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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

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.

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.

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 of each irrigation was 1.5 h and the intensity was 30 mm h^{-1}. No ponding was observed. Soil moisture was measured using Time Domain Reflectrometry (TDR, Tektronix 1502B cable tester), with 0.20 m wave guides (two parallel rods of 6 mm diameter). The calibration was performed according to Roth et al. (1990). Based on this calibration method, uncertainty of volumetric water content calculated from the TDR measurements does not depend strongly on the water content. However, large relative uncertainties were observed for low water content: 16.0% for the very dry soil at 8.0% and only 1.2% for the wet soil at 93%. TDR measurements were made every 300 s. Irrigation was supplied by a rainfall simulator: a metallic disc with a surface of 1 m^2 which is perforated with 100 holes attached to small tubes that lead into a reservoir. The metallic disc is moved by an electric motor, and the irrigation intensity is controlled by a flow meter.

2.4. Dye infiltration experiment

A dye infiltration experiment was carried out in site 1 in order to visualize the heterogeneity of the tracer distribution pathways. In this perspective, 120 L of dye tracer solution were prepared, therefore 480 g of Brilliant Blue FCF powder, also known as food-dye E133, were diluted in ordinary tap water (Concentration = 4 g L^{-1}). On 23rd August 2005, 110 L of the prepared solution were applied at site 1 with a constant rate of

