The impact of orchard management on macro-pore topology and function

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Abstract

We analysed the long-term effect of three common orchard management practices on the soil macropore structure and function: (1) Grass sward and a regular application of compost in the tree row; (2) Soil compaction by tractor wheels in the grassed alleys; (3) Regular application of herbicides in the tree row. We focused on the top 50 mm topsoil of the tree row and under the wheel track in the alley of an organic orchard (Practice 1, 2) and of the tree row in an adjacent conventional apple orchard (Practice 3). Both orchards had the same age, soil type, texture and previous land use. After 12 years the topsoils of the organic orchard had about 30% more soil organic carbon (SOC) sequestered than the topsoils in the tree row of the conventional orchard. We quantified the macro-pore structure (macro-pores = pores > 0.3 mm) of nine undisturbed soil columns (43 mm long, 20 x 17 mm in the plane) for each practice using 3D X-ray computed tomography. The macro-porosity under Practice 1 was significantly greater, with 7.5 ± 2.1%, than that under Practice 2, with 3.6 ± 1.1% and under Practice 3, with 2.4 ± 0.5%. The connectivity of macro-pores tended to be greatest under Practice 1, but this was not statistically significant. The macro-pores under Practice 2 had a significantly greater connectivity than under Practice 3. We simulated the diffusion through the macro-pores of aggregate-scale segments of the columns. The relative diffusion coefficients were similar under Practice 1 and 2, with 0.024 ± 0.008, and 0.015 ± 0.008, respectively, and were significantly greater than under Practice 3, with 0.0056 ± 0.0009. We hypothesize that a higher relative diffusion coefficient at the aggregate scale (e.g. Practice 1 and 2 versus 3) would lead to a lower N_2O production and emission in a wet soil. We conclude that soil carbon management in the tree row of apple orchards like using grass swards and compost, leads to more macro-pores and a better gas exchange and probably less N_2O production and emission under wet conditions compared to a tree row that regularly receives herbicides. Although the compacted soil under the wheel track had less macropores than in the grassed tree row, the gas exchange under wet conditions was still similar.

Key Words

3D X-ray CT, macro-porosity, connectivity, diffusion, soil carbon management.

Introduction

Different definitions exist for the size of macro-pores, to distinguish them from other pores. Following others we defined macro-pores as pores with a diameter larger than 0.3 mm. Macro-pores are important for several soil processes and functions. For example, macro-pores can trigger preferential flow, the fast direct transfer of contaminants such as herbicides from the soil surface to the groundwater. The macro-pore structure of the top 50 mm governs the gas exchange between the soil and the atmosphere under wet conditions. In the case of nitrous oxide (N_2O), the top 50 mm of the soil additionally were shown to be the most active zone for N_2O production (Clayton *et al.* 1994). In most soils N_2O is mainly produced as an intermediate product of denitrification which is promoted by low O_2 concentrations that occur typically in wet soils. Nitrous oxide emissions from soils account for 70% of total N_2O emissions, which are estimated to be responsible for approximately 5% of anticipated global warming. In structured soils under wet conditions, N_2O is produced in the micro-pores of soil. The O_2 concentration around the aggregates is the most important boundary condition influencing N_2O production within aggregates (Sexstone *et al.* 1985; Tiedje 1988). Near saturation, only the soil's macro-pores are filled with air, promoting rapid exchange of O_2. Atmospheric O_2 is exchanged over their interfacial areas with adjacent structures. Therefore, while the N_2O production happens at the scale of micro-pores within aggregates, it is regulated by the O_2 exchange processes at the scale of the soil's macro-pore network. Consequently, a difference in macro-porosities will modify the gas exchange between the soil and the atmosphere. For example, increasing the macro-porosity of wet soils results in greater rates of O_2 exchange with the atmosphere, and as a consequence the production and, therefore, the emission of N_2O may be reduced. Several field experiments have reported reduced N_2O emissions from soils containing comparably larger macro-porosities. We hypothesize that the emission of N_2O from soils is an environmental risk that, *inter alia,* depends on the soil's macro-pore structure.

