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Evaluation of soil compaction using hydrodynamic water content variation: Comparison between compacted and non-compacted soil

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Abstract

A simple method, allowing the evaluation of the effect of compaction on soil structure is presented. The method is based on soil moisture measurements via Time Domain Reflectrometry (TDR). The hydrodynamic variation of soil moisture has indicated two types of compaction: 1) Compaction by load traffic caused a reduction of structure in the top 0.10 m layer. Consequently, no water flow occurred downward. The TDR measurements suggest a poor continuity of pores between top and subsoil. This observation has been confirmed by the measurements of bulk density, macroporosity, and dye infiltration experiments. 2) Compaction by intensive stock trample in which micropores are reduced. Macropores on the contrary are well developed, and resistant to the vertical compression in compacted soil and therefore dominated infiltration. Moreover, in reconstructed soils, micropores carried most of the flow, as demonstrated by the modeling results. Macropores are not yet developed in these young soils.

Keywords: Compacted soil; Reconstructed soil; Hydrodynamic response; Water content; Dual-porosity modeling; Dye tracer

1. Introduction

A number of different methods have been used to characterize the state of compaction of soil layers. Dry bulk density and total porosity are the most frequently used parameters. However, these properties are limited when compaction between different soil types is to be compared. To overcome this problem, the actual-bulk density is expressed as a percentage of a reference-compaction state of a given soil that is called "degree of compactness" or "relative compactness" (Håkansson, 1990; Håkansson and Lipiec, 2000). Although penetration resistance is regarded as a useful measure of soil impedance to root growth (Bengough and Mullins, 1990), it is also limited. One of its drawbacks is its wide spatial variation because it is a point measurement rather than a bulk soil measurement (Lipiec and Hatano, 2003). These methods are unsatisfactory from a more general point of view. They treat the state of compactness and not the vital effects of soil structure in relation to plant growth that are the supply of roots with water and oxygen.

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 (Arvidsson, 1997; Lipiec

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and Stepniewski, 1995). However, experimental data relating the effect of soil compaction on unsaturated flow is very limited.

Kooistra (1994) studied the porosity of tilled sandy loam soils by optical microscopy of thin sections and distinguished macropores (mean diameter > 100 μm) and smaller pores which were considered as micropores. It was shown that total porosity was often less decreased by compaction than the macroporosity, because the microporosity increased. Richard et al. (2001) 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 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 difficulties of such approach are that (i) several measurements of soil hydraulic properties are required; (ii) the change of the relation between the textural pores and the remaining structural pores depends on type, texture, and structure of a particular soil, and (iii) the range of water potential and mechanical pressure leading to the formation of relict structural pores has to be known. To avoid these drawbacks, the determination of the type of flow at field scale under different saturation levels can offer similar if not better-suited information on the effects of compaction on soil structure.

Results from the studies shown above seem to be conflicting because they consider only the morphology of structure rather than the hydrodynamic functionalities. In summary, the studies show the necessity: a) to take into account matrix pores and macropores; b) to consider the field scale of soil profiles rather than the laboratory scale of cores to also assess the heterogeneity induced by compaction, and c) to consider directly the hydrodynamic functionality of the pores in conducting water and air rather than dwelling on the morphology of soil structure.

As an alternative to the existing methods, a simple method based on in situ-soil moisture measurements is proposed in this study. The principal aims of this study are: a) to investigate the effect of soil compaction on functional-soil structure using hydrodynamic variation of water content in response to brief irrigations, and b) to validate the proposed method by comparing its results with those obtained from established procedures.

2. Material and methods

Two projects explain the procedure. a) In the project Frauenfeld we compare our results with those of Gysi et al. (1999) and Kulli et al. (2003); b) in the project Kirchberg, we present hydrodynamic variations of soil moisture and two tracer experiments.

2.1. Location Frauenfeld

2.1.1. Location and soil description

The experimental area is located near Frauenfeld in Switzerland (Swiss topo coordinates: 270 000/707 950). The soil, situated in a wide valley bottom, is a skeleton-free eutric cambisol. Its organic carbon content varies from 0.05% to 0.5%. It consists of a sandy loam between 0 and 0.37 m of depth and of loamy sand between 0.37 and 0.57 m of depth. The bulk density is 1.4 g cm^{-3} and the pre-consolidation load is 80 kPa. A network of macropores is present to a depth of 0.80 m. One year prior to the field experiments, winter wheat was grown at the experimental site and harvested with a plot combine method without ploughing. No plough pan was found with the penetrometer (Gysi et al., 1999; Kulli et al., 2003).

2.1.2. Field experiments

We compared a plot F_1 without wheel traffic (control) with plot F_2 with four passages of a self-propelled six-row sugar beet harvester (model Kleine SF10). The driving speed was 1 m s^{-1} and the total weight of the sugar beet harvester with a partially loaded hopper was 22.4 Mg, that of the fully loaded harvester 27.4 Mg. The tyre pressure p_t was 230 kPa (L_p) and 243 kPa (L_f), the width of the tyres was 0.68 m (Gysi et al., 1999). From a pit, 1 m deep, four soil moisture-probes were horizontally installed under each plot F_1 and F_2. Both plots were successively irrigated twice with a sprinkler with intensities of 24 mm h^{-1} during 1 h. The time interval between the two irrigations was about 24 h. Soil moisture was measured at the four depths of 0.20, 0.40, 0.50 and 0.70 m with Time Domain Reflectrometry (TDR, Tektronix 1502B cable tester), with 0.20 m wave guides (two parallel rods of 6 mm diameter). Calibration was performed according to Roth et al. (1990). TDR measurements were made every 300 s. Irrigation was supplied by a rainfall simulator: a metallic disc with a surface of 1 m^2 perforated with 100 holes attached to small tubes which are leading in a reservoir. The metallic disc was moved by a motor drive. Irrigation intensity was controlled by a flow meter.

