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Dye tracer and infiltration experiments to investigate macropore flow

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Abstract

Dye tracer experiments provide qualitative pictures to illustrate the flow pathways in soil. Combined to the laboratory analysis and *in situ* irrigation experiments they provide better understanding of hydrodynamic aspect of flow processes in soil. This study was conducted to assess the impact of compaction and tillage on soil structure of two different soils. Lateral exchange LE from macropores into the surrounding soil matrix was investigated to show the efficiency of macropores in conducting water. Two sites were compared with each other. Site 1 was used as grassland and site 2 as barley. The highest concentration values of the dye tracer most frequent at the topsoil of grassland and the lowest value of LE show that more tortuous macropores were destroyed by compaction. Consequently, only the larger less tortuous and efficient ones remain. The surface density diagram shows a significant raise of dye coverage below 0.30 m. This is due to an increased network of macropores with decreasing diameters which leads to an enhanced penetration of tracer into the matrix. The only significant difference between topsoil pore volumes of the two sites concerns pores with a diameter larger than 50 μm. In fact, these pores are observed more frequently in the barley site than in the grassland site. The measured porosities and the hydrodynamic variation of water content confirm the loosening tillage effect of the topsoil as well.

Keywords: Macropore flow; Unsaturated zone; Dye pattern; Grassland; Barley soil; Compacted soil; Tillage effect

1. Introduction

Agricultural soils are subject to loosening process by tillage and load bearing processes by traffic during the seasonal production cycle. As a result of different natural and man-induced changes in soil structure and strength, trafficability, in turn, follows a dynamic pattern during a year (Perdok and Kroesbergen, 1999). Soil compaction occurs when the applied stress exceeds the strength of the soil (Guérif, 1994; Van den Akker, 1994) implying strong modifications to soil structure and generally an increase in bulk density (reduction in porosity) whereas, tillage has a loosening effect on soil structure (Alaoui and Helbling, 2006). Schjønning and Rasmussen (2000) reported that under the same conditions, no tillage compared to conventional tillage resulted in lower volume of macropores (>30 μm) on sandy loam.

The effect of soil compaction on saturated water flow is largely governed by larger pores (i.e., preferential flow) (Ehlers, 1975; Lin et al., 1996; Lipiec et al., 1998), that are negatively related to soil compaction (Carter, 1990). It has been shown that increased soil compactness induced by vehicular traffic reduced the volume of stained macropores contributing to water flow (Lipiec et al., 1998; Håkansson and Lipiec, 2000) and their continuity (Lipiec and Stępniewski, 1995; Arvidsson, 1997). This corresponds with other results which show that under conservation tillage the presence of continuous large pores increase saturated hydraulic conductivity despite a higher bulk density (Lipiec and Stępniewski, 1995; Arvidsson, 1997). The active macropores have a significant effect on the water flow. As shown by Alaoui and Helbling (2006), the estimated-macropores volume representing only 0.23 to 2% of total soil volume transported approximately 74 to 100% of total water flow. Lin et al. (1996) reported that 10% of macropores (>0.5 mm) and mesopores (0.06–0.5 mm) contributed about 89% of total water flux.

The contributions of pores of various sizes are interrelated. It was reported that, as the proportion of large pores decreases, the proportion of small pores increases (Walczak, 1977, Assouline et al., 1997; Ferrero and Lipiec, 2000). Richard et al. (2001)

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demonstrated that compaction did not affect the textural porosity (i.e. matrix porosity), but it created relict structural pores that are accessible only through the micropores of the matrix. It was shown that the effect of soil compaction on the hydraulic properties, which can be used as an indicator of the consequences of compaction. It was also suggested that lacunar and structural pores could interact to determine together the hydraulic properties of soil.

The role of soil structure for water infiltration can be assessed by using dye staining techniques to trace the infiltration pathways e.g. in compacted and non-compacted soils. Various studies showed that flow patterns are a sensitive indicator to characterize different infiltration regimes (Ghodrati and Jury, 1990; Flury et al., 1994; Gjettermann et al., 1997; Zehe and Flühler, 2001). Dye stain coverage has been used to examine the number, size and shape of conducting pores in order to provide water transport characteristics of soils (Bouma and Dekker, 1978). Droogers et al. (1998) proposed a system for the quantitative assessment of staining patterns ranging from basic parameters, like the number of pores to more complex expressions, such as fractal dimensions. The methods used by authors to obtain concentration categories are somewhat complicated and rather tedious.