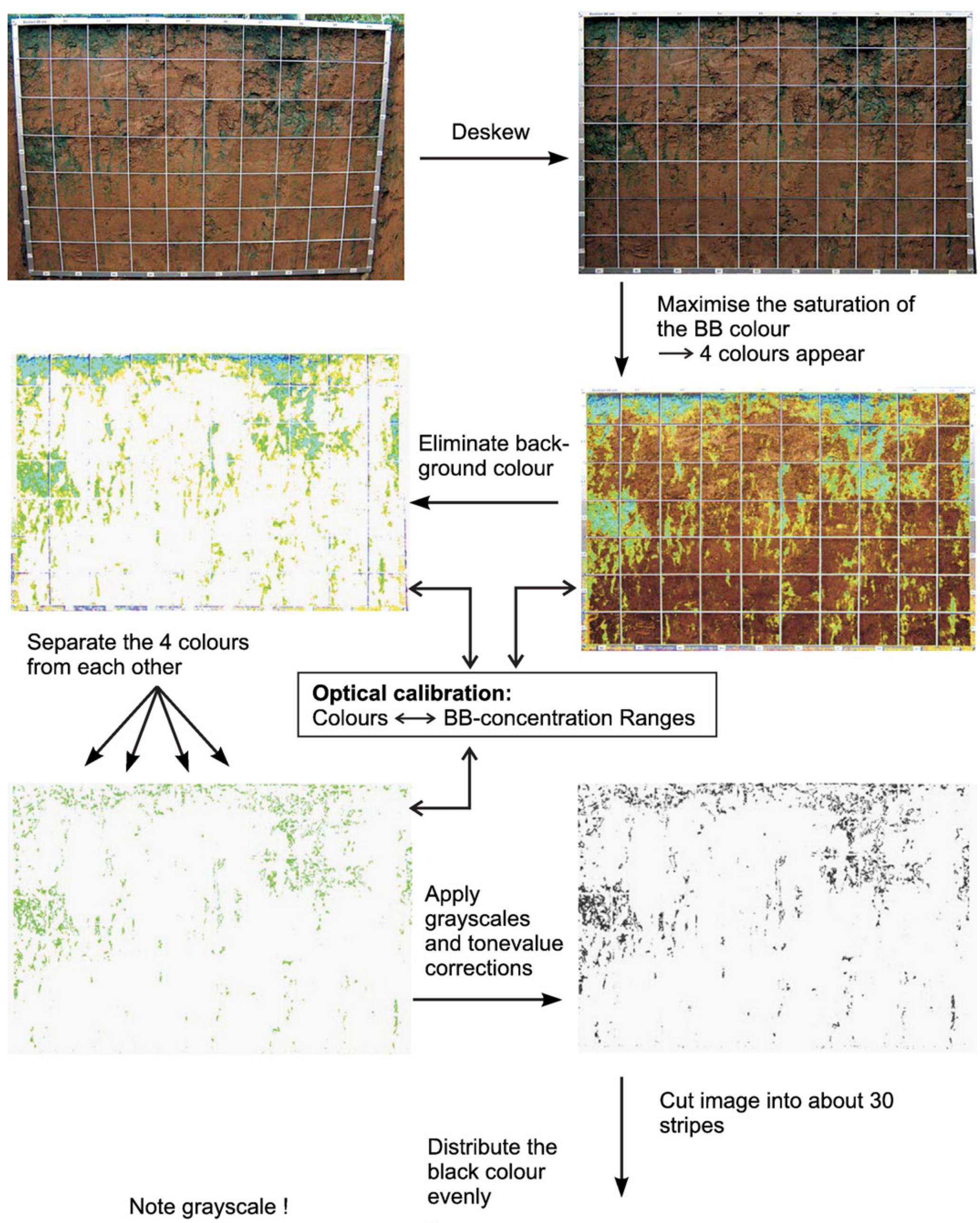

Fig. 1. Schematic illustration of the image analysis procedure in order to obtain diagrams out of images using Photoshop CS2©.

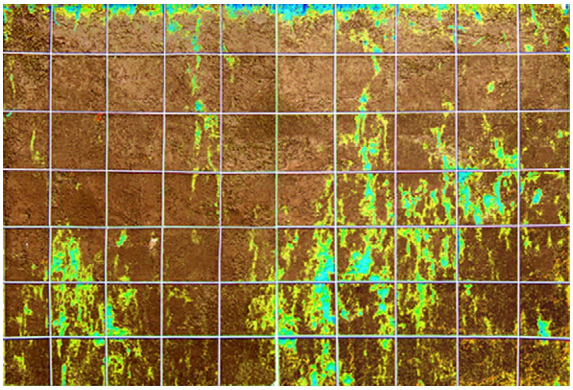

Fig. 2. Photo of the Brilliant Blue distribution of the first section (site 1: Grassland).

47.5 mm h^{-1} using a rainfall simulator. Being neutral or anionic (depending on the pH), Brilliant Blue BB is not strongly adsorbed by negatively charged soil constituents. One day after the irrigation, a soil pit was excavated and vertical profiles were prepared every 0.20 m. A rubber string grid (0.7 m × 1 m) was attached in front of each profile. These profiles were then photographed with a digital camera (hp photosmart 945; resolution: 5 Mega pixels). The digitized 1.0 by 0.7 m cross section grid contained 70 squares. The resultant digital images have a resolution of approximately 2000 × 2000 pixels.

2.5. Image analysis and optical calibration

The final coverage of the stained areas was subsequently determined from profile images according to the following description. The pictures were processed with the image editing program Photoshop CS2©. Several steps were necessary in order to obtain diagrams which could express the colored area specific to depth and concentration (Fig. 1). The first step was to deskew the pictures of certain profiles which could not be photographed orthogonally, then the saturation of the blue stains was maximized. As a result, three colours (yellow, green and blue) and two tinges (light and dark blue) appeared. The third step was to remove the brown colour of the unstained areas. After that, one could easily reduce the number of allowed colours; as a result, only the four BB related tints remained in the image. One could separate these colours by cropping them one after the other and then pasting them on individual JPG-files. By converting these pictures into grayscale-images and applying tone value corrections, the tainted areas turned black, while the rest stayed white. The resulting patterns were then cut into 30 to 35 horizontal stripes. The last couple of steps were to distribute the black colour evenly among the surface of the corresponding stripe and to note the resulting grayscale. Each profile had a surface of 7000 cm^3, but because these profiles had to be cut into stripes only 233 cm^3 could be examined at a time. The more stripes are cut, the more accurate data can be obtained.

In order to allow a quantitative insight concerning different BB-concentrations, a calibration, that linked specific colors with corresponding BB-concentration ranges, had to be carried out. Therefore 10 standard solutions had been prepared (BB-concentration: 0.1, 0.5, 1, 2, 4, 6, 20, 40, 80 und 150 g L^{-1}) before the soil samples were saturated therein for five to six days. After letting them dry for a couple of nights, about 3 mm of the bottom surface of each sample had to be scratched off with a knife, in order to obtain smooth and homogenous surfaces. These were then photographed with the same camera, under the same conditions like on the field. The schematic Fig. 1 explains the simple photo editing process.