2.2. Location Kirchberg

2.2.1. Location and soil description

Three experimental plots (A, B and C) were selected in an area near Bern in Switzerland (Rüdtligen, Kirchberg). The soil of the first one (A) is located in a pasture and is compacted due to intensive passing of the cattle (pugging). Soil of plots B and C are recently reconstructed. The soil of the pasture is a brown luvisol. Its texture is loam between 0 and 0.60 m, and clay loam below this depth. pH is 7 throughout while organic matter varies from 3% at soil surface and 2% below 0.60 m. The vegetation consists of herbs and grasses. A network of macropores comprising particularly earthworm channels is visible to the depth of 0.80–0.90 m. Plot A is of a triangular shape. Site 1 is in the narrow part near the entrance and is subject to a more frequent traffic compared with site 2. The narrow part of the pasture at site 1 is 4 m wide and is the obligatory access to the cattle to the pasture. The high resistance of the soil against drilling reflects intensive pugging.

The soil of plot B consists of loam between 0 and 0.60 m and clay loam below 0.60 m depth. Bulk density is 1.46 g cm^{-3} at depth of 0–0.10 m and 1.62 g cm^{-3} at depth of 0.50–0.60 m (Table 1). pH varies between 5.5 and 6.5 and organic matter varies between 3.5% in soil surface and 1.6% at 0.50–0.60 m. Both topsoil and subsoil were reconstructed in the summer of 2002. In this plot, 5 sites (3, 4, 5, 6 and 7) are established to conduct our experiments.

The soil texture of plot C is loam between 0 and 0.50 m, and clay loam below 0.50 m. pH is 7 throughout soil profile and organic matter varies between 3.4% and 1.35% at depth of 0–0.10 and 0.60–0.70, respectively. Bulk density is 1.49 g cm^{-3} at depth of 0–0.10 m and 1.34 g cm^{-3} at depth of 0.50–0.60 m. The subsoil was reconstructed in the summer of 2001 and topsoil in the summer of 2002. Three sites (8, 9 and 10) are established to conduct the irrigations. In both plots B and C, no heavy machines were used to avoid any soil compaction. To improve the soil quality of reconstructed soil, alfalfa was planted.

Saturated hydraulic conductivity K_{sat} was determined on samples of undisturbed soil with a diameter of 55 mm and length of 42 mm, taken at 50 mm depth increments throughout the soil profile. One sample per depth was taken for the K_{sat} measurements. 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.

2.2.2. Field experiments

TDR probes were inserted obliquely from the soil surface at four depths (0.20 to 0.30, 0.30 to 0.40, 0.40 to 0.50, and 0.50 to 0.60 m). The holes were drilled with a motor-driven auger (ROCKY-Tracked vehicle, type: P50/M50-BFP 602, drill tower: HRS100, company: HUMAX, Switzerland). Drilling (with a diameter of 4 cm) was diagonally made according to an angle of 45° at the 10 sites. To prevent preferential flow along the shafts of the TDR probes, the gaps between them and the soil were sealed with bentonite. Dye infiltration at site 1 confirmed the adequate seal.

To consider different moisture levels, three successive irrigations were conducted at each site. The duration of each irrigation was 1 h followed by 1-h drainage. The intensity was 30 mm h^{-1} and the volume of water infiltrated was 30 L. Each experiment lasted 6.15 h including 15 min before the start of the irrigation. No ponding was observed. Irrigation was supplied by the same rainfall simulator as described for location Frauenfeld.

Table 1
Porosity η, bulk density ρ and saturated hydraulic conductivity K_{sat} of the three plots in location Kirchberg

Depth (m)	Plot A (site 1)			Plot B (site 5)			Plot C (site 8)		
	η (%)	ρ (g cm^{-3})	K_{sat} (cm s^{-1})	η (%)	ρ (g cm^{-3})	K_{sat} (cm s^{-1})	η (%)	ρ (g cm^{-3})	K_{sat} (cm s^{-1})
0–0.10	38.0	1.64	2.38×10^{-3}	45.0	1.46	8.16×10^{-4}	44.0	1.49	1.42×10^{-3}
0.10–0.20	42.5	1.49	1.48×10^{-3}	46.2	1.37	7.96×10^{-5}	44.8	1.37	9.30×10^{-3}
0.20–0.30	42.0[a]	1.55[a]	5.16×10^{-2}	/	/	4.89×10^{-3}	/	/	5.76×10^{-3}
0.30–0.40	49.5	1.34	1.96×10^{-3}	40.0	1.60	3.74×10^{-3}	42.5	1.53	3.74×10^{-3}
0.40–0.50	/	/	1.43×10^{-3}	/	/	4.93×10^{-2}	/	/	9.24×10^{-3}
0.50–0.60	42.8	1.46	1.12×10^{-4}	37.0	1.62	1.01×10^{-4}	43.5	1.34	5.73×10^{-2}
0.60–0.70	/	/	2.15×10^{-4}	/	/	9.46×10^{-4}	/	/	2.23×10^{-5}

[a] Values determined at site 2 of the pasture.

