

Depth distribution of preferential flow patterns in a sandy loam soil as affected by tillage

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Abstract

Dye-tracer studies using the anionic dye Brilliant Blue FCF were conducted on a structured sandy loam soil (Typic Agrudalf). 25 mm of dye solution was applied to the surface of 11 1.6 × 1.6 m field plots, some of which had been subjected to conventional seed bed preparation (harrowing) while others had been rototivated to either 5 or 15 cm depth before sowing. The soil was excavated to about 160 cm depth one or two days after dye application. Flow patterns and structural features appearing on vertical or horizontal cross sections were examined and photographed. The flow patterns were digitized, and depth functions for the number of activated flow pathways and the degree of dye coverage were calculated.

Dye was found below 100 cm depth on 26 out of 33 vertical cross sections made in conventionally tilled plots showing that preferential flow was a prevailing phenomenon. The depth-averaged number of stained flow pathways in the 25–100 cm layer was significantly smaller in a plot rototivated to 5 cm depth than in a conventionally tilled plot, both under relatively dry initial soil conditions and when the entire soil profiles were initially at field capacity. There were no examples of dye penetration below 25 cm depth one month after deep rototivation. Distinct horizontal structures in flow patterns appearing at 20–40 cm depth coupled with changes in flow domains indicated soil layering with abrupt changes in soil structure and hydraulic properties.

Introduction

Preferential flow phenomena can lead to rapid transport of water and surface-applied chemicals to deep subsoil layers, and may thereby increase the leaching losses of a broad variety of chemicals used in agriculture (e.g. Hall & Mumma, 1994; Kladvikova *et al.*, 1991; Isensee *et al.*, 1990; Hall *et al.*, 1989; see also reviews by Bouma, 1991; Jury & Flühler, 1992; Flury, 1996). Tillage processes affect soil structure and hydraulic properties in the topsoil which are expected to be important for the generation of preferential flow (e.g. Beven and Germann, 1982; Horton *et al.*, 1989; Staricka *et al.*, 1991). Systematic effects of tillage on flow patterns and chemical transport are thus expected.

Direct quantification of preferential flow under field conditions, particularly of macropore flow, is very difficult, not only because of spatial variability but also because of the temporal variability which is often involved in the flow processes (Demuth and Hiltbold, 1993). Indirect measures may be obtained, for instance, from the patterns of water and solute discharge through tile drains in response to rain events. Most studies on the effect of tillage on drain water

discharge and preferential flow have been focused on the two extremes of primary tillage, viz. moldboard plough and no-till management systems. The results of this research generally suggest that no-till increases the proportion of water transported in macropores (e.g. Harris *et al.*, 1993; Lal *et al.*, 1994). There are very limited data on the effect of secondary tillage on preferential flow.

Staining techniques as discussed by Flury and Flühler (1995) and applied e.g. by Ehlers (1975), Bouma *et al.* (1977), and Flury *et al.* (1994) do not, in a strict sense, quantify preferential flow. The techniques may, however, be used to visualize the primary flow pathways of water and solutes with high spatial resolution. Dye-tracing is, therefore, a valuable step towards an understanding of preferential flow and transport mechanisms in soil and towards the design of efficient schemes for soil sampling in solute transport studies. For tracing water, the applied dye should preferably be relatively mobile and distinctly visible.

The present work on dye-tracing field experiments investigates the effect of different tillage operations during

seed bed preparation on depth distributions of preferential flow patterns appearing in the upper 1 m layer of a sandy loam soil.

Materials and methods

SOIL AND TILLAGE

The soil (Typic Agrudalf) in this study is at the university experimental farm, Højbakkegaard 20 km west of Copenhagen. The soil is developed on moraine deposits from the Weichsel Glacial Age. The structure is well-developed with vertically orientated earthworm channels of between 1 and 8 mm diameter penetrating into the B- and C-horizons. Rough estimates of the number of channels were made on large lumps of soil taken from the profile. The largest numbers (about 8 per 100 cm² horizontal cross section) were found in the B_t-horizon at about 50 cm depth. Common numbers found in the B_t-horizon between 40 and 80 cm depth were 2–5 channels per 100 cm² horizontal cross section. There were coatings of clay indicating colloidal transport in several channels. Some (old) channels appearing right below the A_p-horizon (0–25 cm depth) were partly filled with soil materials in the upper 10 cm. The number of channels increased abruptly below 35–40 cm depth, and decreased rapidly with depth below about 80 cm. In the spring of 1994, a relatively well defined horizontal interface at about 20 cm depth marked the depth for the last ploughing in October 1993. Some profile characteristics are shown in Table 1.

