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Infiltration and macroporosity of a silt loam soil under two contrasting tillage systems

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Abstract

Infiltration into soils is influenced by macroporosity. The properties of the macropore system are, among other factors, a function of the applied management and tillage system. Therefore, tillage practices are supposed to have considerable impact on surface runoff and generation of floods. On an experimental site with a silt loam soil partly treated with conventional and conservation tillage systems, two different methods for the characterization of the macropore system were performed: Visual inventarization of stained and unstained macropores and tension-adjusted infiltration measurements. Dye tracer experiments with methylene blue yielded a penetration depth of 120 cm on the plot with conservation tillage whereas on the plot with conventional tillage a penetration depth of only 50 cm were observed. The visual inventarization of stained and unstained macropores resulted, for both tillage treatments, in macropore densities ranging between 100 and 1000 macropores per square meter, with macropore numbers greatest in the topsoil and gradually decreasing towards depth. Infiltration rates at saturation were, in the topsoil, slightly higher at the conventionally tilled plot compared to the conservation till plot, whereas below 30 cm depth it was vice versa. For both methods, the macroporosities are at soil depths of 0 – 10 cm higher for conventional tillage, and below soil depths of 20 cm higher for conservation tillage. In combination with the greater depth penetration of dye tracer at the conservation till plot, this indicates a greater continuity of macropores in vertical direction for soils with conservation tillage system. Therefore, this tillage practice could possibly offer a means to reduce surface runoff and flood generation in agricultural landscapes with silty soils.

Keywords: conventional/conservation tillage, soil hydrology, macroporosity, preferential flow, tension infiltrometer, dye tracer, methylene blue

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Zusammenfassung

Wasserinfiltration und Makroporosität eines landwirtschaftlich genutzten Lössbodens unter differenzierter Bodenbearbeitung

Die Infiltration von Wasser in Böden wird u. a. wesentlich durch das Makroporensystem beeinflusst. Die Eigenschaften des Makroporensystems werden besonders durch die Form der Bodenbearbeitung gesteuert und sind so ein relevanter Einfluss im Kontext der Entstehung von Oberflächenabfluss und damit von Hochwässern in Flusseinzugsgebieten. An einem landwirtschaftlichen Untersuchungsstandort auf Löss-Substrat (Adenstedt) wurden unter konservierender und konventioneller Bodenbearbeitung vergleichend zwei Methoden zur Charakterisierung des Makroporensystems untersucht: die visuelle Erfassung von gefärbten und ungefärbten Makroporen nach Farbtracer-Applikation (Methylenblau) und die Tensionsinfiltrometrie.

Mittels visueller Makroporenerfassung wurden für die reduziert bearbeitete Standortvariante Makroporen bis 120 cm Bodentiefe nachgewiesen. Im Gegensatz dazu konnten Makroporen an der konventionell bearbeiteten Variante lediglich bis 50 cm Bodentiefe nachgewiesen werden. Die visuelle Inventur von Makroporen belegt eine Makroporendichte zwischen 100 und 1000 Makroporen pro Quadratmeter bzw. einem Flächenanteil von 0,08 – 0,13 %. Die aus den Infiltrometermessungen berechneten Makroporenzahlen liegen in vergleichbarer Größenordnung wie die entsprechenden Werte aus den Farbtracerexperimenten. Beide Untersuchungsmethoden liefern übereinstimmende Ergebnisse mit Bezug auf die Makroporosität in 0 – 10 cm Bodentiefe für die konventionell bewirtschaftete Variante. Unterhalb einer Bodentiefe von 20 cm ist die Makroporosität jedoch deutlich höher an der konservierend bearbeiteten Variante gegenüber der konventionell bearbeiteten Vergleichsparzelle. Im Zusammenhang mit der größeren Eindringtiefe des Farbtracers unter konservierender Bodenbearbeitung wird auf eine höhere Kontinuität des Makroporennetzwerks in vertikaler Richtung geschlossen. Auf dieser Grundlage wird gefolgert, dass eine konservierende Bodenbewirtschaftung von Lössstandorten eine höhere Infiltration, einen geringeren Oberflächenabfluss und damit ein verringertes Hochwasserrisiko in landwirtschaftlich genutzten Flusseinzugsgebieten induziert. Diese reduzierte Bodenbearbeitung kann daher einen aktiven Beitrag für ein verringertes Risiko der Hochwasserentstehung in Flusseinzugsgebieten bilden.

Schlüsselwörter: konventionelle/konservierende Bodenbearbeitung, Bodenhydrologie, Makroporosität, präferentieller Fluss, Tensionsinfiltrometer, Farbtracer, Methylenblau

1 Introduction

The properties of the soil macropore network, i.e. macropore volume fraction, diameter and continuity of macropores, can have a dominant impact on the infiltration behaviour of agricultural soils (e.g. Ehlers, 1975; Shipitalo et al., 2000). The characteristics of the macropore system, the soil structure and the physical properties of the topsoil are influenced by agricultural management practices (e.g. Frede et al., 1994; Tebrügge and Düring, 1999). Soil management systems are called „conventional" when they involve moldboard plowing and harrowing, the generic term „conservation tillage" refers to management practices with less soil disturbance, reduced penetration depth and without inversion of the topsoil. In „no-till"-systems the seeds are directly drilled into the soil without any further tillage measure.