2.2.3. Oedometer compression test

A standard oedometer was used to perform the mechanical tests. The sample diameter was 6 cm and initial height about 1.5 cm. The vertical load was increased by steps of 1.1, 15, 60, 125, 250, 500 and 1000 kPa. Each stress step lasted at least 24 h to reach deformation equilibrium. The corresponding saturated water contents are shown in Fig. 1 and final value of 20% that corresponds to the critical void ratio was retained. This water content, $\theta_{mcl}=20\%$, will serve as a reference for water content to quantify the soil compaction.

2.2.4. Brilliant blue

To stain the preferential flow path, 10 g of Brilliant Blue powder was diluted in 1 L water and uniformly sprinkled with a hand-held spray onto the 1 m^2 of the soil surface of site 1 and 2 of plot A, as described by Perillo et al. (1999). It was subsequently flushed with 30 L of water at a constant rate of 30 mm h^{-1} using a rainfall simulator. Being neutral or anionic, Brilliant Blue is not strongly adsorbed by negatively charged soil constituents. Initial-soil moisture and irrigation characteristics (intensities and durations) were similar for all experiments. It is important to caution that the analysis of macropore-flow characteristics is relative to the specific conditions of our experiments. Three hours later, a soil pit was excavated and vertical profiles prepared each 0.10 m. The profiles containing a rubber string grid were photographed with a digital camera (hp photosmart 945, with a resolution of 5 Mega pixels) at each profile within a square of 1 m^2 and a height of 0.70 m. The digitized 1×0.7 m cross section contained 70 grids. The resultant-digital images have a resolution of 2000×2000 pixels. The length, diameter and number of stained macropores were first visually quantified in situ during the excavation. The fact that macropores are exclusively earthworm channels and their small numbers make structure analysis easier, according to the observations, we could state that the earthworm channels have a cylindrical form. This yields to a three-dimensional analysis of the macropore volume. The final volume of stained macropores was subsequently determined from the in situ observations and were adjusted if necessary with the profile images.

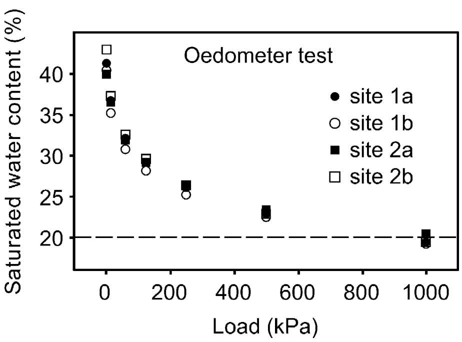

Fig. 1. Saturated water content at maximum compaction vs. load. Each measurement was repeated two times (a and b) at depth of 0.20–0.30 m. Region of Kirchberg.

2.2.5. MACRO model

Jarvis (1994) developed a physically based model MACRO that simulates water and solute transport in macroporous soil. The model divides the total soil porosity into macropores and micropores. Water flow in micropores is calculated with the Richards' (1931) equation, while macropore flow is simulated as a power law function of the saturation level in macropores. An effective diffusion pathlength d, controls mass exchange between the domains. Net rainfall is partitioned into an amount taken up by micropores and an excess amount of water flowing into macropores under non-equilibrium conditions bypassing the matrix flow. The model is calibrated using a grid-search technique (Duan et al., 1992). The optimal parameter combination is identified by the minimum of the root mean square error under two constraints: the slope of the regression between predicted and measured values should be in the range of 0.9 to 1.1 and the coefficient of residual mass in the range of 0.001 to -0.001 (Acutis et al., 2001). Measured parameters used in the modeling are saturated water content, saturated hydraulic conductivity, initial-water content, and bulk density. The parameters characterizing the boundary between the two domains such as boundary water content, boundary hydraulic conductivity, and boundary matric potential were calibrated. The use of MACRO model helped to determine the type of the dominant flow (macropore or micropore flow) during irrigations and to define the boundary between the two domains. This partitioning will help then to evaluate the degree of soil compaction in each domain.

3. Results and discussion

3.1. Location Frauenfeld

In the control plot, water content dropped drastically after rainfall ceased, as is characteristic of macropore flow (Thomas and Phillips, 1979) showing the aeration of soil during drainage (Fig. 2). The existence of macropores showed by the in situ analysis of soil

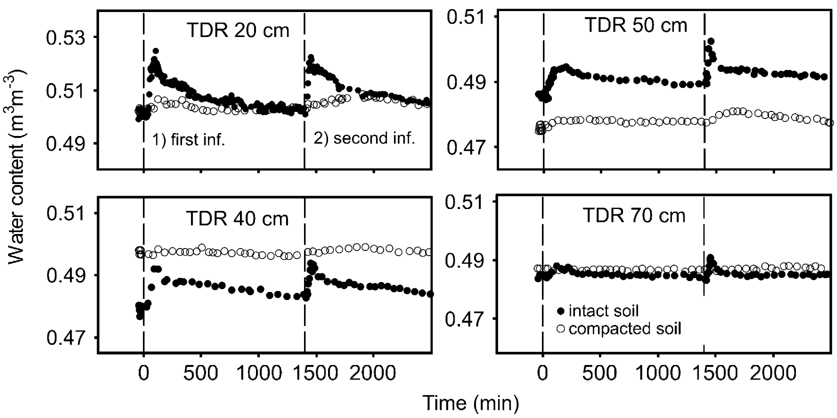

Fig. 2. Water content profiles measured in intact soil (without passage) and in compacted soil (multiple passages) in location Frauenfeld.

profile supported those observations, as they indicate the active contribution of macropores to water flow in intact soil. On the other hand, soil with multiple passages did not show any significant increase of soil moisture, indicating the destruction of its structure or, at least, of the structure allowing rapid flow. This fact was interpreted as a consequence of soil compaction. Indeed, during the infiltration experiments, the water infiltrated the soil of the intact plot directly and instantaneously, whereas it was ponding on the surface of the compacted soil. In the control plot, the increase of soil moisture occurred to a depth of 70 cm as shown in Fig. 2. In the control plot, the increase of water content at depth of 0.20 m was the greatest reaching values of 2.5% and 2.0% during the first and second infiltration run, respectively. The values decreased and attained a value of 0.7% at 0.70 m of depth during the second infiltration run.