Series of dye-tracer experiments were conducted in May, June, and October 1994 on 1.6 by 1.6 m plots laid out each time within a level field not more than 2.0 m from each other. One experiment was conducted within the same undisturbed area in July, 1996. The field was ploughed on 20 October, 1993 with incorporation of straw from the previous winter barley crop. Two seed bed harrowings in different directions were performed in April 1994 to a depth of 4–5 cm, and some of the plots were also rotovated to a depth of either 5 cm or 15 cm. The field

was rolled and planted with Italian rye grass on 28 April, 1994. Plots to be used for tracer experiments in May 1994 were covered with waterproof tarpaulins immediately after seed bed preparation to minimize differences in evaporation. Traffic on the plots was avoided after sowing. In one plot, most of the topsoil was removed immediately before dye application so that the dye could be applied uniformly to a carefully prepared plane surface at 20 cm depth. Care was taken to avoid any disturbance of the soil structure below the new artificial surface.

Pilot investigations in May 1994 revealed that the soil at field capacity was always able to infiltrate 25 mm of water within one hour as applied by the sprinkling apparatus without noticeable surface ponding, whereas an intensity of 50 mm h⁻¹ always resulted in local ponding on the surface. Saturated hydraulic conductivity, K_s, as determined for the vertical direction on 100 cm⁻³ laboratory samples taken at different locations within the field under study was log-normally distributed within each of four sampling depths (Gjettermann *et al.*, 1997). For the 20–25 cm layer including the interface created during the last ploughing, they reported a geometric mean value for K_s of 0.68 μm s⁻¹ and a geometric standard deviation of 2.8; for the 55–60 cm layer the geometric mean and standard deviation were 2.9 and 3.1 μm s⁻¹, respectively. Outlines of the experimental conditions are given in Table 2.

TRACER APPLICATION

The dye tracer used for staining the flow paths of water was Brilliant Blue FCF. Tracer characteristics of Brilliant Blue FCF have recently been given by Flury & Flüher (1994, 1995). The dye is anionic at pH > 5.83 and adsorbs relatively weakly on most soils.

The dye was applied in solution (concentration: 4 g l⁻¹) to the soil surface using an automatized sprinkling apparatus similar in principle to the ones described by Ghodrati *et al.* (1990a) and Flury *et al.* (1994). The device consists of a motor driven spray bar with nozzles aligned for one-dimen-

Table 1. Profile characteristics for the Højbakkegaard soil.

Horizon	Depth (cm)	pH [†]	Org. Texture				ρ _b [‡] (Mg m ⁻³)	Soil structure [§]			Voids [¶]			
			Org. C	0.2–2 mm	20–200 μm	2–20 μm		<2 μm	Grade	Size	Type	Type	Size	Abundance
A _p	0–25	6.3	1.4	23.6	34.9	23.3	16.8	1.39 (0.10)	MO	ME	GR	P	F	F
E	25–40	5.8	0.4	27.4	38.0	18.4	15.8	1.59 (0.08)	MO	ME	AB	C	MC	F
B _t	40–110	6.2	0.2	23.0	35.0	18.6	23.2	1.63 (0.08)	ST	ME	AB	C	MC	C
C	110+	7.7	–	24.4	37.6	20.4	17.6	–	MO	CO	AB	C	MC	V

[†] 0.01 M CaCl₂.

[‡] Determined in April 1994 from 15 100 cm³ soil samples taken about in the middle of the indicated soil layer. Standard deviation in brackets.

[§] According to Food and Agriculture Organization, 1990. Grade: VW=Very Weak, MO=Moderate, ST=Strong. Size: ME=Medium, CO=Coarse, FM=Fine and Medium. Type: GR=Granular, AB=Angular Blocky.

[¶] According to Food and Agriculture Organization, 1990. Type: C=Channels (mainly vertically orientated, continuous earthworm channels), P=Planes (mainly randomly orientated and discontinuous), I=Interstitials (textural voids). Size: V=Very Fine (<0.5 mm), F=Fine (0.5–2 mm), M=Medium (2–5 mm), C=Coarse (5–20 mm), MC=Medium and Coarse. Abundance: F=Few, C=Common, V=Very few.

Table 2. Overview of experimental treatments and conditions.

Identifi- cation [§]	Treatment [†]	Cross sections	Bulk density, ρ_b , and soil moisture content, θ				
			Depth	ρ_b	θ	Depth	θ
			(cm)	(Mg m ⁻³)	(m ³ m ⁻³)	(cm)	(m ³ m ⁻³)
17.05.94	Rot. 15 cm	Vertical	5-10	1.28 (0.12)	0.174	25-35	0.234
18.05.94	Rot. 5 cm	Vertical	0-6	1.21 (0.09)	0.136	25-35	0.255
19.05.94	Convent.	Vertical	0-2	—	0.119 [‡]	25-35	0.251
20.05.94	T. removed	Vertical	—	—	—	25-35	0.261
31.05.94	Convent.	Vertical	5-10	1.62 (0.14)	0.311	25-35	0.288
01.06.94	Convent.	Horizontal [¶]	5-10				
02.06.94	Rot. 15 cm	Vertical	5-10	1.30 (0.11)	0.280	25-35	0.269
03.06.94	Rot. 5 cm	Vertical	0-6	1.27 (0.07)	0.297	25-35	0.273
27.10.94	Convent.	Vertical	5-10	1.37 (0.09)	0.228	25-35	0.229
28.10.94	Rot. 15 cm	Vertical	5-10	1.25 (0.11)	0.201	25-35	0.230
07.07.96	Convent.	Vertical	5-10	1.67 (0.07)	0.281	25-35	0.296

[†] Convent.: conventional soil tillage corresponding to two or three seed bed harrowings in different directions to a depth of 4-5 cm, rolling and sowing (grass). Rot.: Rotovation to 15, respectively 5 cm as supplement to the conventional treatment right after harrowing. T. removed: Topsoil removed before dye application.