Enhanced infiltration capacity, as compared with conventional tillage, is often found under conservation tillage as well as under no-till (e.g. Mukhtar et al., 1985; Douglas and Goss, 1987; Meek et al., 1990; Logsdon et al., 1993; Beisecker, 1994; Frede et al., 1994; Reynolds et al., 1995; Tebrügge and Düring, 1999). On the other hand, in some cases reduced infiltration rates under conservation tillage practices were reported (e.g. Lindstrom et al., 1981; Culley et al., 1987; Zachmann et al., 1987; Heard et al., 1988; Unger, 1992; Reynolds et al., 1995). In other studies, no significant differences of infiltration properties under different tillage practices were observed (e.g. Starr, 1990; Ankeny et al., 1990), or the differences of infiltration properties changed distinctly with time (Dunn and Phillips, 1991).

Number and continuity of macropores for different tillage systems and their influence on infiltration capacity of agricultural soils have been investigated by e.g. Ehlers (1975), Zachmann et al. (1987), Radcliffe et al. (1988), Meek et al. (1990), Dunn and Phillips (1991), and Reynolds et al. (1995). In most cases, greater numbers of macropores and a greater continuity of the macropore system in vertical direction have been found for conservation tillage systems, as compared to conventional tillage, which is mostly attributed to greater abundance of earthworms and less disturbance of the topsoil.

Soil infiltration capacity is often assessed by in situ measurements of infiltration rates, either under saturated conditions with ponded infiltration rings and pressure infiltrometers (Collis-George, 1980; Bond and Collis-George, 1981; Reynolds and Elrick, 1990), or with tension infiltrometers, involving slightly negative pressures (Clothier and White, 1981; Ankeny et al., 1988; Perroux and White, 1988). Tension disc permeameters allow to determine the contribution of different size ranges of macropores by precisely selecting the water supply potential. From the differences in infiltration rates under different supply potentials, numbers and volume fractions of hydraulically effective macropores have been derived in agricultural (Dunn and Phillips, 1991; Trojan and Linden, 1998) and forest (Watson and Luxmoore, 1986; Wilson and Luxmoore, 1988) soils.

Other methods used to characterize the macropore network in soils are dye tracer experiments (e.g. Andreini and Steenhuis, 1990; Droogers et al., 1998), direct counting and inventarization of unstained macropores in the field (e.g. Logsdon et al. 1990; Ela et al., 1992), taking photographic images of macroporous soils (e.g. Edwards et al., 1988), resin impregnation techniques (Singh et al., 1991), and computed x-ray tomography (Anderson et al., 1990; Joschko et al., 1991; Daniel et al., 1997).

Selected investigations of the macroporosity in agricultural and forest soils with different methods are compiled in Table 1. It is obvious, that there is no unambiguous definition regarding the size of macropores. Furthermore, the different methods seem to yield systematically different results for the macroporosity: Whereas macroporosities derived from tension infiltrometry are typically within the range 0.001 - 0.05 %, the macroporosities obtained by visual inventarization of stained and unstained macropores are consistently higher with values up to 2 %.

The objectives of this study are

1. to characterize the properties of the macropore network of an agricultural soil of silt loam texture;
2. to compare macroporosities for this soil as obtained from different measurement methods.

The results will serve for an assessment, whether conservation tillage practices on agricultural soils are capable to enhance infiltration capacity and hence to reduce surface runoff.

The background of this study is to investigate, whether soil management practices in agricultural and forest catchments are capable of increasing the water retention capacity on the scale of whole watersheds in order to eventually reduce flood risk.

2 Materials and Methods

2.1 Study site

Dye tracer experiments and tension infiltrometer measurements were performed near the village of Adenstedt (52°00‘ N, 9°56‘ E), located approximately 50 km to the south of Hannover in the hilly landscape of Lower Saxony. The mean annual temperature here is 8 °C and mean annual precipitation approximately 700 mm per year.

The experimental site at Adenstedt with the rotations sugar beet-winter wheat-winter wheat exists since 1990 with different tillage systems (Brunotte, 1990):

- Conventional tillage (mouldboard plow);
- Conservation tillage with seedbed preparation.

The soil type is an eroded orthic Luvisol above loess of upper Pleistocene (Vistula glaciation) age. The deeper

Table 1:
Selected investigations of macroporosities in agricultural and forest soils

Authors	**Soil texture**	**Minimum diameter of macropores**	**Method**	**Macroporosity**
Ehlers (1975)	silt loam	> 2000 mm	visual inventarization of stained and unstained pores	0.2 – 0.8 %
Watson and Luxmoore (1986)	loamy soils	> 1000 mm	tension infiltrometer	0.04 %
Edwards et al. (1988)	silt loam	> 400 mm	image analysis of horizontal soil cross sections	1.4 %
Wilson and Luxmoore (1988)	loam	> 1500 mm	tension infiltrometer	0.02 – 0.03 %
Ankeny et al. (1990)	silty clay loam	> 500 mm[a]	tension infiltrometer	0.0043 – 0.119 %
Logsdon et al. (1990)	loamy/silty soils	> 400 mm	visual inventarization of stained and unstained pores	0.1 – 2 %
Dunn and Philips (1991)	silt loam	> 750 mm	tension infiltrometer	0.006 – 0.013 %
Ela et al. (1992)	clay loam, silt loam	> 860 mm	tension infiltrometer; visual inventarization of macropores	visible Macropores: 0.02 % (uncovered soil); 0.19 – 0.7 % (covered soil); tension infiltrometer: 0.006 – 0.024 %
Mohanty et al. (1996)	silt loam	> 1000 mm	tension infiltrometer	0.014 – 0.061 %[b]
Wang et al. (1996)	sand	> 500 mm	tension infiltrometer	0.01 – 0.05 %
Trojan and Linden (1998)	silt loam	> 1000 mm	visual inventarization of stained pores; tension infiltrometer	0.29 – 1.3 % (staining); 0.0005 – 0.002 % (infiltrometer)[c]

