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DIVISION S-6—SOIL AND WATER MANAGEMENT AND CONSERVATION

Characterizing Macropores that Affect Infiltration into Nontilled Soil

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ABSTRACT

A 0.5-ha watershed of Rayne silt loam on 9% slope at Coshocton, Ohio was farmed for 20 yr in continuous no-till corn (*Zea mays* L.). With average rainfall >1 m/yr, runoff from this mulch-covered surface averaged <2 mm/yr. Previous dye studies show that even at low rainfall rates, water moves rapidly through vertically continuous macropores (mainly earthworm burrows) in this field that hasn't been tilled since 1960. To characterize the distribution of these pores, we photographed cleaned, horizontal 30.5- by 30.5-cm^2 surfaces at depths of 2.5, 7.5, 15, and 30 cm. The images were scanned with an image analyzer to count and determine the size of open pores. With eight replications at each depth, total number of pores >0.4 mm in diameter per m^2 of surface area ranged from 3369 to 21 151 in the 2.5-cm depth and from 5673 to 28 966 at the 30-cm depth. The overall average was 14 576 pores per m^2, 160 of which were >5 mm in diameter. Mean pore diameter ranged from 1 to 2 mm at all depths and the number of pores was inversely proportional to pore diameter. There were more pores at the lower depth than near the surface. Pores >0.4 mm in diameter accounted for approximately 1.4% of the total area.

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CONSERVATION TILLAGE practices are often defined as those that leave at least 30% of the soil surface covered with residue after the tillage operation. No-tillage, as a form of conservation tillage, easily meets the 30% threshold, often leaving more than 75% of the surface covered. The conservation connotation of such practices derives from the observed reduction in runoff and erosion from fields farmed with conservation tillage practices.

The observed effectiveness of no-till for conserving soil and water varies tremendously as reported by Baker and Laflen, (1983). Although the mechanisms may not be fully understood, the runoff and erosion control may be ascribed directly to the mulch cover (Meyer et al., 1970; Onstad and Otterby, 1979). However, in recent years there have been many reports of increased worm activity in no-till fields with residue-covered surfaces (Lee, 1985; Mackay and Kladivko, 1985), and worm holes have often been reported to increase infiltration in the field.

Lee (1985) cites several reports of worm holes causing 2- to 10-fold increases in infiltration rates. Bouche (1971) was able to pour 100 L of water into a single worm hole that was part of a network of connected burrows. Ehlers (1975) measured a 6-fold increase in infiltration rate due to worm holes in a no-till loess soil as compared to a nearby plowed soil. In a greenhouse study, earthworms caused a 15-fold increase in steady state infiltration rates (Kladivko et al., 1986). In England, earthworm holes in a clay soil let water move through it as if it were a coarse sand (Childs et al., 1957).

Field observations led to models and theoretical descriptions of water flow in worm holes (Beven and Germann, 1982; Smettem, 1986). Ehlers (1975) measured infiltration rates into specific worm holes and Edwards et al. (1979) showed that the number of holes per unit area, their depths, and diameters influenced calculated infiltration rate. Smettem and Collis-George (1985) modeled saturated flow in a fine sandy loam topsoil and reported that one 3-mm diam. macropore per 30-cm diam. soil area contributed more to steady infiltration rate than did flow through the soil matrix.

At the USDA-ARS, North Appalachian Exp. Watershed, Coshocton, OH, we measured rainfall and runoff on small watersheds planted to corn that were conventionally tilled for several years and subsequently no-tilled. On these watersheds, runoff and erosion are both much less under no-till than under conventional tillage. Dye studies have shown that worm holes are involved in the infiltration processes in these watershed soils (Germann et al., 1984).

The purpose of this report is to present a procedure that was developed to quantify and describe characteristics of macropores in no-till soils which may be used to help determine their contribution to the measured high infiltration/low runoff rates. The technique is described and the distribution of macropores in the soil of a watershed cropped with continuous no-till corn for 20 yr is presented.

