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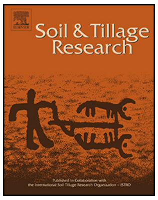

A study on the effect of compaction on transport properties of soil gas and water I: Relative gas diffusivity, air permeability, and saturated hydraulic conductivity

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ABSTRACT

Operation of farm machinery in agricultural fields is the main cause of soil compaction, which may have detrimental effects on soil gas and water transport. However, application of organic matter (OM) reduces the adverse effects of compaction and improves transport properties of soil gases and water. To date, experimental data on the effect of compaction on those transport properties and its relationship to the presence of applied OM remains scarce. The effect of compaction on relative gas diffusivity $(D_p/D_0)_{100}$ and air permeability (k_{a100}) at a soil matric suction of -100 cm H_2O (soil pF 2.0), and saturated hydraulic conductivity (k_s) were investigated using disturbed soil sample taken from 0–15 cm layer mixed with rice husk, rice straw, compost, sawdust, and wood bark at a rate of 20% of the soil volume. The common compaction caused by farm machinery in agricultural fields was simulated in the laboratory using a static compression load of 150, 225, and 300 kPa. The effect of compaction on total porosity (f) and air content at soil pF 2.0 (ε_{100}) was also examined. Compaction reduced f, ε_{100}, $(D_p/D_0)_{100}$, k_{a100}, and k_s, with the more pronounced significant difference between 150 and 300 kPa compactions. The decrease in $(D_p/D_0)_{100}$ was likely attributable to a reduced air content, and the decrease in k_{a100} and k_s was likely attributable to a reduced volume of macropores, as indicated by reduced ε_{100} values. Compared with the control, addition of sawdust and wood bark seemed to have the most positive effect on $(D_p/D_0)_{100}$, k_{a100}, and k_s in term of resistance to compaction, while rice straw had the opposite effect. The presence of OM was likely to block the soil pores and increase capillary water in the bottle-neck, leading to lower values of $(D_p/D_0)_{100}$ and k_{a100} for a given value of ε_{100} ("blockage effect"). These pores blocked by OM, however, seemed to allow the water to flow through the soil matric ("ceramic filter effect"). Further studies on the prolonged application of OM at field scale, taking into account the decomposition process, should be conducted.

1. Introduction

Transport properties of gases and water in soil are important determinants of soil quality for supporting plant growth. The transport properties of soil gases may be used to describe aeration (Glinski and Stepniewski, 1985; Taylor, 1949; Yoshikawa and Hasegawa, 2000), which is important for allowing O_2 intake and CO_2 discharge by plant roots (Hillel, 1998). With better aeration, plant growth may be improved (Jackson, 1962; Liang et al., 1996), while conversely, reduced aeration may reduce plant growth (Wall and Heiskanen, 2009). Other than requiring air for respiration, plants require water, which plays a central role as a major metabolic agent for growth that is a source of H atoms for photosynthesis (Hillel, 1998). Plant roots absorb water from the soil, and thus, transport properties of the soil water become determinants of plant growth.

In agricultural fields, farm machinery used in tillage is recognized as the most common cause of compaction (Hill, 1990; Hill and Meza-Montalvo, 1990), which increases soil bulk density and reduces porosity (Etana et al., 2013; Ishaq et al., 2001) resulting in a decline in permeability so that aeration (Lipiec and Hakansson, 2000; Startsev and McNabb, 2009) and water

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infiltration (Kozlowski, 1999; Plaster, 1997) become difficult. Hydraulic conductivity is also reduced (Etana et al., 2013; Marsili et al., 1998), which leads to drainage becoming more difficult. Other studies have also shown that compaction decreases the growth of plant roots (Glab and Kopec, 2009; Grzesiak, 2009; Janssen and van der Weert, 1977).

Organic matter (OM) application into agricultural fields is a means of improving soil physical properties and hence enhancing crop growth and yield. OM application reduces bulk density and cone penetration resistance (Aggelides and Londra, 2000; Celik et al., 2010) and increases soil aggregation (Garcia-Orenes et al., 2005; Oyedele et al., 1999), porosity (Khan et al., 2000; Oyedele et al., 1999), and water retention (Johnson et al., 2006; Nyamangara et al., 2001) as well as hydraulic conductivity (Gonzalez and Cooperband, 2002; Schjønning et al., 2005). Also, it has been shown to improve soil aeration (Khan et al., 2000; Khan, 1996).

While there are some studies on the effects of compaction on transport properties of soil gases (e.g. Ball and Ritchie, 1999; Berisso et al., 2012; Simojoki et al., 2008) and also soil water (e.g. Etana et al., 2013; Kim et al., 2010; Marsili et al., 1998), experimental data related to the presence of applied OM, particularly data derived from crop debris or its products, are rare. In this study, the effect of compaction on soil gas and water transport was investigated following the application of OM (crop debris and its product) within a very short period after the OM application.