[a] In Ankeny et al. (1990), the minimum diameter for macropores is defined as 0.2 mm (equal to 15 cm tension); here macroporosities are calculated for a tension of 6 cm for better comparison.
[b] recalculated
[c] recalculated; see text for explanations

underground is formed by upper triassic shales. The predominant texture is a silt loam with mean grain size fractions of 12.3 % clay, 85 % silt and 2.7 % sand in the Ap-horizon (Brunotte, 1990). The mean soil characteristic number according to the german agricultural soil taxation is 75. A simplified soil profile is shown in Table 2. Soil physical and hydrological properties at the experimental site Adenstedt have been investigated by e.g. Brunotte (1990) and Roth (1992), soil biological studies were performed by Joschko et al. (1997).

The experiments were performed at the end of April 2000 after an extended period of dry weather. The crop at that time was winter wheat. During the field experiments, the maximum temperature reached 28 °C during the day, whereas it fell to approximately 10 °C at night.

2.2 Dye tracer experiments

For the dye tracer experiments, a confined 0.7 by 0.7 m irrigation plot was selected for each tillage system. The distance between those two plots was 10 m. After the crop had been trimmed to the soil surface, macroscopic pore features such as cracks and holes, wormcasts and the location of the crop rows and rhizomes were traced on transparent plastic sheets. Subsequently, the plot was irrigated homogeneously with 10 mm of a $2.8\cdot10^{-3}$ molar (1 g/liter) methylene blue ($C_{16}H_{18}ClN_3S\cdot2H_2O$) solution at a rate of 30 mm/h with a portable hand sprayer. Methylene blue had been used as a dye tracer in many flowpath visualization experiments in agricultural soils with similar texture and colour as at the Adenstedt site (e.g, Bouma and Dekker, 1978; Bouma et al., 1982; Droogers et al., 1998; Trojan and Linden, 1998). In those studies, it provided a favorable contrast against the soil. After application of the

Table 2:
Simplified soil profile Adenstedt

Horizon	Depth	Soil colour (Munsell)	Structure
Ap	0-30 cm	10 YR 3/2-3	crumbly-subpolyedric
Bt	30-40 cm	10 YR 3/3-4	subpolyedric
Bv1	40-70 cm	10 YR 3/6, weakly rustycoloured (mottles)	subpolyedric -coherent
Bv2	70-150 cm	10 YR 4/2, weakly rustycoloured (mottles)	coherent

dye tracer solution the plots were covered with a plastic sheet to prevent evaporation. Two hours later, staining patterns of the displaced methylene blue solution, visible unstained macropores of > 1000 µm diameter (as proposed by Luxmoore, 1981), and positions of crop rhizomes were recorded. The plots were excavated at defined depth increments. Soil depths of 0.05, 0.1, 0.2, 0.3, 0.4, 0.5, 0.8, and 1.2 m were documented. Images on the plastic sheet were manually digitized and processed by the GIS-software ArcView (ESRI) in terms of stained areas, areas of unstained macropores, rhizome areas, wormcast areas, and intersections between stained and rhizome areas. The results are detailed elsewhere (Hangen et al., 2000, submitted to Soil and Tillage Research). In the following, only the numbers and area fractions of stained and unstained macropores are considered.

2.3 Tension infiltrometer

Tension infiltration measurements were performed simultaneously with the dye tracer experiments with a tension infiltrometer (constructed at the Center for Agricultural and Landscape Research, Müncheberg) at hydraulic potentials ψ [L] of -10, -5, -1 and 0 cm water column (WC) in 0, 10, 30, 50 and 90 cm soil depth, respectively, for each of the two plots, until steady state infiltration rates were observed. The base of the infiltrometer, with a diameter of 20 cm, was covered by a nylon cloth of 55 mm pore size. Before the measurements, the selected site was scraped level with a spatula, and then a plastic ring of 1.9 cm height was driven gently approximately 1 cm into the soil. Care was taken that the rim of the ring was level. Then, a pure fine sand was smoothly leveled within the ring area up to the top rim of the ring. Then the infiltrometer base was placed onto the sand surface with the respective matric potential pre-set. Infiltration was recorded after 30 s, 60 s, and then every minute, until steady state flow conditions had established. This occurred in general after 20 minutes for ψ = -10 cm WC, after 10-12 minutes for ψ = -5 cm WC and after 8-10 minutes for ψ = -1 cm WC and 0 cm WC.