[‡] Calculated by assuming the same dry bulk density as in rotovated plots, 0-6 cm

[§] Date when the excavation proces was initiated and the day after dye application. Identifies each plot / experiment.

[¶] Horizontal to 80 cm depth, vertical below 80 cm.

sional application of the solution directly under the bar and a suction pump connected to tanks containing the dye solution. The impact energy of the sprinkling drops produced was small. 25 mm of dye solution was applied within one hour in all experiments. This was achieved by a timer switching the device on and off at equal time intervals of 2 minutes. The device was designed to ensure a controlled and spatially uniform distribution of dye tracer at the soil surface. The uniformity of application depends on the nozzle distance above the soil surface and on the nozzle pressure. The best combination of these conditions was found in the laboratory. For an inner area of 110 by 110 cm, it was possible to achieve a coefficient of variation of the amount of applied solution of 5-6% in the direction perpendicular to the travel direction, and 2-3% in the travel direction when measuring the amount of irrigation water in 10 by 10 cm trajectories placed side by side. In the field, wind drift was reduced by a wooden frame surrounding the treated area, and all vertical soil profiles were made parallel to the travel direction of the bar. All above-ground plant materials, if any, were removed before dye application.

SAMPLING

The plots were excavated one or two days after dye application to a depth of about 160 cm. An excavator was used to dig a trench in front of the treated area and to remove all loosened soil from the bottom of the excavation. All soil

below the treated area was loosened with hand spades and horizontal or vertical cross sections were prepared for detailed description. The cross sections were trimmed with a trowel and a knife and, in the case of horizontal cross sections, also with a soft brush. Special care was taken to remove all deposits of dye coming from the excavation process. Most plots were excavated systematically in 11 vertical cross sections separated 10 cm from each other. One plot (01.06.94) was excavated horizontally to 80 cm depth, and vertically below 80 cm depth. Flow patterns and relevant structural features appearing on the cross sections or in the soil layer between sections were described and photographed. A 100 by 100 cm square metal frame was placed on all cross sections before taking photos for image analysis. Soil samples were taken before dye application and during the excavation process to determine soil bulk density and moisture content.

IMAGE ANALYSIS

On the photographs all stained dye patterns appearing within the metal frame were transferred manually with a fine black pen to transparent plastic sheets. The only distinction made in this process was whether blue dye was visible or not at the different parts of the photo. A representation of the metal frame (approximate size: 10 by 10 cm) was transferred as well. All transfers were made or controlled by one person.

The new representations of the flow patterns were digitized with a resolution of 300 dpi (dots per inch) by either an Agfa Arcus or a Hewlett Packard scanner. The resulting binary representations were displayed on a datascreen on which were marked the four corners of the metal frame with known coordinates. The computer program then made a projective geometric transformation of that part of the image inside the frame into a quadratic representation with 464 true horizontal rows and 464 true vertical columns. For each row, the computer counted the number of pixels which were turned on (representing a stained area), and the number of transitions from pixels which were turned off to pixels which were turned on. Average values were calculated for each profile depth increment of 8 rows (1.7 cm) to reduce the random error. From these data, average dye coverage (DC, %) and average number of stained flowpathways (NP) were calculated as a function of profile depth.

Results

In the uppermost part of the vertical profiles, there was always a completely stained soil layer (Figs. 1 and 2). Below this layer, the flow pattern became more heterogeneous, this effect being most pronounced in conventionally tilled plots. Flow patterns in the subsoil below 35–40 cm depth were dominated completely by dye deposited at the surface of vertically orientated earthworm channels. It was often possible to follow these channels over long distances in the subsoil by careful excavation with a knife. However, only sections of the stained channels appeared on vertical cross sections. Larger stained areas were found at the ends of some of the channels indicating the existence of internal catchments (e.g. Fig. 2a). Dye was found below 100 cm depth on 26 out of the 33 vertical cross sections made in conventionally tilled plots in May and early June 1994.

Any close relationship between the amount of dye deposited in the subsoil at the surface of earthworm chan-

nels and the area and intensity of the blue flow patterns can hardly be expected because the dye was concentrated within very small soil volumes and because of geometrical and optical factors (e.g. shadows cast over parts of the stained channel surfaces). The dye application caused no noticeable ponding at the soil surface except in the experiment with topsoil removed (20.05.94).

