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Evaluation of X-ray computed tomography for quantifying macroporosity of loamy pasture soils

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ABSTRACT

Macropores are important pathways for rapid infiltration of water into soil as large soil pores allow roots, air, and water to penetrate into the soil. Soil compaction due to dairy cattle trampling may reduce soil macroporosity to the extent that growth or even survival of roots is limited by oxygen availability and soil strength. This study aims to evaluate the feasibility of X-ray computed tomography (CT) for determining macroporosity in dairy pasture soils and to assess the effects of sample volume (both within and between cores of varying sizes) and locations (i.e. site and soil depth) on measures of porosity. Undisturbed soil cores (50 and 65 mm diameter) were collected from two depths (0 to 10 cm and 20 to 30 cm) and from three sampling sites (representing moderately to highly trafficked zones) within a commercial dairy paddock. The intact soil cores were scanned at three resolutions (30, 109 and 138 μm) using X-ray CT, and porosity and mean pore diameter measured in various volumes of these scans. Porosity and mean pore diameter decreased with depth but did not differ across the three sampling sites; this was consistent with measures of porosity based on a traditional bulk density based method and soil water retention curves. There was no significant ($P > 0.05$) effect of analysing porosity at increasing distances from the core edge. Likewise, increasing the volume of soil that was analysed within each core was not found to have a significant ($P > 0.05$) effect on macroporosity. However, mean pore diameter was found to significantly ($P < 0.05$) increase with increasing volume of soil measured (both within a soil core and with increasing core size) and significantly ($P < 0.05$) decrease with increasing resolution of the scans. The results suggest that while absolute measures of macroporosity might not change with core size or the volume of soil analysed, the pore-space characteristics that are captured differ significantly. Macroporosity values for various pore size classes (0.2 to 298 μm pore diameters) assessed using soil–water retention curves compared with those determined using the X-ray CT were found to be comparable. Consequently, X-ray CT is a valuable tool for characterising pore-space from the macro- to the micro-scale, however, sampling and analysis strategies must be appropriate for the specific research aims. The practical implications of the results are discussed.

1. Introduction

The influence of macroporosity i.e. pores larger than 30 μm in diameter, on soil infiltration, water retention and movement of agrochemicals and bacteria through soil profiles and subsequently into the sub-surface is well recognised around the world (Allaire-Leung et al., 2000; Amer et al., 2009; Anderson et al., 2010; Asare et al., 2001; Perret et al., 1999). Understanding the influence of soil macropore distribution on aeration and soil water relationships is important for evaluating root growth and root respiration. In grazing systems, maintaining pasture growth is integral to productivity. However, soil compaction due to livestock grazing can be substantial (Betteridge et al., 1999; Chaichi et al., 2005; Drewry et al., 2008; Greenwood and McKenzie, 2001; Greenwood et al., 1997; Singleton et al., 2000; Stavi et al., 2011), and this reduces soil macroporosity (e.g. Krümmelbein et al., 2009) and breaks vertical pore continuity (Greenwood and McKenzie, 2001; Reszkowska et al., 2011) through the disruption of aggregates into smaller particles and the repacking of smaller particles to fill existing voids (Cattle and Southorn, 2010). Soil compaction may reduce macroporosity to the extent that growth or even survival of roots is limited by oxygen availability and high soil strength.

Traditionally, the soil–water retention method has been used widely around the world for characterising the macroporosity and pore-size distribution of soils (e.g. Amer et al., 2009; Rachman et al., 2005; Stingaciu et al., 2010; Vogel, 2000). This method involves laboratory measurement of soil–water content at various soil–water matric potentials and inferring porosity using the relationship between pore diameter and liquid flow. However, this method does not provide distribution of pores larger than 300 μm in diameter nor their continuity.

Advances in the application of computed tomography (CT) for evaluation of soil porosity have added a new research tool for investigating

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macroporosity distribution and pore diameters (Anderson et al., 1990, 2010; Borges et al., 2012; Cortina-Januchs et al., 2011; Kim et al., 2010; Munkholm et al., 2012, 2013; Taina et al., 2008; Vaz et al., 2011). Computed tomography is a non-invasive imaging technique that allows high resolution, three-dimensional, non-destructive imaging of heterogeneous soils and permits actual, rather than inferred, characteristics of soil pores (Cortina-Januchs et al., 2011; Grevers et al., 1989). X-ray CT scanning methods have been used effectively for measuring pore size, shape, distribution and arrangement of soil pores, surface area and pore connectivity (Kumar et al., 2010; Udawatta et al., 2008). CT methods provide a fine resolution of measurement, on a millimetre to micrometre-scale (Gantzer and Anderson, 2002; Kim et al., 2010; Kumar et al., 2010) and hence have the potential to detect small differences in pore geometry and other spatial parameters.

Despite the value of CT as a technique for understanding the impacts of animal compaction on soil macroporosity and subsequent implications for pasture productivity, very limited information is available (Pires et al., 2004) on the optimum sampling strategies (both within and between intact soil cores) for measuring pore characteristics of pasture soils using X-ray CT. There is also a lack of information available (but see Rachman et al., 2005; Stingaciu et al., 2010; Vogel, 2000) on the comparison of CT-measured and soil–water retention method soil porosity. The objectives of this study were to: (i) evaluate the effects of sample core diameters and spatial resolutions on porosity characteristics of loamy pasture soils using X-ray CT technology; (ii) quantify the effect of sample volume and edge effect on porosity characteristics using CT technology; (iii) determine vertical variations in porosity characteristics within collected samples and compare with whole-sample-measured values; and (iv) compare porosity measured by X-ray CT technology with porosity measured by traditional methods.