Assuming the pore space consists of capillary tubes, the relationship between pore radius r [L] and hydraulic potential ψ [L] is according to the equation of capillarity:

$$r = \frac{2\sigma \cos\alpha}{\rho g |\psi|} \tag{1}$$

Here, s is the surface tension of water [MT^{-2}] (= 73.4 mN/m at 15 °C), a the contact angle between the water-air interface and the solid surface (assumed here to be ~ 0), r the density of water [ML^{-3}] (= 1000 kg / m^3), and g the acceleration due to gravity [LZ^{-2}] (= 9.81 m / s^2).

According to equation (1), infiltration at water potentials of -1, -5, and -10 cm water column will exclude pores of equivalent diameters greater than 3, 0.6, and 0.3 mm, respectively.

To ensure comparability with the dye tracer experiments, macropore flow, q_m [LT^{-1}], is defined here as the difference between infiltration rates at 0 and 3 cm tension, i.e. flow through pores with diameters greater than 1 mm. Since the infiltration was not measured at 3 cm tension (the tensions at the infiltrometer were fixed), the flux at 3 cm tension was calculated as the geometric mean between the infiltration fluxes at –1 and –5 cm water potential.

An upper bound for the number of hydrologically effective macropores per unit area, N_m, results from the Hagen-Poiseuille equation for laminar flow through a capillary tube (Watson and Luxmoore, 1986; Wilson and Luxmoore, 1988; Dunn and Phillips, 1991):

$$N_m = \frac{8\eta q_m}{\pi g \rho r_m^4} \tag{2}$$

Here, η denotes the dynamic viscosity of water [$ML^{-1}T^{-1}$] (taken here as 0.00115 Pa s for a temperature of 15 °C), and r_m [L] is the minimum radius for macropores (equal to 0.5 mm). Implicit assumed in equation (2) is a unit hydraulic gradient, i.e. steady-state conditions during infiltration flow.

The effective macroporosity, θ_m, is estimated as:

$$\theta_m = N_m \pi r_m^2 \tag{3}$$

Since r_m is the minimum radius of macropores, θ_m is an estimate of the minimum value for the macroporosity. Using the infiltration data alone, the maximum radius of macropores is *a priori* unknown.

3 Results and discussion

3.1 Dye tracer experiments and unstained macropores

Two-dimensional horizontal distributions of stained and unstained macropores (Fig. 1) reveal no distinct dependence of staining patterns from the spatial location of plant structures on the soil surface, neither for the conventional, nor for the conservation tillage. In 30 cm soil depth, the number of macropores is evidently much higher in the conservation tilled plot as compared to the conventional tillage plot. This observation is in accordance with the results of Joschko et al. (1997), who found by X-ray tomography for the conservation tillage at 30 cm a much higher macropore volume fraction and connectivity as was detected for the conventional tillage system. At the surface of the conventional tillage plot, numerous elongated dessication cracks were observed, while no such cracks were visible at the conservation tilled plot. This may be attributed to the higher surface coverage by plant residues at the conservation tillage plot.

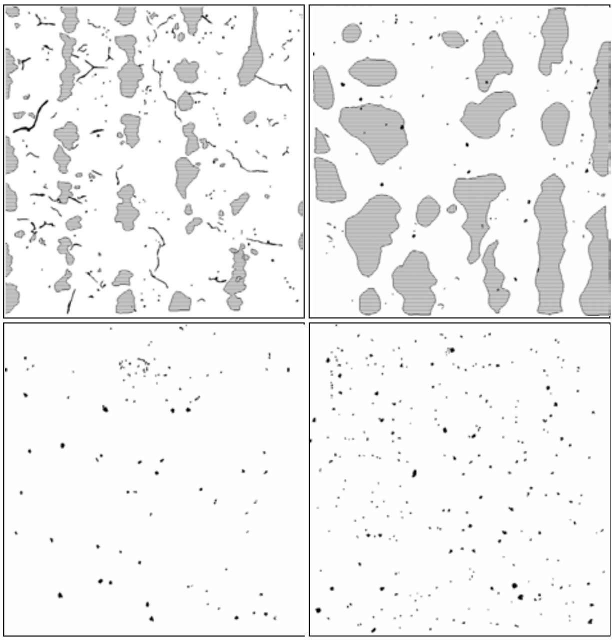

Fig. 1:
2D-horizontal distribution of stained areas and unstained macropores (dark), plant structures on the soil surface (horizontal hatching) and worm casts (vertical hatching). Left side: conventional tillage; right side: conservation tillage; upper row: soil surface; bottom row: 30 cm soil depth. The width of each horizontal plane is 70 cm.

Total numbers of macropores per square meter obtained by the dye tracer experiments and the visual inventarization of unstained macropores exhibit for both tillage systems a pronounced maximum at a soil depth of 5 cm (Fig. 2, Table 3), and a gradual decrease of macropore density towards the bottom of the soil profile. Whereas the macropore number is higher for the conventional tillage plot at the surface and at a depth of 10 cm, as compared to the conservation tillage plot, it is higher for conservation tillage at all the other depths investigated. This is especially evident at soil depths greater than 20 cm.