3. Results and discussion

3.1. Dye infiltration experiment

The conducted dye infiltration experiment produced 2D-images that visualised the heterogeneous tracer distributions for every excavated section. The 2D distribution pathways presented in Fig. 2 shows clearly the limited tracer density between 0.05 and 0.30 m, indicating weak lateral mass exchange for this particular layer and consequently stronger macropore flow. Thus, the few included macropores conducted the applied solution efficiently. Below this layer an increase of surface density occurred. A plausible explanation for this particular stain pattern is that a denser network of macropores with decreasing diameters below 0.30 m led to a greater lateral spread promoting the flow transfer from the more tortuous macropores to the matrix. These results were most likely due to the compaction effect on soil surface; the bulk density was 1.66 g cm^{-1} between 0 and 10 cm and 1.55 g cm^{-1} between 10 and 30 cm. Kulli et al. (2003) noted a drastic decrease in permeability of the topsoil caused by the vehicle traffic which lead to local ponding and consequently enhanced preferential flow in the compacted plots. Our results are in agreement with the results obtained by Alaoui and Helbling (2006) in a loamy soil. They showed a weak lateral exchange between macropores and micropores in the topsoil due to the compacted matrix, while a larger interaction was observed in subsoil indicating no effect of soil compaction at this horizon. Because of small matrix conductivities of such fine texture, the linings of macropores strongly limit mass exchange (Köhne et al., 2002; Gerke and Köhne, 2002). Fig. 3 clearly illustrates this information: this transversal section photographed at 0.30 m

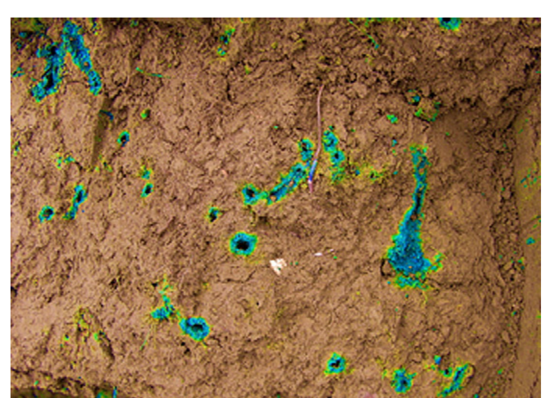

Fig. 3. Transversal section at 0.30 m depth showing the limited interaction between macropores and matrix in the silty clay material.