ROTOVATION

Average values for NP and DC as a function of depth are shown for the plots excavated in vertical cross sections in Fig. 3. This figure and the images shown in Figs. 1 and 2 clearly suggest an effect of rotoavation on the penetration of dye patterns. The average number of stained pathways below 25 cm depth, NP₂₅, and the average degree of dye coverage above 25 cm depth, DC₂₅, were derived for each of the 11 cross sections made within each plot. The Shapiro-Wilk statistic for Normality (Shapiro & Wilk, 1965) was calculated for both variables, except for NP₂₅ in plots without dye penetration into the subsoil (17.05.94 and 02.06.94). The statistic did not, in any plot, lead to a rejection of the hypothesis that the observed values represented normal distributions ($P > 0.05$). Within-plot average values and standard deviations for NP₂₅ and DC₂₅ are shown in Table 3. There were no examples of dye penetration below 25 cm in May or in June after deep rotoavation, whereas NP₂₅ in conventionally tilled plots at approximately the same dates, was significantly different from zero ($P < 0.001$). In May, when the uppermost soil layers were relatively dry (Table 2), there were only a few examples of dye penetrating the upper part of the subsoil in the superficially rotoavated plot, and the difference between values of NP₂₅ for the superficially rotoavated and the conventionally tilled plots was strongly significant ($P < 0.001$). NP₂₅ was also smaller in a superficially rotoavated plot than in a conventionally tilled plot in June, when the moisture content of the whole profiles, including the

Table 3. Average number of stained pathways in the 25–100 cm subsoil layer, NP₂₅, and average degree of dye coverage above 25 cm soil depth, DC₂₅ in differently treated plots. Standard deviations in brackets (n=11). ns, *, **, and ***: difference between conventional and rotoavated plots at the time of excavation either non-significant or significant at the 95, 99 or 99.9% level, respectively, according to t-test.

Time of excavation	Treatment							
	Conventional		Rotovated 5 cm		Rotovated 15 cm		Topsoil removed	
	NP ₂₅	DC ₂₅	NP ₂₅	DC ₂₅	NP ₂₅	DC ₂₅	NP ₂₅ [†]	DC ₂₅ [‡]
Mid May 1994	2.4 (1.0)	46 (5)	0.0*** (0.0)	34*** (4)	0.0*** (0.0)	48 ^{ns} (4)	8.6 (2.7)	66 (9)
Early June 1994	2.5 (2.2)	40 (10)	0.7* (0.7)	39 ^{ns} (5)	0.0*** (0.0)	39 ^{ns} (8)	–	–
Late October 1994	2.6 (1.3)	44 (8)	–	–	1.0** (0.8)	44 ^{ns} (7)	–	–
July 1996	3.7 (0.7)	61 (5)	–	–	–	–	–	–