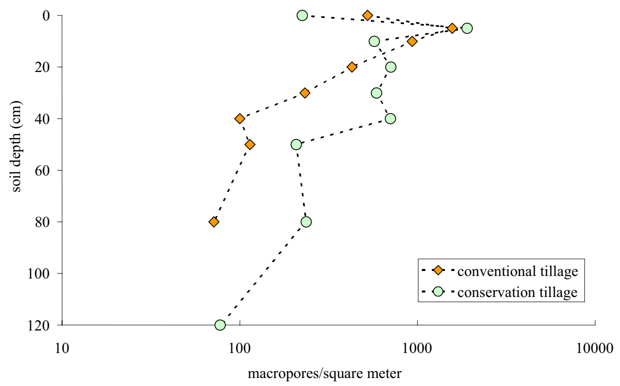

Fig. 2:
Total numbers of macropores per square meter obtained from the dye tracer experiments and visual inventarization of unstained macropores.

At the soil surface (0 cm soil depth), the macropore numbers termed „unstained macropores“ refer to visible macropores traced immediately before the dye tracer application. At soil depths 5 and 10 cm, essentially all the macropores were stained, additionally, at 5 cm depth the stained areas consist to a high degree of pors smaller than macropores. For depths greater than 10 cm the numbers of unstained macropores surpass those of stained pores.

At the conservation tillage plot, the dye tracer reached a soil depth of 120 cm, whereas at the conventional tillage plot no dye traces were observed below a soil depth of 50 cm. At the conservation tillage plot, numerous unstained macropores were present at a depth of 120 cm, whereas at this depth no macropores were found at the conventional tillage plot. These are pronounced indications for a much higher connectivity of the macropore system at the conservation tillage plot. The numbers of macropores found here are within the same order of magnitude as those reported for other similar soils of agricultural landuse: For a macroporous silt loam under parallel conventional tillage and no-till, Ehlers (1975) reported macropore den-

Table 3:
Macropore density (macropores/m^2) obtained by dye tracer experiment and visual inventarization of unstained macropores

	conventional tillage			conservation tillage		
depth (cm)	stained macropores	unstained macropores	stained and unstained macropores	stained macropores	unstained macropores	stained and unstained macropores
0	-	467	467	-	155	155
5	1567	-	1567	1904	-	1904
10	935	-	935	571	-	571
20	196	233	429	67	641	708
30	80	153	233	33	555	588
40	8	92	100	8	696	704
50	55	59	114	6	202	208
80	-	71	71	2	235	237
120	-	-	-	2	76	78

sities (for macropore diameters > 2 mm) between 27 and 363 macropores per square meter. The macropore numbers given by Ehlers are consistently higher for the no-till plot as compared to the tilled plot. In contrast to our findings, however, Ehlers found very large macropore numbers in a soil depth of 60 cm, both for conventional tillage and no-till. Similar results are reported by Logsdon et al. (1990) for different soils of loamy to silty texture. These authors found maximum macropore (diameter > 0.4 mm) numbers for soli depths below 30 cm. Similar results were reported by Edwards et al. (1988), who obtained for a silt loam under no-till maximum macropore (diameter > 0.4 mm) numbers at 30 cm (the greatest depth investigated). On the other hand, Singh et al. (1991) found for a loam soil under no-till maximum macropore (diameter > 1.6 mm) numbers at a depth of 15 cm and under conventional tillage at a depth of 25 cm. These results are in line with our results. But, in contrast to the macropore characteristics obtained here for the Adenstedt site, the macropore numbers for the no-till plot of Singh et al. (1991) do not surpass those of conventional till system for soil depths between 25 and 55 cm. Trojan and Linden (1998) found by tracing of visible stained and unstained macropores for a Waukegan silt loam between 0 and 40 cm soil depth macropore (diameter > 1 mm) numbers between approximately 400 and 800 per square meter. Similar to our results, the macropore density of their soil in most cases decreases with increasing soil depth, and macropore densities are higher for no-till than for conventionally tilled soil.

The relationship of macropore area coverage vs. depth (Fig. 3, Table 4) shows a similar overall trend as the macropore numbers vs. depth: Except for the soil surface and 10 cm soil depth, the conservation till plot exhibits higher area percentages than conventional tillage. For both plots, the maximum area percentage is at 5 cm soil depth. The bulk of the stained area at this depth, however, are not macropores, so the area fractions of 3.1 and 4.1 % given in Table 4 do not reflect the real macroporosity at this depth. At the soil surface, the macropore area fraction is distinctly higher for the conventional tillage (0.7116 %) than for the conservation tillage (0.1314 %). Dessication cracks, however, contribute to a high degree to the macroporosity for the conventional tillage. The value of 0.1314 % found for the conservation tillage is comparable to the macroporosity of 0.2 % at 2 cm soil depth reported by Ehlers (1975) for comparable site conditions under no-till. Ela et al. (1992) report for a mulch-covered silt loam inoculated with earthworms macroporosities (diameter > 1 mm) at the surface between 0.2 and 0.4 %. Trojan and Linden (1998) obtained for their Waukegan silt loam soil, integrated over 40 cm soil depth for the conventionally tilled plots macroporosities ranging between 0.29 and 0.51 %, and for the no-till plots between 0.89 and 1.3 %.