Our results are supported by those obtained by Kulli et al. (2003). By using dye-tracer experiments, the authors demonstrated that only very few flow paths pass the topsoil right underneath the area of the passage of the wheel. In addition, taking into account several factors including change in bulk density, air permeability, macroporosity and pre-consolidation pressure, Gysi et al. (1999) demonstrated the evidence of soil compaction to a depth of at least 0.17 m and at most 0.32 m under a full-wheel load in wet conditions. On the contrary, no compaction effect was ascertained in subsoil in spite of the high wheel load of 11.2 mg. In summary, these studies show the discontinuity of structure between topsoil and subsoil as a consequence of soil compaction. In our investigations, this result was confirmed by the absence of an increased water content throughout the soil profile in the multiple passages plot, showing that no flow downward occurred. In addition, rainfall intensity used in the study by Kulli et al. (2003) was equal to 5 mm h^{-1}. The authors suggested that with increasing intensity, preferential flow would become obvious. In our investigations, no evident preferential flow occurred in the multiple passages plot in spite of the high rainfall intensity of 24 mm h^{-1}. Alakukku (1996) found that in the 0.20–0.50 m layer of the organic soil, macroporosity was reduced and microporosity (under 30 μm) was increased by the heavy loading. It was found that total porosity did not reveal the effects of compaction on the organic soil. In fact, specific conditions leading to the change of microporosity/macroporosity in subsoil have to be determined for each soil type. This drawback can be overcome by investigating the continuity of the structure in terms of a hydrodynamic function rather than the structure morphology (Alaoui, 2002).

3.2. Location Kirchberg

3.2.1. Porosity and density measurements

The porosity of the pasture is 38.0% at a depth of 0–0.10 m (bulk density = 1.64 g cm^{-3}). These values reflect the relative high compaction at this depth in comparison with those observed in reconstructed soil. The porosity increases slowly below to reach a value of 42.5% (bulk density = 1.49 g cm^{-3}) at a depth of 0.10–0.20 m and 42.0% (bulk density = 1.55 g cm^{-3}) at a depth of 0.20–0.30 m (Table 1). These values indicate a less pronounced compaction between 0.10 and 0.30 m. The porosity increases subsequently to reach a value of 49.5% (bulk density = 1.34 g cm^{-3}) at a depth of 0.30–0.40 m which is greater than the value measured in reconstructed soils. This may indicate an increase of microporosity as a consequence of soil compaction (Alakukku, 1996; Kooistra, 1994; Richard et al., 2001).

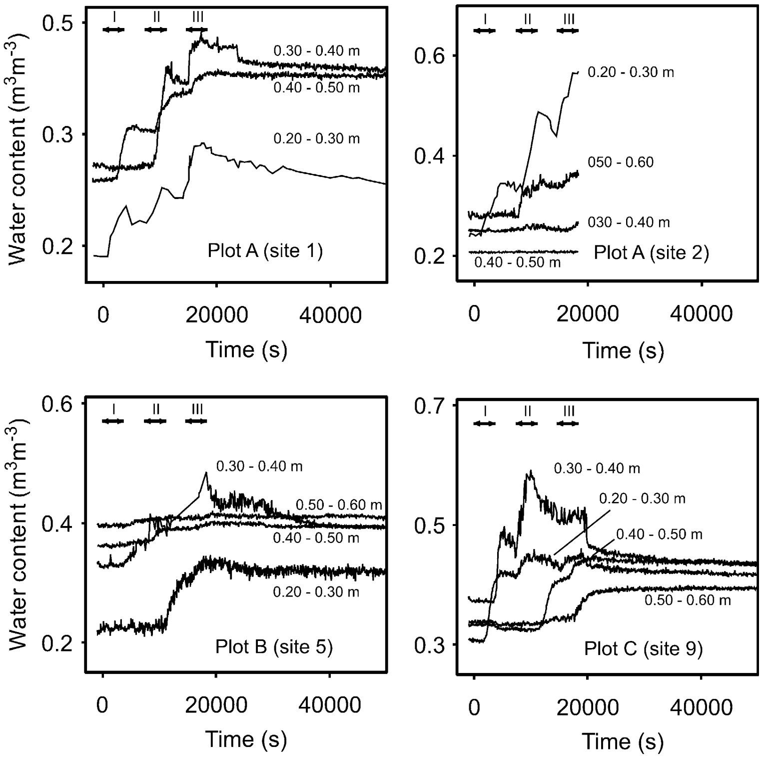

Fig. 3. Hydrodynamic variation of soil moisture measured at different depths in plot A (sites 1 and 2), plot B (site 5) and plot C (site 9). TDR measurements at depth of 0.50–0.60 m of site 1 are missing.