[†] 25–100 cm below the original soil surface

[‡] 20–25 cm below the original soil surface

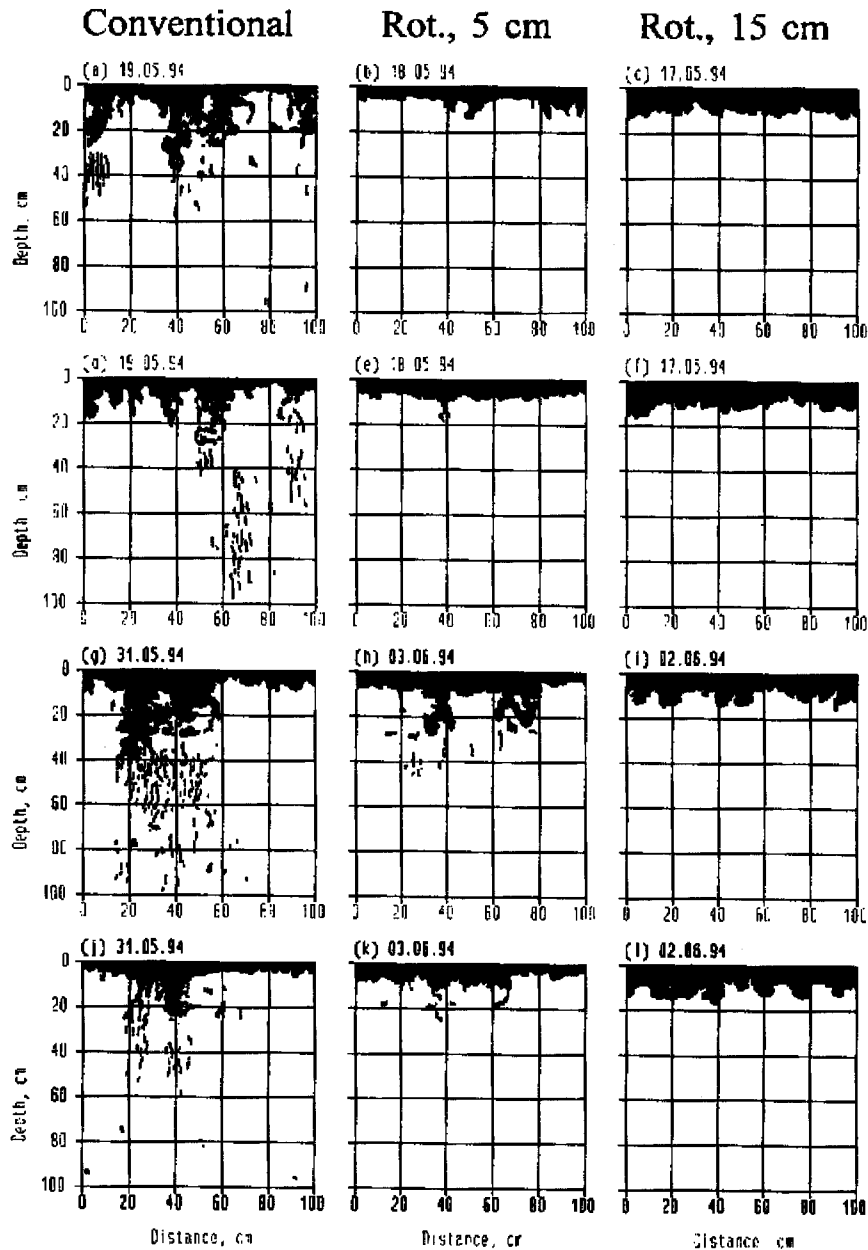


Fig. 1. Digitized and geometrically corrected flow patterns from vertical cross sections made in May or early June 1994 in (a,d,g,j); conventionally tilled plots, (b,e,h,k); plots rotovated to 5 cm depth, and (c,f,i,l); plots rotovated to 15 cm depth.

uppermost few cm, was close to the field capacity after rewetting ($P < 0.05$), although the number of stained channels in the subsoil of the rotovated plot was increased significantly ($P < 0.001$) compared with the situation in May. DC_{25} was significantly smaller in the superficially rotovated plot than in the conventionally tilled plot in May ($P < 0.001$) but not in June.

NP_{25} was smaller in a deeply rotovated plot than in a conventionally tilled plot also in late October 1994, 6 months after seed bed preparation ($P < 0.01$, cf. Table 3). The depth functions for DC were obviously different at that time, DC being higher above 15 cm depth and lower

below 15 cm depth for the deeply rotovated plot compared with the conventionally tilled plot (Figs. 2 and 3).

FLOW PATTERNS ON VERTICAL PROFILES AS AFFECTED BY SOIL STRUCTURE IN THE 20–40 CM SOIL LAYER

In conventionally tilled plots the patterns often changed abruptly in shape at the interface created during the last ploughing operation at about 20 cm or at 30–35 cm depth (Figs. 1 and 2). Local minima for NP and DC were found at about 30 cm depth, both in 1994 (Fig. 3) and in 1996.

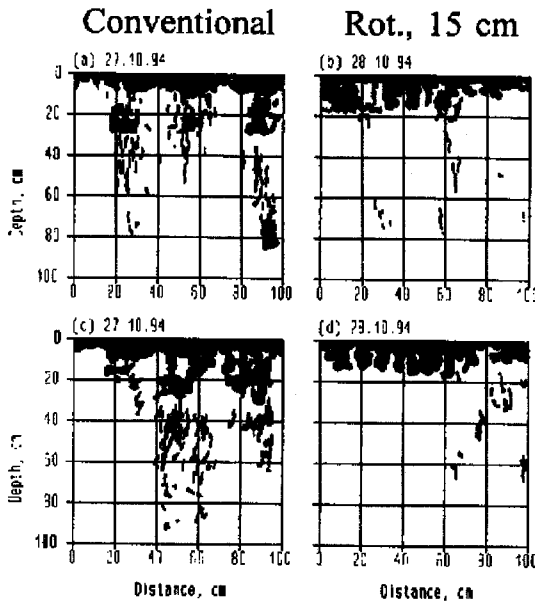


Fig. 2. Digitized flow patterns from vertical cross sections made in October 1994 in (a,c): conventionally tilled plots and (b,d): plots rotated to 15 cm depth.

Thus, conditions creating local minima for NP and DC at about 30 cm depth still existed in the third year grass field. The fact that local maximum values for NP were found at about 40 cm depth corresponds with the profile description that the number of vertically orientated open earthworm channels are larger for the B_t-horizon than for the A- and E-horizons.

Other indications of the modifications of flow patterns in the 20–40 cm soil layer were obtained from the plot with topsoil removed (20.05.94). Very distinct horizontal structures in the flow patterns at 5–15 cm depth (25–35 cm below the original soil surface) indicate soil layering with abrupt changes in hydraulic properties (Fig. 4). These changes may be related to soil compaction or to earlier tillage operations. The upper level boundary receiving an even amount of dye solution was located from 0 to about 4 cm above the interface made during the last ploughing operation. The number of stained pathways increased dramatically and abruptly below 10–15 cm depth (Fig. 4a–d). It seems most likely that the conditions for this change in the flow patterns were created during an earlier ploughing. Later, the structure along this deep interface may have been modified, for instance through biological activity. Only horizontal transport at the interface can explain the extensive activation of channels appearing very often exactly at that depth. When looking at moist, more or less smeared vertical profiles in the field, it was generally impossible to see any horizontal channels, with the exception of a few larger ones. However, when breaking dried samples in the laboratory, the number of horizontally orientated root channels of diameter < 0.5 mm was generally

much larger just above the interface than just below. It is concluded that the deep interface at 30–35 cm depth had a dominating effect on the appearance of flow patterns in experiment 20.05.94 with removed topsoil. The extent to which this interface affected flow patterns in intact soil profiles is less obvious.