We compared the soil's macro-pore structures and function of the top five centimetres of soil subject to three different orchard management practices. We addressed two questions: 1) Are the soil's macro-pore structures under three different orchard management practices significantly different? 2) Is the gas exchange around aggregates under wet conditions significantly different under the three different management practices?

Methods

Study sites

We selected a pair of soils under apple orchards in Hawke's Bay (North Island of New Zealand). The topsoils are of alluvial origin, and have a silt loam texture. One of the sites contained the grassed tree rows and alleys of an organic orchard (Practice 1 and 2) and the other site had the herbicided tree rows of a neighbouring integrated apple production system (Practice 3). Both orchard systems are 12 years old. Green-waste compost has been applied to the topsoil of the tree rows of the organic system once a year at a rate of 5 to 10 t ha^{-1}. A 0.5-m wide strip under the trees has been kept vegetation-free by regular herbicide applications in the integrated system.

Analysis of the soil's 3D macropore structure

1. *Sample selection and preparation:* We took three undisturbed columns (70 mm diameter, 100 mm length) from each of the tree orchard management practices. The top of the columns were level with the soil surface and the main axis of the columns was perpendicular to the soil surface. Prior to the X-ray imaging we carefully cut each soil column into four sub-columns of equal dimensions. Three out of the four sub-columns of each column were randomly selected for X-ray imaging.

2. *Three-dimensional X-ray Computed Tomography:* For X-ray tomography imaging we used a Metris X-tek Benchtop CT system (Metris X-tek Systems Ltd., Hertfordshire, United Kingdom) at SIMBIOS Centre of the University of Abertay (Dundee, Scotland) with the 160 kV X-ray source and a 12-bit CCD camera. The three-dimensional images of attenuation coefficients with the isotropic voxel size of 86 μm were translated into a continuous stack of two-dimensional 8-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 86 μm and an in-plane resolution of 86 x 86 μm.

3. *Digital image processing and analysis:* We conducted the digital image processing and analysis using the public domain software ImageJ (developed by W. Rasband at the National Institute of Health, USA; http://rsb.info.nih.gov/ij/), the soil-specific package of plugins for ImageJ, SCAMP, that was developed by SIMBIOS (University of Abertay, Dundee, Scotland), and a package of C-functions for image analysis QuantIM, Version 4 (Vogel 2008). We visualized the three-dimensional macro-pore structures with the software OpenDX (open source software version of IBM's Visualization Data Explorer; http://www.opendx.org/index2.php).

The image processing and analysis consisted of four steps. Firstly, we cropped the three-dimensional image data set of each sub-column to a length of 43 mm and a dimension of 20 x 17 mm in the plane. Secondly, we transformed the stack of 8-bit TIFF slices to a stack of binary images (black = pore space; white = solid phase) using a bi-level segmentation algorithm. Next, we removed all pores smaller than 344 μm in diameter from the binary images, limiting our analysis to macro-pores larger than 0.34 mm. Finally, we quantified the macro-pore volume density (i.e. macro-porosity) and the three-dimensional connectivity of macro-pores. The latter was quantified with the volumetric Euler-Poincaré characteristic for pores with a minimum pore diameter of 0.3 mm. The higher the value of the volumetric Euler-Poincaré characteristic the smaller is the connectivity of the respective pore system. For convenience we use the term 'Euler number' to denote the value of the volumetric Euler-Poincaré characteristic.

Simulation of gas diffusion through a soil's macro-pore network

We simulated the gas diffusion through segments of the three-dimensional macro-pore network and derived gas diffusion coefficients for the measured macro-pore structures. The segments were 4.3 mm long and had the dimension of 20 x 17 mm in the plane. Our objective was to analyze the gas diffusion in the macro-pores around soil aggregates. The mean weighted diameter (MWD) of water-stable aggregates in the 0-0.1 m depth of the tree rows of the organic and integrated orchard system was 1.8 mm and 1.3 mm, respectively (Deurer *et al.* 2008). Therefore, the 4.3 mm length of each segment was at least twice the MWD of the aggregates of the orchard soils, and we assume represented the relevant dimensions of gas exchange around aggregates.