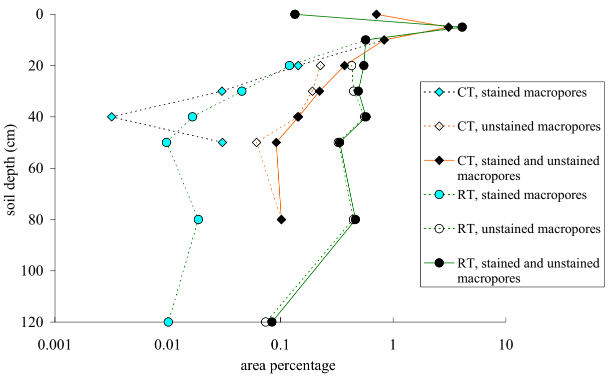

Fig. 3:
Area percentages of macropores obtained from the dye tracer experiments and visual inventarization of unstained macropores (CT = conventional tillage; RT = conservation tillage)

3.2 Tension infiltrometer

Measured infiltration rates at soil depths of 0, 10, 30, 50 and 90 cm are depicted in fig. 4 for the conventional

Table 4:
Macropore area fraction (%) obtained by dye tracer experiment and visual inventarization of unstained macropores

	conventional tillage			conservation tillage		
depth (cm)	stained macropores	unstained macropores	stained and unstained macropores	stained macropores	unstained macropores	stained and unstained macropores
0	-	0.7116	0.7116	-	0.1343	0.1343
5	3.1062	-	3.1062	4.0894	-	4.0894
10	0.8312	-	0.8312	0.5695	-	0.5695
20	0.1440	0.2258	0.3698	0.1205	0.4291	0.5496
30	0.0303	0.1924	0.2227	0.0455	0.4459	0.4914
40	0.0032	0.1421	0.1453	0.0166	0.5577	0.5743
50	0.0306	0.0614	0.0920	0.0098	0.3262	0.3360
80	-	0.1018	0.1018	0.0187	0.4448	0.4636
120	-	-	-	0.0101	0.0739	0.0840

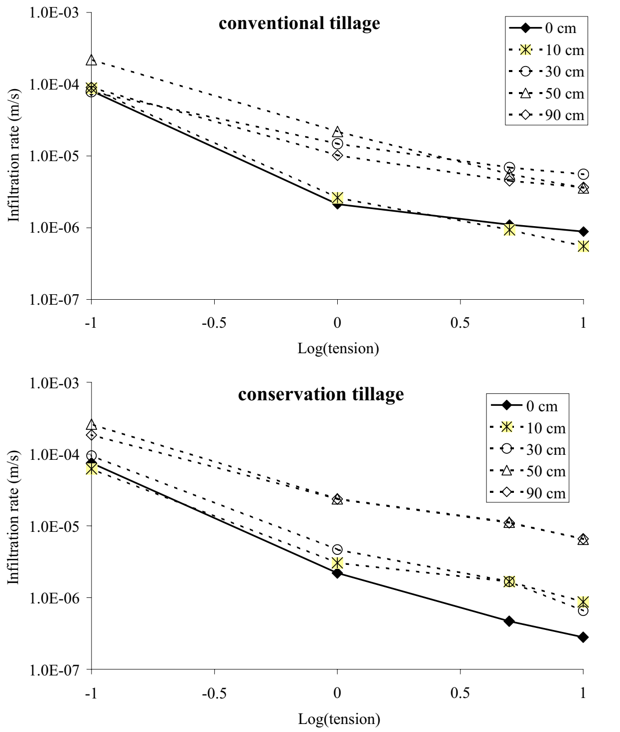

Fig. 4:
Infiltration rates as a function of the logarithm of the applied suction for different soil depths. Top: Conventional tillage; bottom: Conservation tillage. In order to take the logarithm, the suction of zero is assigned a value of 0.1 cm water column.

tillage (top) and the conservation tillage plot (bottom). The double logarithmic plot of the infiltration rate (m/s) vs. applied tension (cm water column) in the most cases yields an approximately linear relationship for a single depth. A similar relationship was described by e.g. Ankeny et al. (1990) for a silty clay loam under corn and soybean. At zero applied tension, the measured infiltration rates at Adenstedt range between 0.078 and 0.22 mm/s for conventional tillage and 0.062 and 0.26 mm / s for conservation tillage. Ankeny et al. (1990) found 0.232 mm/s for their no-till plot and 0.293 mm/s for a conventional tillage plot. The saturated infiltration rates reported by Trojan and Linden (1998) for a silt loam soil are distinctly lower with 0.0026 – 0.013 mm/s for a conventionally tilled plot and 0.0063 – 0.012 mm/s for no-till. A silt loam under rye and vetch described by Dunn and Phillips (1991) yielded saturated infiltration rates of 0.022 – 0.039 mm / s for conventional tillage and 0.03 – 0.057 mm/s for no-till. At Adenstedt, the differences between the infiltration rates at saturation and at the applied tensions amount to at least one order of magnitude. Compared with values for agricultural soils of similar texture (Ankeny et al., 1990; Dunn and Phillips, 1991; Trojan and Linden, 1998), these differences seem exceptionally high. Wilson and Luxmoore (1988), on the other hand, for a loam soil under forest report similar differences between infiltration rates

Table 5:
Macropore density (macropores/m^2) derived from tension infiltrometer measurements

depth (cm)	conventional tillage	conservation tillage
0	380	353
10	415	285
30	326	440
50	998	1164
90	398	807

at 0 and –2 cm water potential, as obtained at Adenstedt for 0 and –1 cm water potential. Similar increases in infiltration rates near saturation are also reported by Jarvis and Messing (1995) for several fine textured agricultural macroporous soils of Sweden.