FLOW PATTERNS ON HORIZONTAL CROSS SECTIONS

Digitized and geometrically corrected images of flow patterns on horizontal, 100 by 100 cm cross-sections made in a conventionally tilled plot in May are shown in Fig. 5. At 8 cm depth, the patterns were strongly orientated (Fig. 5a, much more evident on the original colour reprints). The direction indicated by the patterns corresponds closely to the direction of the last seed bed harrowing. The degree

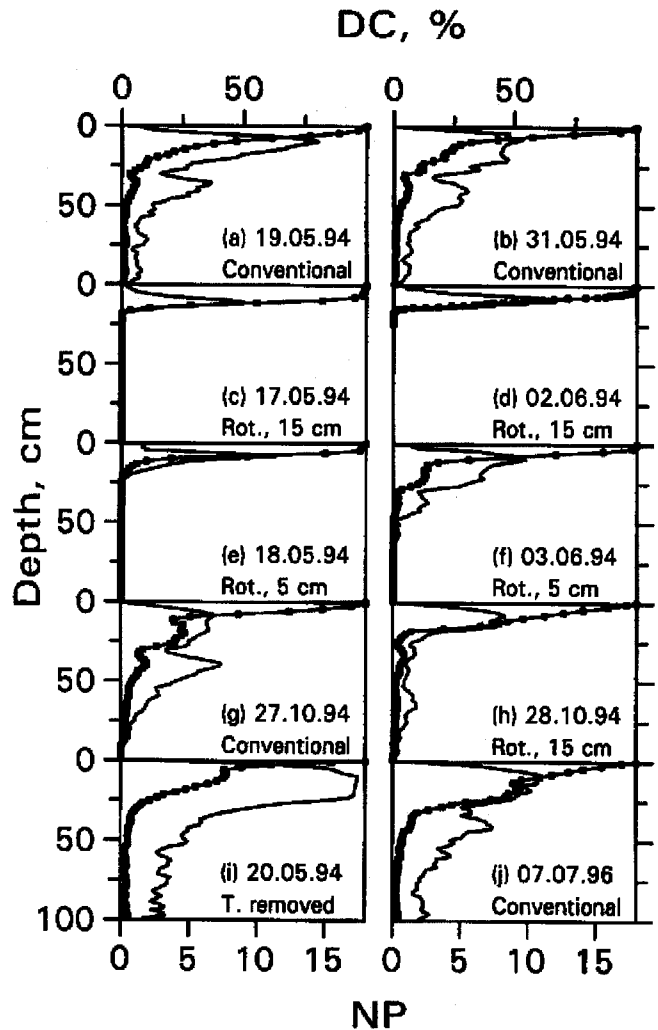


Fig. 3. Depth profiles of the average number of flow pathways, NP (—) and the average degree of dye coverage, DC (—■—■) in single plots. For (i): depth indications refer to the uncovered artificial soil surface.

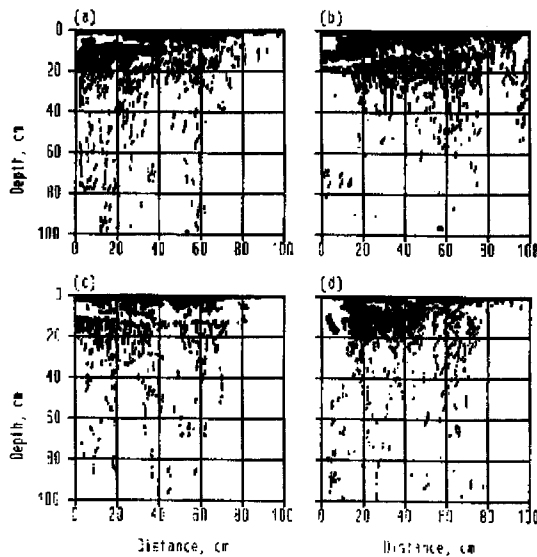


Fig. 4. Digitized flow patterns from vertical cross sections in plot with topsoil removed (20.05.94).

of dye coverage is much less at 15 cm depth and the effect of seed bed preparation is no longer obvious (Fig. 5b). The flow patterns tend to be more concentrated in cracks, probably between structural units left unbroken by the plough. The direction of ploughing in 1993 was parallel to the second axis. From about 15 cm to the ploughing depth, there were areas with buried, partly decomposed crop residues (straw) covering up to about 5% of the cross section. The dye patterns reaching these areas from above tended to spread both horizontally and vertically along the residues. There was considerable earth worm activity, especially in the areas with straw but its influence on the continuity of preferential flow pathways is not clear.