The package QuantIM (Vogel 2008) contains an algorithm for simulating gas diffusion through a continuous stack of two-dimensional binary images. For the simulation we assumed the following set of initial and boundary conditions. At the top of the segment the concentration was fixed to a constant value while the concentration at the bottom of the segment was set to zero throughout the simulation. The initial concentration within the pore space of the segment was set to zero. The vertical boundaries of the segment were assumed to be impermeable to gas. Once the gas flow at the bottom of the sample reached an asymptotic state, the relative apparent diffusion coefficient D_r [-] was calculated by relating the simulated asymptotic diffusive flow through the macro-pore space at the bottom of the segment to the diffusive flow through the same segment that now consisted only of free air (= 100% porosity).

Results

We analysed how different orchard management practices impact on the macro-pore structure of topsoils. The Practice 1 of using a grass sward and the regular application of compost represents a typical soil carbon management that is known to increase both soil carbon sequestration and soil health and is used in organic orchard systems (Deurer *et al.* 2008). The Practice 2 represents the typical impact of soil compaction by long-term tractor traffic in a grassed alley that occurs both in organic and integrated orchard systems. The Practice 3 represents the lack of any soil carbon management as is typical for the tree rows of most integrated apple orchard systems. We reconstructed the detailed macro-pore networks in three dimensions with X-ray CT (Figure 1). Under Practice 1, with 7.5 ± 2.1 Vol.%, the macro-porosity was significantly ($P < 0.05$) higher than under Practice 2 with 3.6 ± 1.1 Vol.%, and under Practice 3 with 2.4 ± 0.5 Vol.% (Table 1). Other studies with a similar definition of macro-pores reported similar macro-porosities ranging from 1.3 to 14 Vol.% for fine-textured top-soils under arable or pastoral land use. The connectivity tended to be highest under Practice 1 (Table 1). However, this was not statistically significant as the variability of the Euler number under Practice 1 was extremely high (Table 1). Practice 2 limited macro-porosity less than did Practice 3 (Table 1). Our range of Euler numbers for pores with a diameter larger 0.3 mm agreed well with other comparable studies.