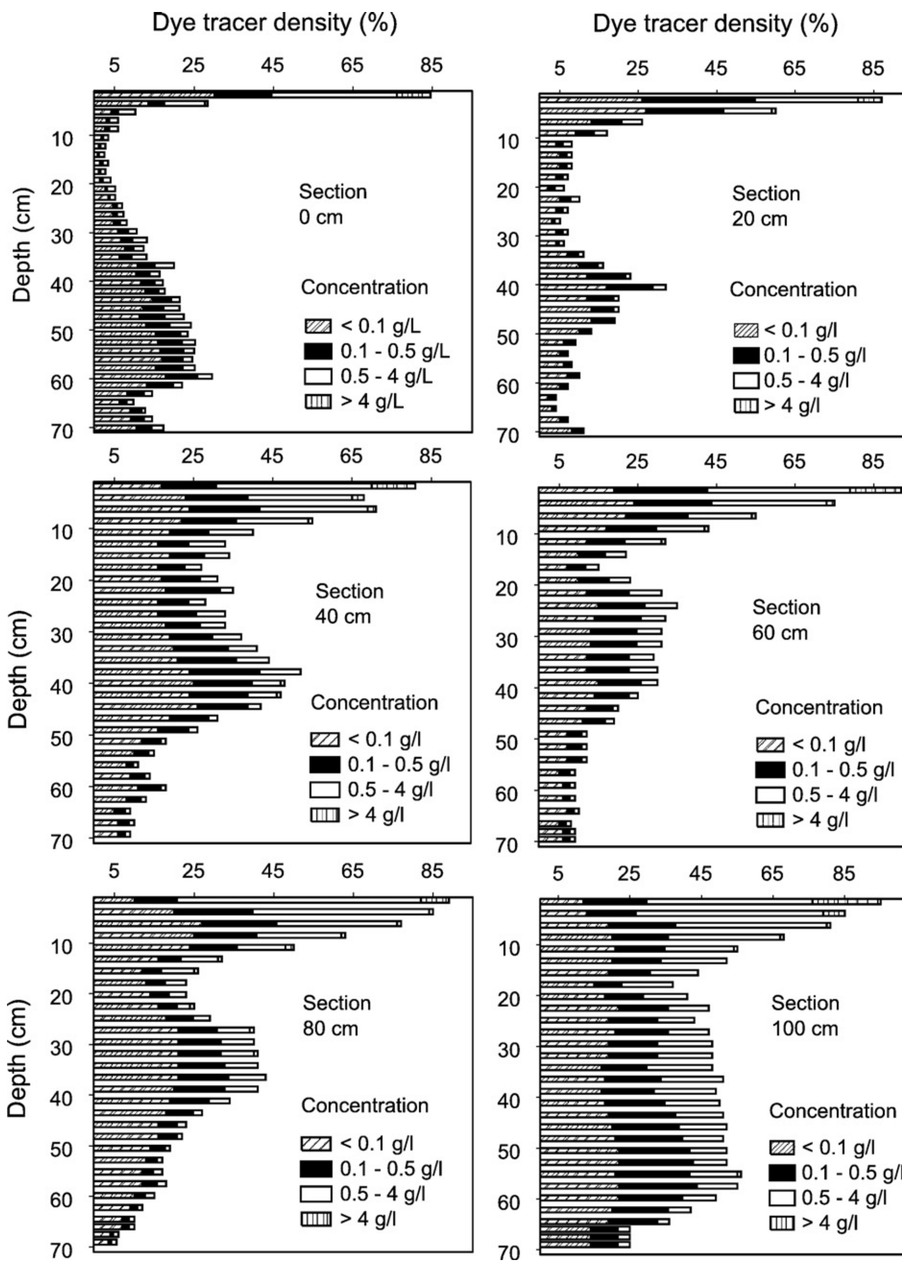

Fig. 4. Surface density of the Brilliant Blue (%) vs. depth in site 1 (Grassland).

depth visualizes the limited lateral mass exchange between macro- and micropores. The average glaze of penetration did not exceed 4.5 mm for macropores with a mean diameter of 6 mm. The macropores in the grassland site are exclusively biopores because of the high biological activities (abundance of earthworms) and present a high stability due to the compacted fine matrix. Boone et al. (1986) and Lindström and McAfee (1989) reported that among the macropores, biopores may be the most resistant to vertical compression. The improved macropore continuity and stability in undisturbed soils lead to a reduction of the critical limit of air-filled porosity in an undisturbed soil compared to disturbed soil. Therefore, structure of the channels and their functions can be an effective measure of soil 'quality' as they are relatively resistant to vertical compression (Alakukku, 1996).

Another observation related to the dye tracer distribution was that the BB color covers larger part of soil as we move from section 0 cm to section 100 cm (Fig. 4). This fact shows a

Table 2
Comparison of the topsoil and subsoil pore volume distributions of the two sites

	Diameter			
	<3.2 μm	32–3.2 μm	50–32 μm	>50 μm
Topsoil				
Grassland [%]	85.01	8.02	1.40	5.56
Barley soil [%]	84.50	5.03	1.55	9.72
Subsoil				
Grassland [%]	92.16	3.67	0.22	3.96
Barley soil [%]	84.59	5.62	2.63	8.55