Although it was easy to identify the bottom of the furrow layer at about 22 cm depth, either as a plane of weakness or from its tendency to stop many flow patterns from above, it was difficult to uncover the bottom as a whole. The horizontal cross section shown in Fig. 5c was made as close to the bottom as possible. Also, at this depth, the shapes of the dye patterns indicated that flow took place mainly in cracks. Many of the stained cracks were running parallel to each other. Generally, these cracks could be traced below the ploughing depth; it is assumed that they were created originally by the shearing action of the plough.

Clearly the patterns change from 22 to 32 cm depth (Figs. 5c and 5d, respectively). There were no stained cracks at 32 cm depth. Most of the patterns were more or less round, small spots. Due to some inevitable smearing of the moist surface of the cross sections, it was seldom possible to see any central orifice in these dyed spots. However, by breaking dried soil samples, most of the flow pathways in this layer proved to be channels less than 1 mm in diameter (mostly root channels), in addition to a number of larger, stained earthworm channels. In some

cases, the small dyed spots lay very close to each other, thereby comprising larger stained unities. Patterns on horizontal cross sections made below 40 cm depth appeared as spots (up to about 1 cm in diameter) enclosing central earthworm channels of diameters in the range of 1–8 mm.

Discussion

The fact that many channels below 30–35 cm can be fed by relatively few pathways above this depth means that these uppermost pathways have to be efficient. The local minimum for NP at about 30 cm depth suggests a shift from flow mainly in relatively large cracks to flow taking place mainly in channels. Local minima for NP and DC at about 30 cm depth were also reported by Gjettermann *et al.* (1997) for dye tracing experiments conducted in conventionally tilled plots in 1994 and 1995 at the same field area but only for large dye application rates (50, 25, and 12.5 mm h⁻¹), rather than for low rates (6.3 and 3.1 mm h⁻¹). They reported that, for the application intensity of 3.1 mm h⁻¹, all stained earthworm channels penetrating to more than 90 cm depth could be traced all the way to the soil surface. The most extensive activation of channel flow ever found in the present work was observed in experiment 20.05.94 with topsoil removed and ponding 20 cm below the original soil surface. The activation of channel flow in the transition zone between tilled and untilled soil may be supported by a pressure build-up in the soil water in this zone.

The average number of activated flow channels in the depth interval 25–100 cm, NP₂₅, was larger in experiment 07.07.96 than in experiment 19.05.94 ($P < 0.01$) whereas the difference between experiment 07.07.96 and 31.05.94 was

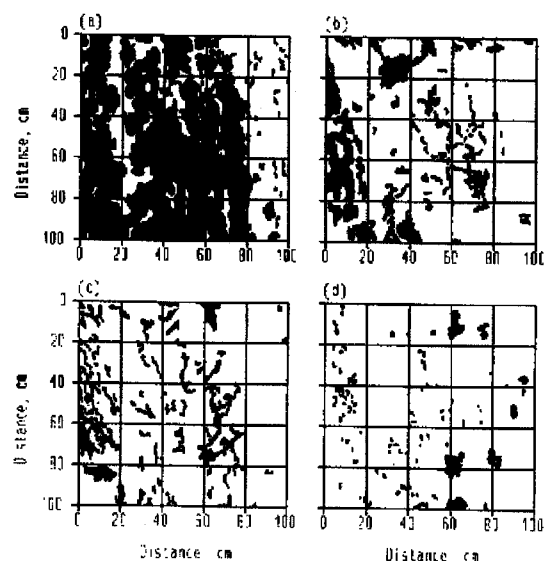


Fig. 5. Digitized flow patterns from horizontal cross sections in a conventionally tilled plot (01.06.94) made in (a): 8 cm depth, (b): 15 cm depth, (c): 22 cm depth, and (d): 32 cm depth.

non-significant (Table 3). The average degree of dye coverage above 25 cm depth, DC₂₅, was significantly larger in July 1996 than in the early experiments in 1994 ($P < 0.001$). The flow patterns in July 1996 may have been affected by a large number of living roots present in the topsoil at that time. Nevertheless, the uppermost completely stained soil layer was typically less than 1 cm thick in July 1996 which is less than the typical thickness (2–4 cm) found in the conventionally tilled plots in 1994.

Ghodraty *et al.* (1990b) investigated the effects on flow patterns in the root zone of disturbing the soil structure in the upper 30–40 cm with a trencher. They worked with a sandy soil without visible macropores and the anionic dye tracer Acid-Red 1. The disturbance altered the flow patterns dramatically. Both the tendency of finger formation just below the treated soil layer and the percentage of dye coverage in the subsoil below 70–80 cm were increased. In the present study, however, soil disturbance by rotovation reduced the depth of penetration of dye patterns. The different results may be explained by differences in soil type and soil treatment, a homogenizing effect of soil disturbance on soil structure being more likely in the present study. Furthermore, Ghodraty *et al.* (1990b) applied 100 mm of irrigation water to their plots compared with 25 mm in the present study.