3.2.2. Water content measurements

In this study, a positive reaction of soil during irrigation means an increase of soil moisture in contrast to no reaction (no variation in soil moisture). For the sake of simplicity, this terminology is adopted throughout this section. Moreover, the quantitative analysis was focused on the 0.20−0.30 m layer because of the lack of some measured parameters deeper in the soil (0.20−0.30, 0.40−0.50 and 0.60−0.70 m) of plot A. Fig. 3 shows soil moisture evolution in the plots A (sites 1 and 2), B (site 5) and C (site 9). Site 1 shows a positive reaction to all infiltration runs except at depth of 0.30−0.40 m during the first run. In comparison, site 2 shows less frequently positive reactions. Two conclusions can be drawn in relation to these results: (i) the two sites, located in the pasture, particularly site 1, show both positive reactions in spite of their compacted soil; (ii) site 1 has a different reaction in comparison with site 2 in terms of frequency and magnitude. These two points will be discussed in the following.

Table 2 shows the magnitude of the decrease of water content $\Delta\theta$ at the soil surface within 2 h during the drainage process of the third infiltration run. The value of $\Delta\theta$ is the highest for site 2 (11.0%), which can be attributed to the rapid draining of macropores. This phenomenon is less pronounced in site 1 ($\Delta\theta = 7.0\%$). In contrast, reconstructed soil of plots B and C shows lower values of $\Delta\theta$ during the drainage ($0 \leq \Delta\theta \leq 4.8\%$) which is due to diffusive flow dominated by capillarity (Germann, 1990; Alaoui et al., 2003).

The value of θ_{max} equal to 57.0% measured at a depth of 0.20–0.30 m at site 2 is high in comparison with the value of the porosity at the same depth (42.0%,

Table 2
Decrease of water content $\Delta\theta$ during the drainage stage of the third infiltration run at 0.20–0.30 m depth for plots A (sites 1 and 2), B (sites 3–7) and C (sites 8–10); θ_{end} is the lower water content measured within 2 h after that maximum water content θ_{max} was reached

Sites	$\Delta\theta = \theta_{max} - \theta_{end}$ (%)
1	7.0
2	11.0
3	4.7
4	4.8
5	0.5
6	2.3
7	0.0
8	2.3
9	0.9
10	0.0

Table 1). The value of θ obtained from TDR reflects the high contribution of macropores in the flow process. Note that the TDR system measures soil moisture in a great volume of soil (approximately 720 cm^3), in comparison with a soil core taken for the laboratory analysis (100 cm^3), and may include both macropore and micropore domains. The big difference between the two values cannot be explained by the uncertainties of the TDR measurements at a large range of water contents. Based on the calibration method of Roth et al. (1990),