2. Materials and methods

2.1. Site description

This study, which took place in spring 2011, was conducted on a 2 ha paddock of a commercial grazing system dairy farm located 150 km south east of Melbourne, south eastern Australia (38° 13′ S and 145° 48′ E). The paddock elevation ranged from 114 to 126 m above sea level and the landform comprised undulating rises. The soil type of the paddock, classified according to Australian Soil Classification System (Isbell, 2002), is a Brown Dermosol and according to Word Reference Base System (IUSS Working Group WRB, 2007) is Umbric Alisol. This soil is formed mostly on cretaceous parent material with some tertiary and paleozoic sediments. The long-term mean annual rainfall, for the period 1902 to 2011, recorded 10 km away from the study site was 1004 mm. The mean annual temperature is 18 °C and can range from 0 °C in winter to 40 °C in summer.

In the grazing systems typical of this region, the herd spends the majority of their time grazing pasture paddocks and typically about 10% of their time in the milking facility. The study paddock has been used as one of the ‘night’ paddocks, for 15 years i.e. where the milking herds are held between the evening and morning. In 2007 the paddock was resown to a permanent pasture after first ploughing and sowing a summer crop of turnips (*Brassica* spp) in the previous spring (2006). The pasture was dominated by perennial ryegrass (*Lolium perenne* L.) with low white clover (*Trifolium repens* L.) content. Lime was applied at 1 tonne ha^{-1} when the turnip crop was planted. Urea has been applied annually at a rate of 70 kg ha^{-1} while phosphorus and potash were applied as 1 & 1 fertiliser (4.4% P, 25.0% K, 5.5% S and 9.5% Ca) at 250 kg ha^{-1} annually from 2001 to 2009. Silage has been harvested from this paddock every year for the past ten years.

2.2. Soil sampling

Three sites were selected within the study paddock: gateway, upper slope, and lower slope. At each site a 5 m × 5 m area was established and within this area eight sampling locations were selected randomly by throwing a pencil backward. Soil samples were collected using 50 mm PVC tubes (50 mm diameter × 63 mm long, with a wall thickness of 3 mm) at four of the eight locations and at the other four locations soil samples were collected using 65 mm PVC tubes (65 mm diameter × 63 mm long × 3 mm). At each sampling location, the intact soil samples were collected from the 0 to 10 cm and 20 to 30 cm soil depths giving a total of 48 samples. The PVC tubes were driven into the soil gently with a falling weight hand corer. The intact core samples were trimmed, sealed in plastic and stored at room temperature (22 °C) until scanned. Macroporosity and pore diameters were measured in the 48 intact cores using CT. At each of the sampling locations, additional intact samples were taken at corresponding soil depths using 73 mm diameter by 63 mm long brass cores for measuring porosity characteristics using a soil water retention method.

Additional soil was collected at each core location for analysis of routinely measured soil properties. Mean values of some physical and chemical properties for three sampling sites at two soil depths are presented in Table 1. Clay content did not vary between the three sites (gateway, upper slope or lower slope) or the two soil depths; silt content increased and coarse sand content decreased with depth only at the gateway. Fine sand was the dominant soil fraction (54–59%), followed by silt content (25–29%). Soil texture, determined according to the ISSS system (Leeper, 1974), showed that silty loam was the dominant soil texture at both soil depths. Most chemical properties did not vary between sites but varied with depth. Total carbon (TC) content was consistently higher in the 0 to 10 cm than in the 20 to 30 cm depth. Calcium and Na were higher in the upper soil depth but EC, pH and K were similar at both depths. Calcium was the major cation in these soils.

2.3. Porosity characteristics using X-ray CT

2.3.1. X-ray CT system and image analysis procedures

Intact soil cores were scanned using a Vtomexs system (GE Phoenix, Germany) fitted with an X-ray microfocus tube (240 kV source, 4 μm spot size, tungsten reflective target) and a 512 × 512 pixel array detector. Cores were scanned using a full 360° rotation of the sample. Digital

Table 1
Mean soil chemical and physical properties at three sites (gateway, upper slope, lower slope) and two soil depths in the study paddock.

	Site					
	Gateway		Lower slope		Upper slope	
	Depth (cm)		Depth (cm)		Depth (cm)	
	0–10	20–30	0–10	20–30	0–10	20–30
Soil property						
Clay (%)	12	12	11	10	11	11
Silt (%)	25	29	25	26	25	25
Fine sand (%)	55	54	59	58	58	59
Coarse sand (%)	8	4	5	6	5	5
Total sand (%)	63	59	64	64	64	64
TC (%)	5.1	1.4	4.4	1.0	4.3	2.0
EC (dS/m)	0.1	0.1	0.2	0.1	0.1	0.1
pH (water)	5.2	4.8	4.8	5	5.4	4.9
pH ($CaCl_2$)	4.6	4.2	4.4	4.4	4.7	4.3
Exchange cations (cmol$^{(+)}$ kg^{-1})						
Ca	3.6	1.0	3.4	0.93	3.6	1.1
Mg	1.2	0.4	0.8	0.3	1.1	0.4
K	0.5	0.1	0.2	0.1	0.2	0.2
Na	0.2	0.1	0.1	0.1	0.1	0.1
Sum of four cations	5.4	1.6	4.6	1.3	5	1.7

TC, total carbon.