 1000" increases in soil organic carbon stock in temperate regions: Evidence from long-term experiments at Rothamsted Research, United Kingdom. Glob. Change Biol., 24(6): 2563-2584. DOI:10.1111/gcb.14066

Poulton, P.R., Pye, E., Hargreaves, P.R., Jenkinson, D.S., 2003. Accumulation of carbon and nitrogen by old arable land reverting to woodland. Glob. Change Biol., 9(6): 942-955. DOI:10.1046/j.1365-2486.2003.00633.x

Qian, Y.H., Dhumieres, D., Lallemand, P., 1992. Lattice BGK models for Navier-Stokes equation. Europhysics Letters, 17(6BIS): 479-484. DOI:10.1209/0295-5075/17/6/001

Rabbi, S.M.F. et al., 2016. Physical soil architectural traits are functionally linked to carbon decomposition and bacterial diversity. Sci Rep, 6: 9. DOI:10.1038/srep33012

Rabbi, S.M.F., Minasny, B., McBratney, A.B., Young, L.M., 2020. Microbial processing of organic matter drives stability and pore geometry of soil aggregates. Geoderma, 360: 4. DOI:10.1016/j.geoderma.2019.114033

Rabbi, S.M.F. et al., 2018. Plant roots redesign the rhizosphere to alter the three-dimensional physical architecture and water dynamics. New Phytol., 219(2): 542-550. DOI:10.1111/nph.15213

Schlüter, S., Albrecht, L., Schwarzel, K., Kreiselmeier, J., 2020. Long-term effects of conventional tillage and no-tillage on saturated and near-saturated hydraulic conductivity - Can their prediction be improved by pore metrics obtained with X-ray CT? Geoderma, 361: 12. DOI:10.1016/j.geoderma.2019.114082

Schlüter, S. et al., 2018. Long-term effects of conventional and reduced tillage on soil structure, soil ecological and soil hydraulic properties. Geoderma, 332: 10-19. DOI:10.1016/j.geoderma.2018.07.001

Schlüter, S., Sheppard, A., Brown, K., Wildenschild, D., 2014. Image processing of multiphase images obtained via X- ray microtomography: A review. Water Resour. Res., 50(4): 3615-3639. DOI:10.1002/2014wr015256

Schlüter, S., Weller, U., Vogel, H.J., 2011. Soil-structure development including seasonal dynamics in a long-term fertilization experiment. J. Plant Nutr. Soil Sci., 174(3): 395-403. DOI:10.1002/jpln.201000103

Simunek, J., Jarvis, N.J., van Genuchten, M.T., Gardenas, A., 2003. Review and comparison of models for describing non-equilibrium and preferential flow and transport in the vadose zone. J. Hydrol., 272(1-4): 14-35.

Sizmur, T. et al., 2017. Milled cereal straw accelerates earthworm (Lumbricus terrestris) growth more than selected organic amendments. Applied Soil Ecology, 113: 166-177. DOI:<https://doi.org/10.1016/j.apsoil.2016.12.006>

Soto-Gomez, D. et al., 2020. Percolation theory applied to soil tomography. Geoderma, 357: 9. DOI:10.1016/j.geoderma.2019.113959

Totsche, K.U. et al., 2018. Microaggregates in soils. J. Plant Nutr. Soil Sci., 181(1): 104-136. DOI:10.1002/jpln.201600451

Vogel, H.J., Kretzschmar, A., 1996. Topological characterization of pore space in soil - Sample preparation and digital image-processing. Geoderma, 73(1-2): 23-38. DOI:10.1016/0016-7061(96)00043-2

Vogel, T., Gerke, H.H., Zhang, R., Van Genuchten, M.T., 2000. Modeling flow and transport in a two-dimensional dual-permeability system with spatially variable hydraulic properties. J. Hydrol., 238(1-2): 78-89. DOI:10.1016/s0022-1694(00)00327-9

Wang, B., Brewer, P.E., Shugart, H.H., Lerdau, M.T., Allison, S.D., 2019. Soil aggregates as biogeochemical reactors and implications for soil-atmosphere exchange of greenhouse gases-A concept. Glob. Change Biol., 25(2): 373-385. DOI:10.1111/gcb.14515

Watts, C.W., Clark, L.J., Poulton, P.R., Powlson, D.S., Whitmore, A.P., 2006. The role of clay, organic carbon and long-term management on mouldboard plough draught measured on the Broadbalk wheat experiment at Rothamsted. Soil Use Manage., 22(4): 334-341. DOI:10.1111/j.1475-2743.2006.00054.x