In a hydrological context, many studies have dealt with the effect of soil compaction on soil hydrologic properties (e.g. Alakukku, 1996; Assouline et al., 1997; Betz et al., 1998), however, few investigations were concerned with the effect of soil compaction on infiltration (Van Dijck and Van Asch, 2002). Quantitative analysis of infiltration under different saturation levels may offer better-suited information on the effects of compaction on soil structure (Alaoui and Helbling, 2006).

In this study we present the results of field experiments that were designed to investigate macropore flow in unsaturated zone. Therefore our objectives were: (1) to combine a dye tracer technique with the laboratory analysis and *in situ* infiltration experiments to assess flow processes; (2) to investigate the impact of compaction and tillage on changes of soil structure. However, a simplified method based on the image analysis to visualize macropore pathways was presented.

2. Material and methods

2.1. Location and soil description

Table 1
Basic soil properties of investigated area in Oensingen

Depth interval (cm)	Particle size distribution (%)			Texture	Organic matter OM (%)	pH
	Clay (<2 μm)	Silt (2–60 μm)	Sand (>60 μm)			
0–25	43.0	47.5	9.5	Silty clay	2.8	5.5
25–40	45.2	46.3	8.5	Silty clay	1.3	5.9
40–60	47.6	45.9	6.5	Silty clay	0.6	5.9
60–70	52.4	41.6	6.0	Silty clay	0	5.9

Texture, organic matter OM and pH of Oensingen soil. Textural analysis was according to the USDA soil taxonomy.

The experimental area is located near Oensingen in Kanton Solothurn, Switzerland (Swiss topo coordinates: 622 350/237 390). The soil is situated in the Swiss Central Plateau (450 m above sea level) and has developed on clayey alluvial deposits down to a depth of about 1.6 m. The soil has been classified as Eutric-Stagnic Cambisol. Its texture consists of silty clay to a depth of 0.80 m (Table 1). Its organic carbon content varies from 2.8% (topsoil) to 0% (subsoil). The porosities lie between 0.44 and 0.49 m^3 m^{-3}. A pH of 5.5 was measured near the soil surface, the value slowly increased to 5.9 below 0.25 m. Because of the high clay content (43–52%) the soil also has moisture expansion properties which causes cracks when the material is dry. Below the B1 horizon, the water table varies between −1 and −2 m, but may drop below −4 m during extreme dry periods, as observed in summer 2003. A network of macropores comprising root and earthworm channels was visible to a depth of 0.70 m.

A field track for the machines separates the grassland and the barley fields. Site 1 is the nearest to this track which is occasionally used by heavy machines. This may reflect a relative compaction on its soil surface. At site 1 the sections were excavated parallel to the field track. Section 0 cm was closest to the field track while section 100 cm was furthest away. Consequently, we expect an increasing soil compaction effect from section 100 to section 0 cm.

On the 3rd August 2004 winter wheat was harvested with a combine harvester, eleven days later the soil was loosened to a depth of 0.1 m using a chisel plough; shortly afterwards winter barley was sowed, which was harvested with two combine harvesters on 14th July 2005. A week later stubble and soil treatment was conducted to a depth of 0.2–0.3 m by using a chisel plough. Three successive water irrigations were applied on both sites 1 and 2 on 11th July and 8th August 2005 respectively. On 23rd August 2005, a dye infiltration experiment was carried out in site 1.

2.2. Laboratory analysis

Saturated hydraulic conductivity K_{sat} was determined on samples of undisturbed soil with a diameter of 55 mm and length of 42 mm. K_{sat} was determined with a constant head permeameter (Klute and Dirksen, 1986). Porosity and bulk density were determined on samples of undisturbed soil with a diameter of 115 mm and length of 98 mm whereas organic matter was determined by weight loss on ignition. The pore volume distribution was determined by a vacuum pressure membrane apparatus with hanging water column for a $pF<2.5$ and with a gaz adsorption porosimetry using N_2 for $2.5<pF<3$. All parameters were taken at 50 mm depth increments throughout the soil profile. Three samples per depth were taken for the porosity, bulk density, K_{sat} and one for pore volume distribution measurements.

2.3. Water infiltration experiments

Three diagonal TDR probes were inserted from the soil surface at three depths (0.20 to 0.30 m, 0.30 to 0.40 m, and 0.60 to 0.70 m) at site 1 and two (0.30 to 0.40 and 0.60 to 0.70 m) at site 2. In order to consider different soil moisture levels, three successive irrigations were conducted at each site. The duration