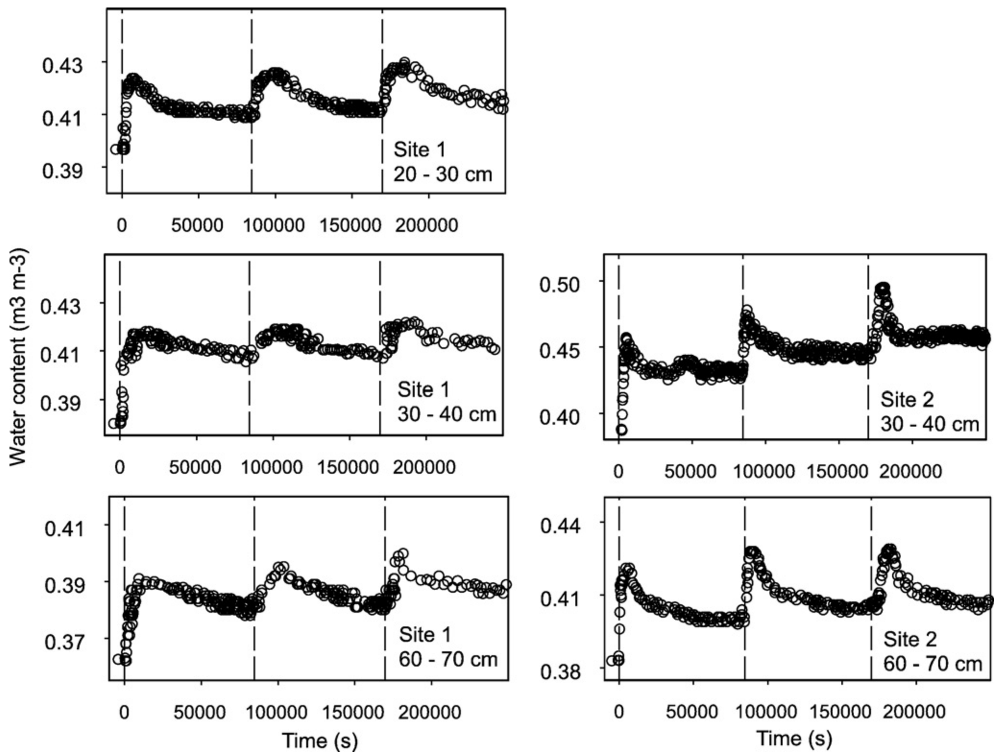

Fig. 5. *In situ* TDR measurements for both sites.

decreasing soil compaction effect from section 0 cm to 100 cm as expected. In fact, the section 0 cm was closest to the field track while section 100 cm was furthest away.

Fig. 4 gives a good idea of the stain characters, as far as concentration distributions are concerned. The largest area of high BB-concentrations (0.5 to 4 g L^{-1}) was always found close to the surface (comprised between 0.5 and 0.45 m), showing the dominant role of macropores. The corresponding minimum usually lay at the bottom part of the excavated soil profiles. It was exactly the other way round for low BB-concentrations (smaller than 0.1 g L^{-1}), here a maximum was found from 0.60 to 0.70 m depth, while the feeblest concentrations had a minimum between 0.05 and 0.30 m. However, there was no visible trend found for the medium dye tracer concentration range (0.1 to 0.5 g L^{-1}). It is never the less possible to discuss these patterns; due to the fact that only the colored surfaces are of interest here, it is possible to say that the soil had more time to adsorb the dye tracer at deeper layers. Even though the amount of clay increased with increasing depth, the tracer penetrated deeper into the soil matrix and thus caused another ratio between the three different BB-concentration ranges. This means, the solution moved through the more tortuous macropores as its depth increased, and thus was able to wet a larger part of the matrix (Fig. 2).

3.2. Comparison of the two sites

The saturated hydraulic conductivities K_{sat} of two sites were compared with each other. Site 1 was used as grassland and the site 2 as barley. By executing a couple of *t*-tests (α = 5%), it became obvious that the respective top- and subsoil K_{sat}-values did not differ significantly out of a statistic point of view.

The average topsoil-porosity (0–0.50 m) of the grassland site was 0.47 m^3 m^{-3}, while the barley site had an average of 0.49 m^3 m^{-3}. By applying a statistic *t*-test, one can say that the

Table 3
Characteristics of infiltration experiments conducted on sites 1 and 2

Irrigation	θ_{init}	θ_{max}	θ_{end}	$\Delta\theta_1$	$\Delta\theta_2$
Site 1					
Depth: 20–30 cm					
I	0.397	0.424	0.410	0.027	0.014
II	0.410	0.426	0.413	0.016	0.013
III	0.413	0.428	0.414	0.015	0.014
Depth: 30–40 cm					
I	0.380	0.420	0.407	0.040	0.013
II	0.407	0.419	0.409	0.012	0.009
III	0.410	0.422	0.411	0.012	0.010
Depth: 60–70 cm					
I	0.363	0.390	0.381	0.027	0.009
II	0.381	0.394	0.383	0.013	0.011
III	0.383	0.399	0.387	0.016	0.012
Site 2					
Depth: 30–40 cm					
I	0.350	0.460	0.430	0.110	0.030
II	0.430	0.480	0.440	0.050	0.040
III	0.440	0.490	0.460	0.050	0.030
Depth: 60–70 cm					
I	0.380	0.420	0.400	0.040	0.020
II	0.400	0.430	0.410	0.030	0.020
III	0.410	0.430	0.410	0.020	0.020