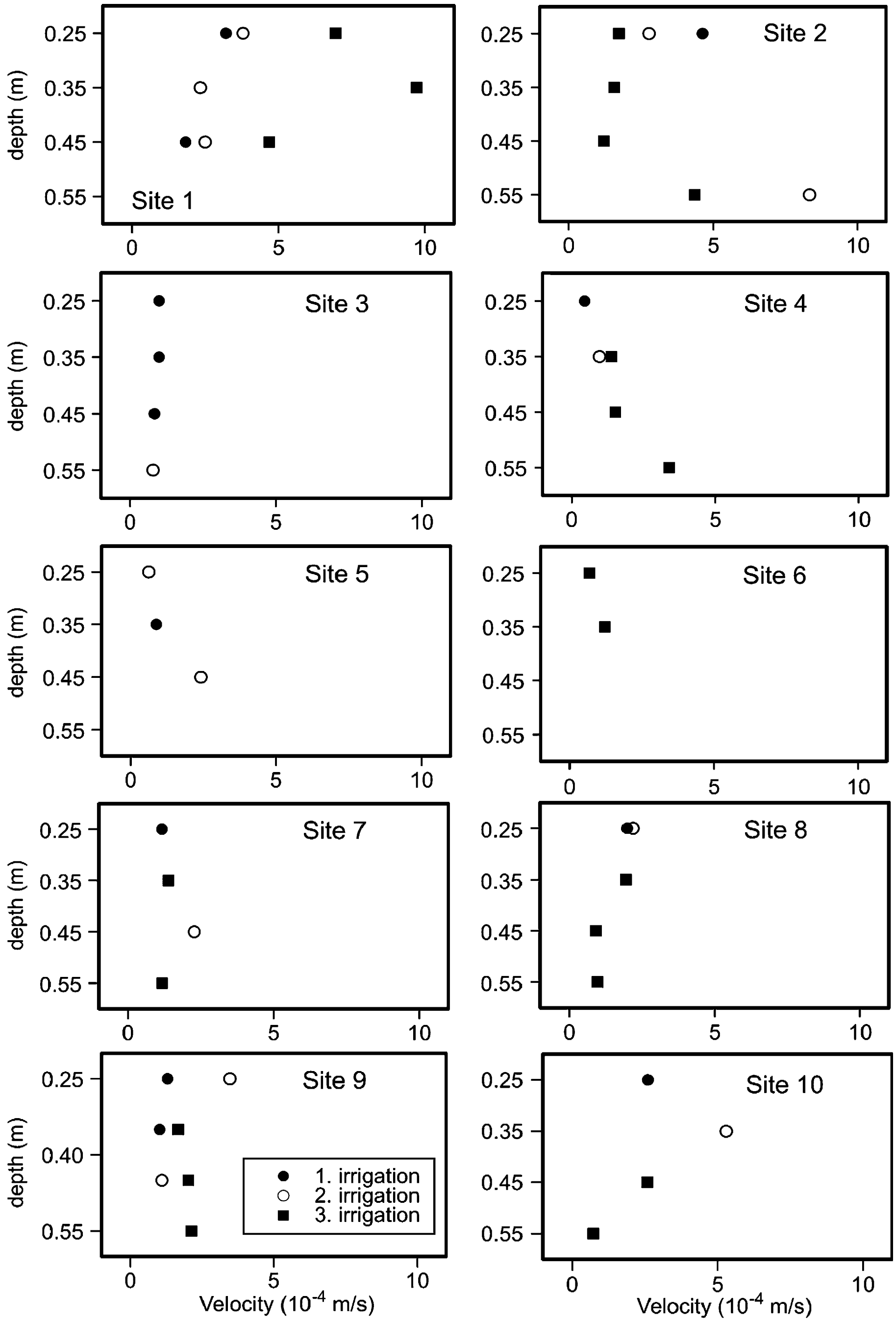

Fig. 4. Velocities of the wetting-front progression measured at the plot A (sites 1 and 2), B (sites 3, 4, 5, 6 and 7) and C (sites 8, 9 and 10) during the three irrigations.

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 very dry soil at 8.0% and only 1.2% for the wet soil at 93.0% (Roth et al., 1990).

Calculated velocities of the wetting-front progression during each infiltration run in plots A, B and C at different depths are illustrated in Fig. 4. These results show two different behaviours when considering hydrodynamic soil moisture variations. The velocity in site 1 is the greatest reaching a value of 9.72×10^{-4} m s^{-1} at a depth of 0.30–0.40 m. In site 2, the maximum measured velocity is 8.33×10^{-4} m s^{-1} at a depth of 0.50–0.60 m. In plots B and C, all calculated velocities are within the range of 0.1 to 3.810^{-4} m s^{-1} except at depth of 0.30–0.40 m in site 10.

3.2.3. Dye infiltration experiments

Fig. 5 shows an example of stained macropres in the pasture (sites 1 and 2). Two significant observations related to the quantitative analysis of the structure morphology, are that the diameter of macropores in site 1 is greater than the one measured in site 2 (Table 3), and that macropore volume in site 1 is 10 times greater than in site 2. Nevertheless, the number of macropores observed in the topsoil of site 2 is relatively high. This can explain the high increase of soil moisture during the third infiltration run which reached 57.0%. Moreover, we note a discontinuity of the pore network

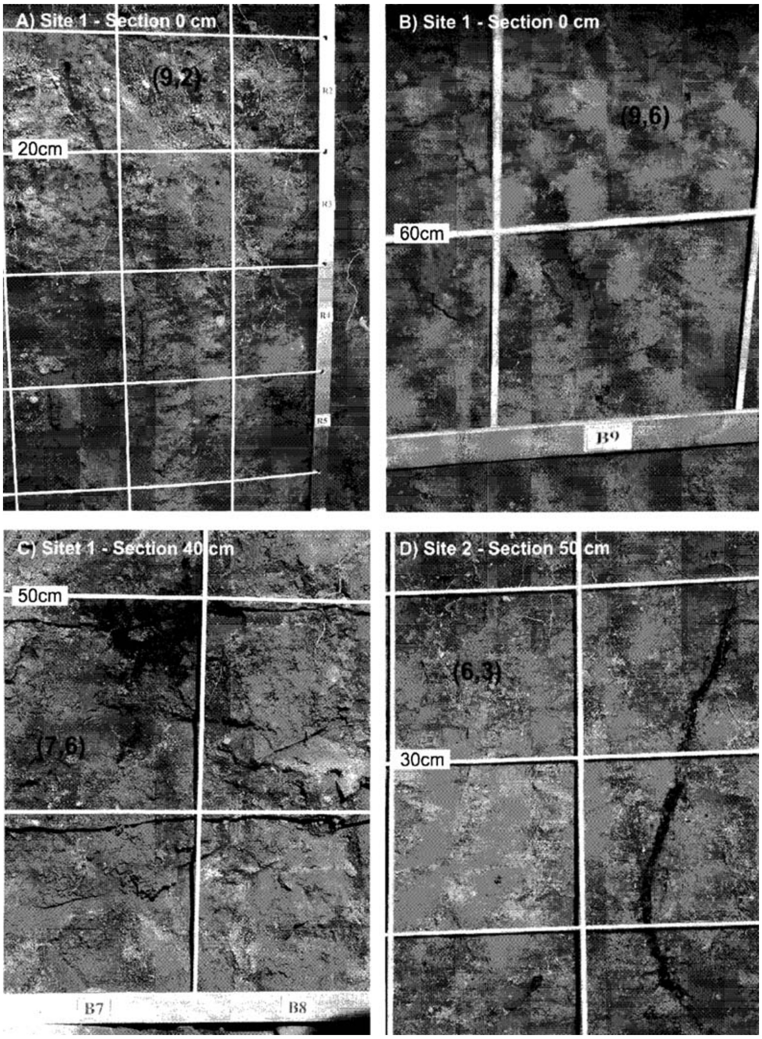

Fig. 5. Images of the stained macropores at sites 1 and 2; (x, y) are the coordinates of the considered cell, x is the number of the cell accounted from the left and y is the number of the cell accounted from the top.