For both, the conventionally and the conservation tilled plot, infiltration rates increase with depths, showing maximum values at 50 cm soil depth.

Macropore numbers, calculated from the measured infiltration data with equation (2), are depicted in Fig. 5 and compiled in Table 5. Although the values are within the same range as the macropore numbers obtained by the visual inventarization (Fig. 2, Table 3), i.e. approximately 100 – 1000 macropores per square meter, the depth dependence of macropore density is distinctly different for the two methods: Whereas with the method of visual inventarization macropore densities show maximum values at 0 – 20 cm soil depth and decreasing values with increasing soil depths, the values obtained from the tension infiltrometer data are lower in the topsoil and indicate a distinct maximum at 50 cm soil depth. Although the depth dependence of macropore number density obtained with the tension infiltrometry is in somewhat better accordance with the results of Ehlers (1975) and Edwards et al. (1988), who found by visual inventarization increasing macropore numbers with increasing soil depth, it is by no

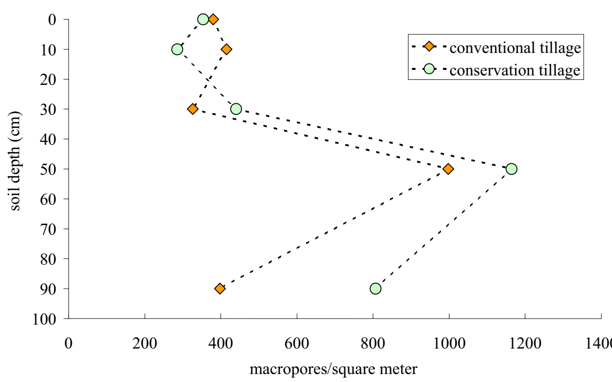

Fig. 5:
Total numbers of macropores per square meter obtained from the tension infiltrometer measurements.

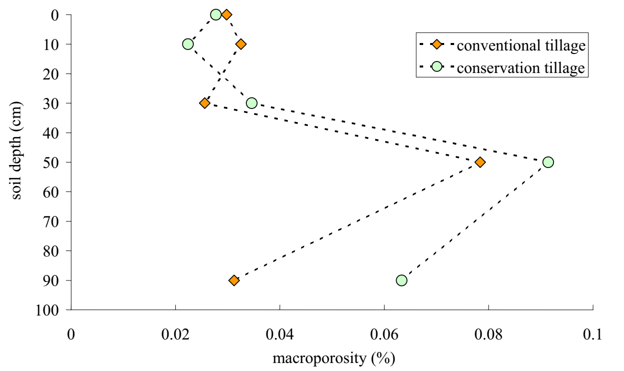

Fig. 6:
Macroporosity obtained from the tension infiltrometer measurements. Values obtained by multiplying the calculated pore numbers per square meter by the area of the minimum pore radius for macropores (= 0.5 mm).

Table 6:
Macroporosity (%) derived from tension infiltrometer measurements. Values obtained by multiplying the calculated pore numbers per square meter by the area of the minimum pore radius for macropores (= 0.5 mm)

depth (cm)	conventional tillage	conservation tillage
0	0.0298	0.0278
10	0.0326	0.0224
30	0.0256	0.0346
50	0.0784	0.0914
90	0.0312	0.0634

means clear, which of these values determined for the relation of macropore numbers vs. depth at the site Adenstedt, is the „true" one. Possible explanations for these differences are the spatial variability of macropore properties, since the tension infiltrometer measurements and dye tracer experiments were performed approximately 50 cm apart from each other. Moreover, the macropore numbers were calculated with equation (2), using a constant minimum macropore radius of 0.5 mm for all depths. Therefore a maximum number of macropores for a given macropore flux is obtained. Macropore diameters, however, vary as a function of soil depth: For the conservation tillage plot, macropore areas obtained with the visual inventarization are increasing distinctly with depth and could to a high degree account for the differences of macropore numbers vs. depth obtained with the two methods. For the conventionally tilled plot, however, the increase of macropore area with depth is much less pronounced.

Multiplying the calculated macropore numbers with the minimum area of one macropore, with a radius of 0.5 mm, yield estimates for the mimimum hydraulically effective macroporosity (Fig. 6, Table 6). The values range between 0.02 and 0.1 %, approximately one order of magnitude lower than those obtained by visual inventarization (Fig. 3, Table 4). Macroporosities derived from tension infiltrometry reported by other authors are within the same range (cf. Table 1): Watson and Luxmoore (1986) and Wilson and Luxmoore (1988) obtained for loamy soils within a forested catchment macroporosities of 0.02 – 0.04 %. Dunn and Phillips (1991) report for a silt loam under agricultural management macroporosities between 0.006 and 0.013 %. Clay loam and silt loam soils described by Ela et al. (1992) yield macroporosities of 0.006 – 0.024 %. Wang et al. (1996) obtained for a sandy soil macroporosities beween 0.01 and 0.05 %. The investigation of Trojan and Linden (1998) deserves special attention, since they estimated macroporosities for an agricultural silt loam also using the same two methods as applied in our experiment. The macroporosities given in Trojan and Linden (1998, Table 3) as calculated from tension infiltration data range between 0.4 and 1.2 %, in approximate agreement with their macroporosities obtained with visual inventarization, but distinctly higher than the macroporosities reported by the other authors cited above. The equation given by Trojan and Linden (1998, equation 3) for the calculation of the macroporosi-