Conclusions

Based on field dye tracer experiments on the 1 m scale conducted on a structured sandy loam soil, it is concluded:

1. Preferential flow was a prevailing phenomenon in the topsoil and in the subsoil of conventionally tilled plots.
2. Preferential flow in terms of channel flow was generated at structural interfaces located in the 20–40 cm depth interval.
3. Rotovation as a supplement to conventional seed bed preparation significantly reduced the penetration of stained flow patterns into the subsoil.

References

- Beven, K. and Germann, P. 1982. Macropores and water flow in soils. *Wat. Resour. Res.*, **18**: 1311–1325.
- Bouma, J., Jongerius, A., Boersma, O., Jager, A. and Schoonderbeek, D. 1977. The function of different types of macropores during saturated flow through four swelling soil horizons. *Soil Sci. Soc. Am. J.*, **41**: 945–950.
- Bouma, J. 1991. Influence of soil macroporosity on environmental quality. *Adv. Agron.*, **46**: 1–37.
- Demuth, N. and Hiltpold, A. 1993. 'Preferential flow': Eine Übersicht über den heutigen Kenntnisstand. *Z. Pflanzenernähr. Bodenk.*, **156**: 479–484.
- Ehlers, W. 1975. Observations on earthworm channels and infiltration on tilled and untilled loess soil. *Soil Sci.*, **119**: 242–249.
- Food and Agriculture Organization. 1990. *Guidelines for Soil Description*. 3rd ed. Food and Agriculture Organization of the United Nations, Rome. 70 pp.
- Flury, M. 1996. Experimental evidence of transport of pesticides through field soils.—A review. *J. Environ. Qual.*, **25**: 25–45.
- Flury, M. and Flühler, H. 1995. Tracer characteristics of Brilliant Blue FCF. *Soil Sci. Soc. Am. J.*, **59**: 22–27.
- Flury, M. and Flühler, H. 1994. Brilliant Blue FCF as a dye tracer for solute transport studies—A toxicological overview. *J. Environ. Qual.*, **23**: 1108–1112.
- Flury, M., Flühler, H., Jury, W.A. and Leuenberger, J. 1994. Susceptibility of soils to preferential flow of water: A field study. *Wat. Resour. Res.*, **30**: 1945–1954.
- Ghodraty, M., Frederick, F.E. and Jury, W.A. 1990a. Automated spray system for application of solutes to small field plots. *Soil Sci. Soc. Am. J.*, **54**: 287–290.
- Ghodraty, M. and Jury, W.A. 1990b. A field study using dyes to characterize preferential flow of water. *Soil Sci. Soc. Am. J.*, **54**: 1558–1563.
- Gjettermann, B., Nielsen, K.L., Petersen, C.T., Jensen, H.E. and S. Hansen. 1997. Preferential flow in sandy loam soils as affected by irrigation intensity. *Soil Technology*, **11**: 139–152.
- Hall, J.K. and Mumma, R.O. 1994. Dicamba mobility in conventionally tilled and non-tilled soil. *Soil Tillage Res.*, **30**: 3–17.
- Hall, J.K., Murray, M.R. and Hartwig, N.L. 1989. Herbicide leaching and distribution in tilled and untilled soil. *J. Environ. Qual.*, **18**: 439–445.
- Harris, G.L., Howse, K.R. and Pepper, T.J. 1993. Effects of mowing on soil-water and runoff from a drained clay soil. *Agric. Wat. Manag.*, **23**: 161–180.
- Horton, R., Allmaras, R.R. and Cruse, R.M. 1989. Tillage and compactive effects on soil hydraulic properties and water flow. In: W.E. Larson, G.R. Blake, R.R. Allmaras, W.B. Voorhees and S.C. Gupta (Editors), *Mechanics and related processes in structured agricultural soils*. Kluwer Acad. Publ., Dordrecht, pp. 187–203.
- Isensee, A.R., Nash, R.G. and Helling, C.S. 1990. Effect of conventional vs. no-tillage on pesticide leaching to shallow groundwater. *J. Environ. Qual.*, **19**: 434–440.
- Jury, W.A. and Flühler, H. 1992. Transport of chemicals through soil: Mechanisms, models, and field applications. *Adv. Agron.*, **47**: 141–201.
- Kladivko, E.J., Van Scoyoc, G.E., Monke, E.J. Oates, K.M. and Pask, W. 1991. Pesticide and nutrient movement into subsurface tile drains on a silty loam soil in Indiana. *J. Environ. Qual.*, **20**: 264–270.
- Lal, R., Logan, T.J., Eckert, D.J., Dick, W.A. and Shipitalo, M.J. 1994. Conservation tillage in the corn belt of the United States. In: M.R. Carter (Editor), *Conservation tillage in temperate agroecosystems*. Lewis Publishers, London, pp. 73–114.
- Shapiro, S.S. and Wilk, M.B. 1965. An analysis of variance test for normality (complete samples). *Biometrika*, **52**: 591–611.
- Staricka, J.A., Allmaras, R.R. and Nelson, W.W. 1991. Spatial variation of crop residue incorporated by tillage. *Soil Sci. Soc. Am. J.*, **55**: 1668–1674.