θ_{init}: Water content prior to infiltration; θ_{max}: maximum water content measured during infiltration; θ_{end}: lower water content measured within 24 h during drainage process; $\Delta\theta_1$: increase of water content at the beginning of irrigation ($\theta_{max} - \theta_{init}$); $\Delta\theta_2$: decrease of water content during the drainage stage ($\theta_{max} - \theta_{end}$).

difference is significant. The subsoil-porosity (0.60–0.70 m) of the grassland soil was 0.46 m^3 m^{-3}, whereas the corresponding barley-porosity was 0.44 m^3 m^{-3}; the difference here is significant too. In contrast, no significant difference was observed at depth of 0.50–0.60 m. Because of these obtained results, it is possible to conclude that tillage has a loosening effect on the topsoil at least to a depth of 0.30 m. This fact was also confirmed by the θ_{sat} values and the pore volume distribution. The measured θ_{sat} for site 1 was 0.47 m^3 m^{-3} between 0 and 0.50 m and 0.46 below that depth. In comparison, θ_{sat} of site 2 was higher between 0 and 0.50 m (0.49 m^3 m^{-3}) and smaller below. Between 0.50 and 0.60 m there was no great difference amongst θ_{sat} of the two sites, compared to site 1 (0.46 m^3 m^{-3}) it decreased below 0.60 m in site 2 (0.435 m^3 m^{-3}). Regarding the pore volume distribution of the topsoil, there was no significant difference among the pores of smaller radius (<50 µm). The only significant difference, concerns pores with a diameter larger than 50 µm (Table 2). The subsoil pore volume distributions between the two sites were significantly different for all pore sizes. The subsoil of the grassland site had more pores with a diameter smaller than 3.2 µm; all the other ones were more frequent at the barley site.

In order to improve the comparison between the two sites, it would be necessary to accomplish an identical dye infiltration experiment at the barley site.

In addition to other irrigation characteristics, Table 3 shows the magnitude of the decrease of water content within 24 h during the drainage process $\Delta\theta_2$. The observations related to the analysis of hydrodynamic water content variation during the irrigations can be explained as follows:

1) The decrease of water content during the drainage process $\Delta\theta_2$ was the highest between 20 and 30 cm at site 1 compared to subsoil of same site (Fig. 5). This fact can be attributed to the rapid draining of macropores (Thomas and Phillips, 1979; Germann and DiPietro, 1996; Alaoui et al., 2003).
2) Considering the layer between 30 and 40 cm, $\Delta\theta_2$ was higher and showed a more pronounced drainage at site 2 compared to site 1 confirming the observations derived from the pore volume distribution and dye tracer experiment.
3) The maximum water content θ_{max} measured at site 2 was higher compared to the values measured at site 1. These observations are in agreement with the values of θ_{sat} for both sites.

4. Conclusions

1. The interaction between matrix and macropores based on the transversal section analysis is of great interest in evaluating macropore flow.
2. At the topsoil of grassland site, the macropores are very efficient. This phenomenon is confirmed by regarding the ratio between the three BB-concentration ranges throughout the whole profile. The highest concentration values most frequent at this depth and the limited LE show that more tortuous macropores were destroyed by compaction. Consequently, only the larger and less tortuous macropores remain. This fact was also confirmed by the decrease of water content during drainage which was more pronounced at the topsoil.
3. With regard to the comparison between the grassland and the barley soils, the only significant difference between the pore volumes of the two sites concerns pores with a diameter larger than 50 µm observed at the topsoil. In fact these pores are observed more frequently in the barley site than in the grassland site. This difference can be explained by the loosening effect of tillage. The laboratory analysis (porosities and saturated water contents) and the hydrodynamic variation of water content confirm this fact as well.

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