Table 3
Morphological characteristics of macropores resulted from the dye infiltration experiments and the in situ-profile analysis for sites 1 and 2 (see text for more details)

Characteristics of macropores	Site 1	Site 2
Mean diameter (mm)	8	5
Mean length (m)	0.70	0.50
Network	Continuous	Discontinuous
Total volume (m^3 m^{-3})	0.014	0.0016

between topsoil and subsoil in site 2 expressed by the absence of increased soil moisture in the layers 0.30–0.40 and 0.40–0.50 m (Fig. 3). Based on the in situ-profile observations and considering a total soil volume of 0.70 m^3, the macropore volume was estimated to be 0.014 m^3 m^{-3} in site 1 and 0.0016 m^3 m^{-3} in site 2. The macropores in the pasture are exclusively biopores because of the high biological activities (abundance of earthworms) and present a high stability due to the very 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 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 tracing was the lack of interaction between macropores and matrix at the soil surface between 0 and 20 cm depth whereas interaction was detected below this (Fig. 5, C). This fact may reflect qualitatively that the flow interaction of macropores–matrix was limited to the subsoil, indicating no effect of soil compaction at this horizon. Such matrix–macropores interaction and its importance largely determine the impact of macropores on the overall infiltration process and mixing regime of solutes (Weiler and Naef, 2003).

3.2.4. Modelling of water content

In general, the model successfully reproduced the patterns of soil moisture measurements (Fig. 6). However, some discrepancies were observed between measured and simulated water content during the first infiltration run in site 9. But this difference in magnitude was negligible when considering the increase of

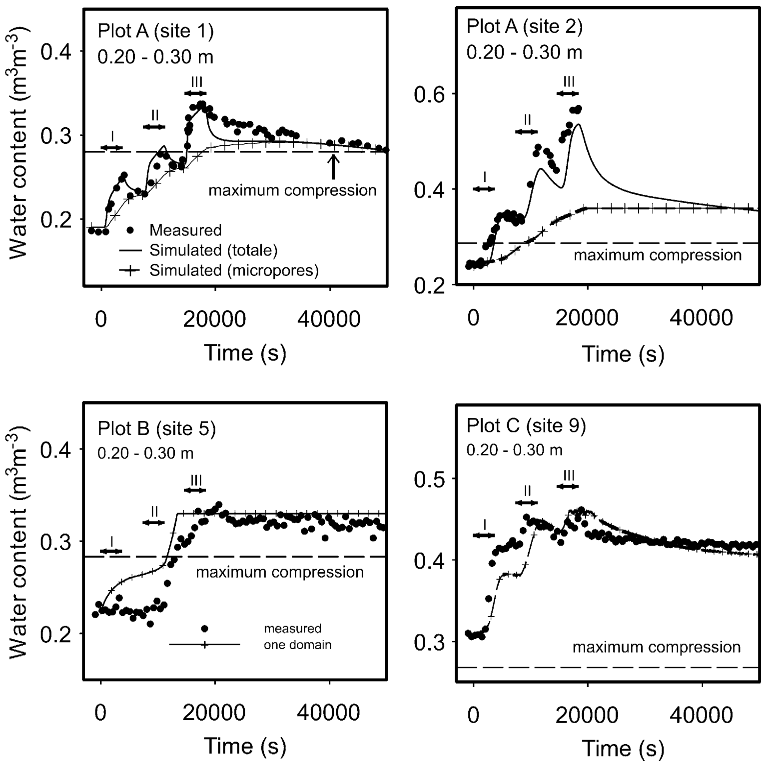

Fig. 6. Soil moisture variations at depth of 0.20–0.30 m at the sites 1, 2, 5 and 9: the points represent measured values, the line represents the simulated one (total water content), the dots represent maximum compression obtained from the oedometer-compression test and the plus represents simulated-water content in micropores.

total soil moisture. In sites 1 and 2 the best simulations were obtained considering two-flow domains, confirming also our field observations (existence of macropores). In reconstructed soil of plots B and C (sites 5 and 9, respectively), the best simulations were obtained considering one-flow domain excluding preferential flow.

In the third infiltration (1 h), we set the initial-water content as a reference. The estimated-macropore volume represents only 2.00% and 0.23% of the total soil volume and transported approximately 100% and 74% of total water flow at sites 1 and 2 in the topsoil, respectively. Lin et al. (1996) reported that 10% of macropores (>0.5 mm) and mesopores (0.06–0.5 mm) contributed approximately 89% of total water flow. As shown by Ehlers (1975), the maximum infiltrability of conducting channels in the stronger untilled soil was more than 60 mm h^{-1}, although the volume of these channels only totaled 0.2 vol.%. These values are similar to our results. Results of the dye infiltration experiment show the reduced role of micropores in site 1 due to the compaction of the soil matrix. In fact, during the dye infiltration, heterogeneity in the wetting-front dispersion was observed, which was difficult to emphasize with the images in Fig. 5 because of the low dye concentration. Fig. 7 shows the very low water exchange rate from macropores to micropores predicted by the model. Two significant conclusions drawn from these results are that macropore flow dominates the flow process in the pasture and was very high during all runs, whereas micropore flow is dominant in reconstructed soil and takes more time to reach its maximum value (obtained during run 3) showing the slow saturation of the matrix.