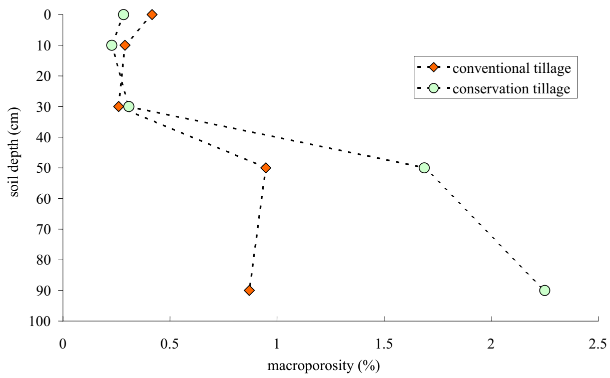

Fig. 7:
Macroporosity obtained from the tension infiltrometer measurements. Values obtained by multiplying the calculated pore numbers per square meter by the median values for the macropore areas obtained from the dye tracer experiments and the visual inventarization of unstained pores.

Table 7:
Macroporosity (%) derived from tension infiltrometer measurements. Values obtained by multiplying the calculated pore numbers per square meter by the median values for the macropore areas obtained by the dye tracer experiments and the visual inventarization of unstained pores

depth (cm)	conventional tillage	conservation tillage
0	0.4164	0.2827
10	0.2894	0.2283
30	0.2604	0.3083
50	0.9470	1.6876
90	0.8705	2.2506

ty, however, is flawed. Moreover, it is not clear, whether they use the minimum radius of macropores or some average. A re-evaluation of the infiltration data given by Trojan and Linden (1998, Table 1), using equations (2) and (3) and the minimum radius of macropores (0.5 mm) results in macroporosities between 0.0005 and 0.002 %. This means, that the discrepancy of macroporosities estimated with these two different methods in this experiment is even more pronounced compared to our results.

In case the actual mean radius of macropores in a soil segment is known, one could obtain more realistic values of the hydraulically effective macroporosity. From our visual inventarization of stained and unstained macropores at Adenstedt, the area of each documented macropore is known. Since the macropore areas are not normally distributed, we used the median values of macropore area for each soil depth. Using equation (3), the macropore numbers calculated from tension infiltration data, and the median values of macropore area, the estimates of the hydraulically effective macroporosity (Fig. 7, Table 7) are distinctly higher than those using a minimum radius of macropores. The values are within the same order of magnitude as those obtained by visual inventarization. The decrease in macroporosity with increasing soil depth as obtained with the visual inventarization, however, is unparalleled also when applying this modification.

3.3 Synopsis of results of dye tracer experiments, tracing of unstained macropores, and tension infiltrometry

The dye tracer experiments revealed a greater continuity and connectivity of the macropore system for the experimental plot under conservation tillage compared to the conventionally tilled plot, since at RT, the methylene blue solution reached a soil depth of 120 cm, whereas dye tracer displacement at CT came to a halt at 50 cm depth. Similar results were obtained by dye tracer experiments in silty soils by e.g. Ehler (1975) and Trojan and Linden (1998). The greater connectivity of the macropore network at RT is corroborated by the greater number of visible macropores, especially at soil depths greater than 20 cm, and the greater density and areal coverage of hydraulically effective macropores at soil depths greater than 10 cm for the conservation tillage plot, as compared to the conventionally tilled plot.

Estimation of macroporosities with the two different methods, visual inventarization of stained and unstained pores and water infiltration under slightly negative hydraulic pressures, resulted in distinctly different values, even after accounting for the mean diameters of macropores in the different soil compartments. It is, however, not perfectly justified to use mean macropore diameters derived from one method (visual inventarization), then use these values for the other method (tension infiltrometry), and eventually compare the results of those two methods. More important, however, the macroporosities estimated by these two methods have per definitionem a different physical significance: Whereas the macroporosities obtained by tension infiltrometry are a measure for the „hydraulically effective“ macropore space, integrated over horizontal distances of 20 cm and vertical distances of approximately 10 cm, the macroporosities obtained by visual inventarization give the macropore space which is vertically continuous from the soil surface, in case of stained pores, and the total macropore space, irrespective of its hydraulic function, in case of unstained pores. One would expect, that the hydraulically effective macroporosity estimated by tension infiltrometry, is normally lower than the total macroporosity obtained by visual inventarization.

4 Conclusions

Both visual inventarization of stained and unstained macropores and tension infiltrometry, yielded macroporosities that are relatively higher for conventional tillage at soil depths of 0 – 10 cm, and higher for conservation tillage at soil depths of 20 cm and deeper. In combination with the greater depth penetration of dye tracer at the conservation tillage plot, this indicates a greater continuity of macropores in vertical direction for soils under a conservation tillage systems. Therefore, tillage practices with reduced soil disturbance could possibly offer an opportunity to reduce surface runoff and eventually flood generation in agriculturally used watersheds with silty soils. The effect of this local-scale soil hydrological property on the hydrological behavior on the scale of whole watersheds on the mesoscale (100 – 500 km^2), however, needs yet to be tested by simulations with physically based hydrological models.

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