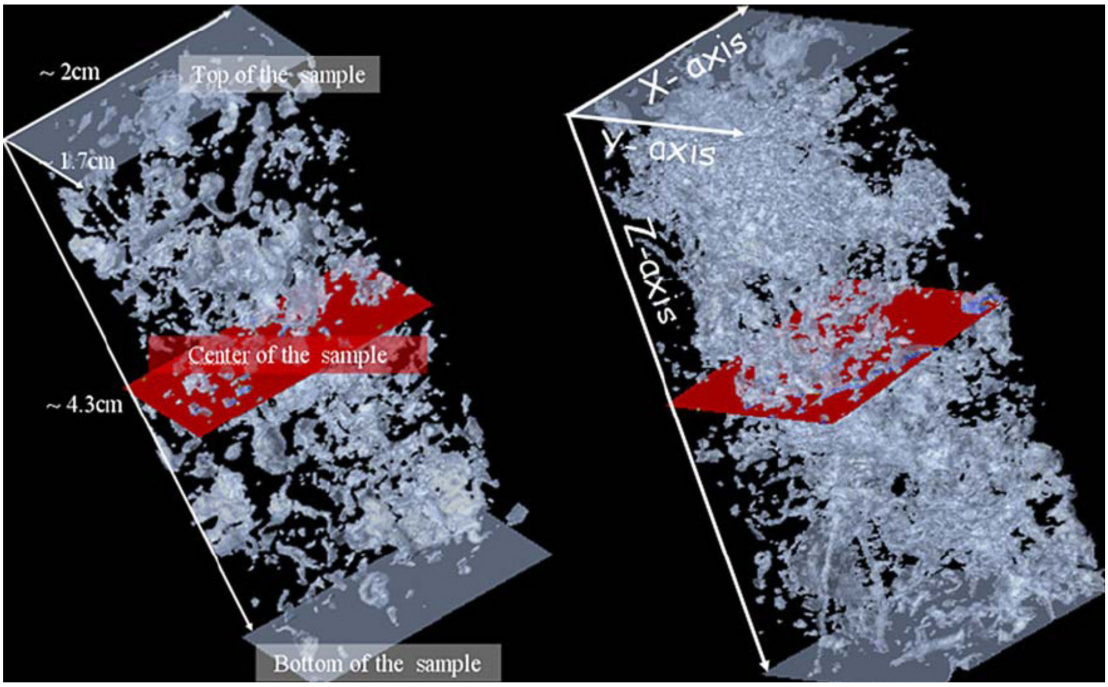

Figure 1. Examples of macro-pore networks in the top 50 mm of soil in the tree rows of two apple orchard systems in Hawke's Bay, New Zealand. The gray coloured areas are macro-pores. The three x-y planes are shown to mark the top, centre and bottom of the sample. Left: **Macro-pore network of the herbicided tree row of the integrated orchard system (Practice 3). The macro-porosity is 2.9 Vol.%.** Right: **Macro-pore network of the grassed tree row of the organic orchard system (Practice 1). The macro-porosity is 8.3 Vol.%.**

From our gas exchange simulations around the aggregates for wet conditions we found that the relative diffusion coefficients were similar under Practice 1 and 2, with 0.024 ± 0.008, and 0.015 ± 0.008, respectively, and were significantly higher than under Practice 3, with 0.0056 ± 0.0009 (Table 1). We suggest that the larger relative diffusion coefficients in the soils of the organic orchard (Practices 1 and 2) indicate less favourable physical conditions for N_2O production and emission. Therefore, this indicates that soil C management as Practice 1 possibly combats climate change in two ways. It firstly leads to C sequestration, and secondly might also contribute indirectly to a reduction in N_2O emissions.

Table 1. Macropore structure and function as consequence of three different apple orchard management practices. Practice 1: Using a grass sward and the regular application of compost in the tree row. Practice 2: Soil compaction by the tractor wheels in the grassed alley. Practice 3: Regular application of herbicides in the tree row. The values represent the means of three soil columns with the standard deviation of the mean in brackets.

Property	Practice 1	Practice 2	Practice 3
Macro-porosity [Vol.%]	7.5 (2.1)	3.6 (1.1)	2.4 (0.5)
Euler number [/mm^3]	6.6×10^{-3} (2.9×10^{-2})	6.3×10^{-3} (3.3×10^{-3})	2.0×10^{-2} (4.8×10^{-3})
Relative diffusion coefficient [-]	2.4×10^{-2} (7.9×10^{-3})	1.5×10^{-2} (7.9×10^{-3})	5.6×10^{-3} (9×10^{-4})

Several studies have stressed that diffusive gas exchange in soils depends on both the porosity and the connectivity of the gas-filled pore space, especially at the wetter end of the soil water content range (Tuli and Hopmans 2004; Weerts *et al.* 2001). In a multiple regression, 76% of the variability of the aggregate scale relative diffusion coefficient in the soil under Practice 3 was explained with macro-porosity and the Euler number as the significant variables. However, in the regression for the soil under Practice 1 and 2 only the macro-porosity was a significant variable and explained 71% and 83% of the variability respectively.

Conclusions

We studied how three different orchard management practices affected the soil macro-pore structure and the near-surface gas exchange under wet conditions. We found that all three orchard management practices had an impact on soil macro-pore structure and function of the top 50 mm of soil. We conclude that soil carbon management in the tree row like using grass swards and compost (Practice 1) leads to more macro-pores and a better gas exchange under wet conditions and probably less N_2O production and emission compared to a tree row that regularly receives herbicides (Practice 3). Although the compacted soil under the wheel track (Practice 2) had less macropores than in the grassed tree row, the gas exchange under wet conditions was still similar.

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