3.2.5. Evaluation of soil compaction

To evaluate the degree of soil compaction, water content was determined in relation to θ_{mcl}, since the micropore water content expresses the state of hydrodynamic functionality of micropores. A high value leads to greater functionality and consequently, the damage caused by soil compaction is lower. Setting θ_{mcl} as a reference (Fig. 6), the estimated-micropore water content contributing to water flow represents 0% in site 1 and 26% in site 2 during the third irrigation with the remaining flow attributable to the macropore water content (100% and 74% for site 1 and site 2, respectively). In comparison, micropores began to play a major role during drainage to reach their maximum values 3 h after the third infiltration ceased, especially for site 1. It is important to note that the sites 1 and 2 had a different initial-water content θ_{init3} (measured before the start of the third irrigation). θ_{init3} was 26.2% in site 1 and 44.0% in site 2. However, the

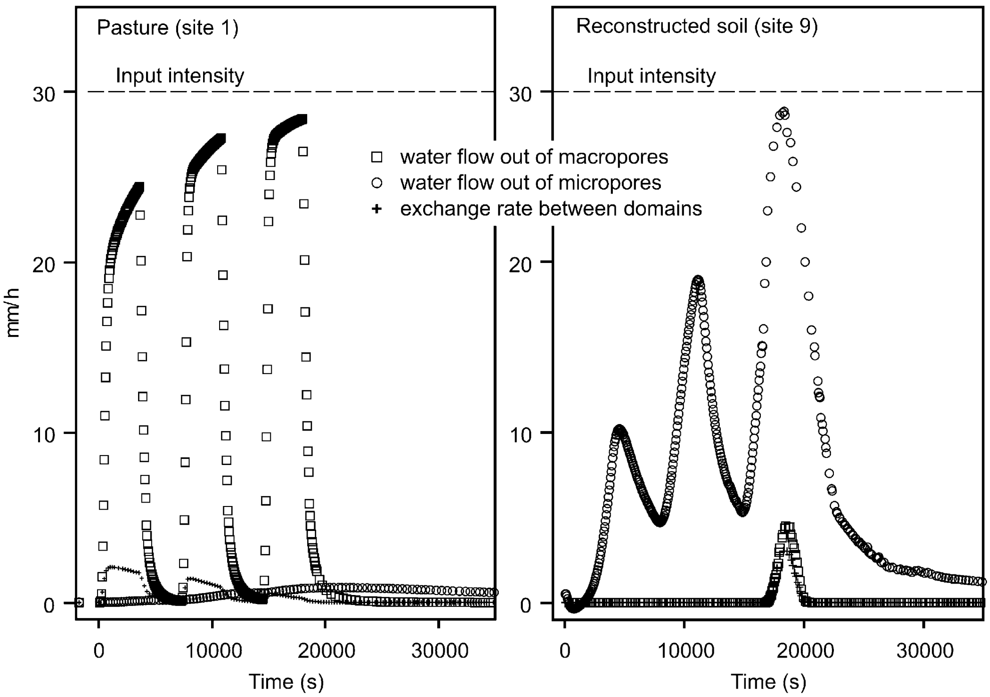

Fig. 7. Predicted water outflow (mm h^{-1}) out of macropores and micropores at depth of 0.20–0.30 m and predicted water exchange rate (mm h^{-1}) at same depth (positive from macropores to micropores) by the MACRO model in the pasture and reconstructed soil.

initial conditions before the start of the first irrigation θ_{init1} were comparable in the two sites (18.3% in site 1 and 24.0% in site 2). They differed only by a factor of 5.7%. On the other hand, maximum water contents (θ_{max3}) measured during the third irrigation differed by a factor of 23.3% (33.7% in site 1 and 57.0% in site 2). The high discrepancies between the values of θ_{max3} can be explained by several combined facts:

(i) The rapid flow bypassed micropores and the majority of the soil's reactive surface as observed in the vertical-soil profiles.
(ii) Initial-water content was low in site 1 and can partially explain the difference in θ_{max3}. Note that no precipitation occurred during the five days before the infiltration runs. This allowed us to get similar initial conditions. This fact shows that the low value of θ is not related to the weather conditions but to the difference in soil porosity. Quisenberry et al. (1994) reported that initial-soil water content, rainfall amounts and intensity are important factors, but that their significance is controlled by the pore system of the particular soil.
(iii) The damage on the microporosity in site 1 due to the soil compaction reduced the increase of soil moisture and macropores that dominated the flow at all moisture levels; the matrix became slowly involved in the wetter blocks and took more time to reach its maximum saturation in comparison with site 2.

When we consider the plot B (site 9) and the pasture (site 2), the initial-water content θ_{init1} is 24.0% in site 2 and 30.0% in site 9. Although this small difference, resulted θ_{max3} reaches a value of 57.0% in the pasture and only 45.0% in reconstructed soil. They differ by a factor of 11.8%, which is high. The high saturation in site 2 is due to the dominant role of macropores in the flow compared to the exclusive micropore flow in site 9. In the pasture only a fraction between 0% and 26% of micropores are involved in the flow, clearly indicating the reduced role of the matrix compensated by the macropore flow.

4. Conclusions

A simple and non-destructive method, allowing the evaluation of the effect of the compaction on soil structure has been presented. This method is based on soil moisture measurements via TDR method. The method presented can be used as an alternative to established procedures, which are expensive, time consuming and require the determination of many soil properties. One of the advantages of the TDR method is that it measures soil moisture of a great volume of soil taking into consideration both micropore and macropore domains. Moreover, with this method, the entire-vertical profile can be investigated.

In this study, two types of compaction effects on soil structure can be distinguished.

- Compaction by load traffic implying a decrease of structure in the top 0.10 m layer. Consequently, no flow occurs downward. In fact, in the multiple passages plot, the TDR measurements show a poor continuity of pores between topsoil and subsoil. This observation was confirmed by the measurements of density, macroporosity and dye infiltration experiments.
- Compaction by intensive stock trample or pugging in which micropores are reduced. Macropores on the contrary are well developed and resistant to the vertical compression in compacted soil and therefore dominate the water flow.

Moreover, in reconstructed soil, micropores provide the totality of flow. The MACRO model was shown to be useful in determining the relative contributions of the micropores and macropores in soils.

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