2. Materials and methods

2.1. Soil sampling and compaction experiment

Samples of a sandy loam volcanic ash soil (Table 1) were collected at a depth of 0–15 cm from the "Takizawa" experimental field of Iwate University (39°46′59.5″N, 141°07′35.7″E) in Iwate prefecture, northern Japan. The field has been fallow for the last four years and only subjected to mowing four times annually using a mowing tractor; the soil quality of this field is poor as implied by low gas transport properties shown in Table 1. The collected samples were lightly sieved (4.76 mm) and gravel and crop debris were carefully removed. The samples were set for 0.70 g g^{-1} in water content referring to the original state of the soil when the sampling was conducted. A 471 cm^3 cylinder (10 cm wide and 6 cm long) with collars at both the upper and lower sides of it was then filled with the soil sample. Subsequently, the sample was gently tamped using small and light tamper until the targeted cylinder (471 cm^3) and one-third volume of both the upper and lower collars of it were filled. The sample was then uniaxially compacted under static loads of 150, 225, and 300 kPa using a modified triaxial test machine in the laboratory (Fig. 1). Finally, excessive parts of the soil over the both ends of the targeted cylinder were trimmed. The static loads were chosen to simulate soil compaction which commonly occurs in agricultural fields because of the farm machinery operation. The mechanism of static compression used for the compaction (Fig. 1) provided a concomitant downward and upward compression by which friction between soil sample and cylinder wall may be suppressed by about a half. The device also allows the production of a rather large diameter of soil specimen which suppresses edge effects between the soil sample and cylinder wall so that possible leakage or bypass through the cylinder edge can be minimized.

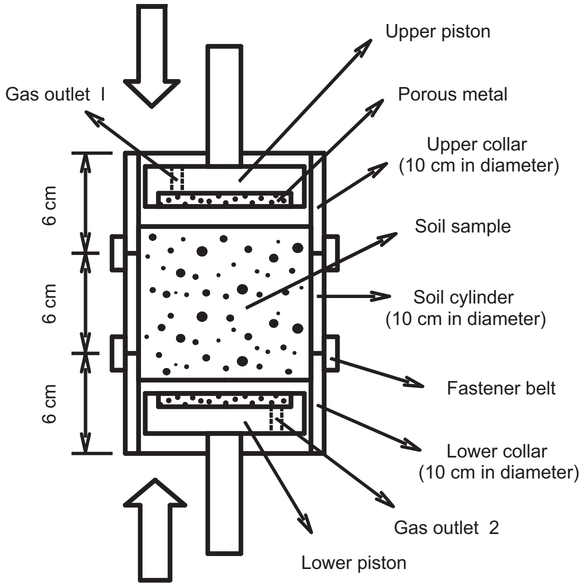

Fig. 1. Schematic diagram of a floating-type soil cylinder and a piston for static compression (attached to the triaxial cell test machine).

2.2. Organic matter (OM) treatment

A soil sample without any applied OM treatment was used as a control. For the soil with applied OM treatments, samples of each of rice husk, rice straw (cut into 2 cm lengths), wood bark compost, sawdust, and wood bark (Table 2) were mixed with the soil at a rate of 20% by volume immediately before they were repacked into the soil cylinder and compacted. This rate of 20% OM was considered to be practical and yet distinctive to see the effectiveness of the applied OM in changing soil physical properties. For the soil volume determination, volume of soil at field condition when the sampling was conducted was taken as a basis. Thus, the volume of soil could be determined from the data of field wet bulk density (1.19 g cm^{-3}) and the mass of the prepared soil (0.7 g g^{-1} in water content). The volume of the applied OM could easily be determined by multiplying the volume of soil by 0.2.

2.3. Measurements

The compacted soil specimen was preliminarily saturated with water for measurement of saturated hydraulic conductivity (k_s)

Table 1
Physical properties of the undisturbed soil and its texture.

Organic matter content (%)	20.2
Gravimetric water content (g g^{-1})	0.70
Particle density (g cm^{-3})	2.52
Dry bulk density (g cm^{-3})	0.700
Relative gas diffusivity at soil pF 2.0 ($m^2 s^{-1} m^{-2} s$)	0.003
Air permeability at soil pF 2.0 (μm^2)	0.448
Saturated hydraulic conductivity (cm s^{-1})	4.8×10^{-5}
Texture:	
Sand [2–0.02 mm] (%)	72.5
Silt [0.02–0.002 mm] (%)	16.1
Clay [<0.002 mm] (%)	11.4

Table 2
Physical properties of the applied OM.

	Solid phase density[a] (g cm^{-3})	Dry bulk density[b] (g cm^{-3})	Organic content[c] (%)
Rice husk	1.61	0.106	78.8
Rice straw	1.54	0.071	87.5
Wood bark compost	1.64	0.199	82.1
Sawdust	1.48	0.135	99.1
Wood bark	1.51	0.078	97.4

[a] Pycnometer method.
[b] Gravimetric method.
[c] Muffle oven test (750 °C).