Wilpiszeski, R.L. et al., 2019. Soil Aggregate Microbial Communities: Towards Understanding Microbiome Interactions at Biologically Relevant Scales. Appl. Environ. Microbiol., 85(14): 18. DOI:10.1128/aem.00324-19

Young, I.M., Crawford, J.W., 2004. Interactions and self-organization in the soil-microbe complex. Science, 304(5677): 1634-1637. DOI:10.1126/science.1097394

Young, I.M., Crawford, J.W., Nunan, N., Otten, W., Spiers, A., 2008. MICROBIAL DISTRIBUTION IN SOILS: PHYSICS AND SCALING. In: Sparks, D.L. (Ed.), Advances in Agronomy, Vol 100. Advances in Agronomy. Elsevier Academic Press Inc, San Diego, pp. 81-121. DOI:10.1016/s0065-2113(08)00604-4

Yudina, A., Kuzyakov, Y., 2019. Saving the face of soil aggregates. Glob. Change Biol., 25(11): 3574-3577. DOI:10.1111/gcb.14779

Zhang, X.X., Crawford, J.W., Flavel, R.J., Young, I.M., 2016. A multi-scale Lattice Boltzmann model for simulating solute transport in 3D X-ray micro-tomography images of aggregated porous materials. J. Hydrol., 541: 1020-1029. DOI:10.1016/j.jhydro1.2016.08.013

Zhang, X.X., Qi, X.B., Qiao, D.M., 2010. Change in macroscopic concentration at the interface between different materials: Continuous or discontinuous. Water Resour. Res., 46: 12. DOI:10.1029/2009wr008853

Zhang, X.X. et al., 2020. A comparison between water uptake and root length density in winter wheat: effects of root density and rhizosphere properties. Plant Soil: 12. DOI:10.1007/s11104-020-04530-3

Zhang, Z.B. et al., 2019. Linking saturated hydraulic conductivity and air permeability to the characteristics of biopores derived from X-ray computed tomography. J. Hydrol., 571: 1-10. DOI:10.1016/j.jhydrol.2019.01.041

Zhou, H.X. et al., 2019. Pore-scale lattice Boltzmann modeling of solute transport in saturated biochar amended soil aggregates. J. Hydrol., 577: 8. DOI:10.1016/j.jhydrol.2019.123933

**Table 1.** Average and coefficient of variation (CV) of porosity and permeability of the aggregates under different treatments.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Porosity | | Permeability (μm2) | |
|  | Mean | CV | Mean | CV |
| Woodland | 0.331 | 0.129 | 0.568 | 0.545 |
| FYM | 0.377 | 0.119 | 0.595 | 0.295 |
| N3 | 0.236 | 0.274 | 0.102 | 0.719 |
| No p | 0.248 | 0.405 | 0.146 | 1.149 |
| Control | 0.226 | 0.213 | 0.108 | 0.611 |

**Table 2**. Average and coefficient of variation (CV) of porosity and permeability of the cores under different treatments.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Treatment | Porosity | | Vertical permeability (μm2) | | Horizontal permeability (μm2) | | |
| Mean | CV | Mean | CV | | Mean | CV |
| Woodland | 0.375 | 0.0912 | 3386.43 | 0.2184 | | 4002.6 | 0.2184 |
| FYM | 0.166 | 0.3476 | 110.87 | 0.6514 | | 560.7 | 0.6514 |
| N3 | 0.055 | 0.5275 | 8.31 | 1.9652 | | 37.09 | 1.9652 |
| No p | 0.024 | 0.3865 | 0.42 | 1.4753 | | 0.66 | 1.4753 |
| Control | 0.093 | 0.3733 | 43.87 | 1.0168 | | 98.79 | 1.0168 |



**Figure 1**. X-ray CT images of cores (40μm resolution) taken from plots under different fertilizations and the woodland



**Figure 2**. Representative greyscale (top panel) and segmented (bottom panel) images of the aggregates in cores taken from plots under different fertilizations and the woodland. (a) Farmyard manure, (b) N3, (c) No P, (d) CK, and (e) woodland.







**Figure 3**. Pore-size distribution (A), tortuosity (B), and porosity-permeability relationship for aggregates taken from all treatments (C). The porosity-permeability for aggregates in FYM and in the woodland was fitted separately to power-laws, while the aggregates in soils unfertilized and fertilized with inorganic fertilizers were grouped.





**Figure 4**. Average pore-size distribution and tortuosity for all cores (B).





**Figure 5**. Macroporosity-permeability relationship for all cores taken from different treatments. Results for the vertical permeability (A), and the horizontal permeability (B).

(A)



(B)



**Figure 6**. The increase in permeability with soil carbon at aggregate scale (A), and core scale (B).