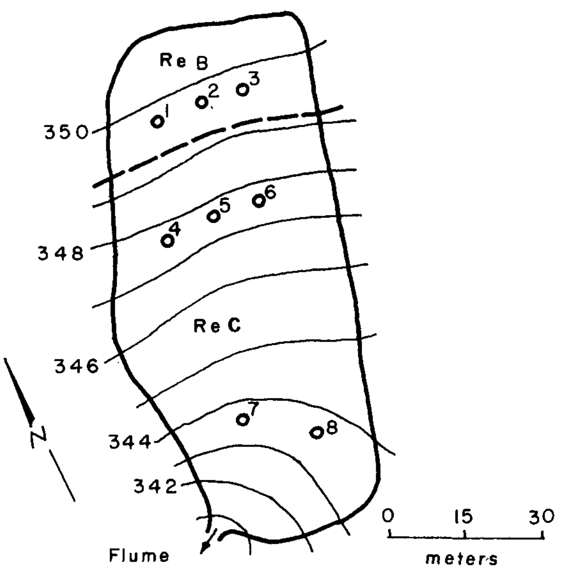

Fig. 1. Map of Watershed no. 191 showing sampling sites. Re = Rayne silt loam; B = 2 to 6% slopes; C = 6 to 12% slopes. Contour elevations in meters.

MATERIALS AND METHODS

Experimental Site

The field work was done in Watershed 191 at the USDA-ARS, North Appalachian Exp. Watershed, Coshocton, OH. The area is in the unglaciated uplands of the Allegheny Plateau where the soils developed under forest vegetation in well-drained residuum or colluvium.

Rainfall and runoff measurements at this 0.5-ha watershed began in 1939. Prior to 1964 conventional tillage was used in the production of corn, small grains, and grass-legume meadow in rotation. Since 1964, the crop has been continuous no-till corn, with all crop residue being left on the surface. In most years, strawy manure was added each winter.

Fertility has been maintained with broadcast applications of N–P–K at planting time, with corn yields normally ranging from 9 to 11 Mg/ha. Weed control has been by herbicides, mainly triazines, at rates of 3 to 5 kg/ha. In recent years, different insecticides have been used in the row at planting time.

Soil

The dominant soil in this watershed is Rayne silt loam (fine-loamy, mixed, mesic, Typic Hapludults). Slopes are 2 to 6% on the upper third of the watershed, and 6 to 12% on the lower two-thirds. The soil developed in colluvium and residuum from fine grained sandstone and shale. In the upper, gently sloping part of the watershed, the uppermost 25

Fig. 2. Camera support stand with side-mounted flash attachment and surface prepared for photographing.

to 50 cm of the soil is quite silty and may be a thin capping of loess.

The uppermost 5 to 8 cm of the A horizon is very dark grayish brown (10YR 3/2) silt loam. This is felt to be a darkening due to an accumulation of organic matter near the surface, since residue has not been incorporated during the 20 yr of no tillage (Dick, 1983). This darkened zone has weak, medium platy structure, parting to moderate, medium granular. The remainder of the old plow layer (Ap) to a depth of about 21 cm is brown (10YR 4/3) friable silt loam, with moderate, medium, subangular blocky structure. The Bt horizon is mostly yellowish brown (10YR 5/6) silt loam in the upper part and loam or channery loam in the lower part. Small chips of fine grained sandstone and shale, mostly >5 cm in diameter and >1 cm thick, comprise 5 to 10% of the A and Bt horizons and 15 to 25% of the BC horizon. Shattered, partially weathered sandstone and shale bedrock occurs at depths of 1 to 2 m.

Under conventional tillage, this soil has moderate permeability (1.5–5 cm/h), a moderate to deep rooting zone (>1 m), and a moderate available moisture capacity (15–23 cm). Additional physical and chemical characteristics are given by Kelley et al. (1975).

Macropore characterization

At eight locations in Watershed 191 (Fig. 1), the surface 2.5 cm of soil was carefully removed from a rectangular area of approximately 35 by 50 cm. Under relatively dry soil conditions, the surface was smoothed with a flat scraper and loose material was removed using a portable vacuum cleaner (Fig. 2).

A camera support frame (Fig. 2), constructed from light angle iron and thin plywood, was positioned on the prepared soil surface and a 35-mm color slide of the surface was taken. The camera lens fit snugly into a round hole in the top of the frame which positioned the camera consistently at the desired height and aimed it vertically downward at the center of the prepared surface. A flash attachment, mounted on an opening low on one side of the camera frame, illuminated the smoothed soil surface while leaving the macropores below the surface dark.

Table 1. Total rainfall, intense rainfall, and runoff for Watersheds 191 and 123, 1979–1985.

Year	Total precipitation	Intense rainfall†	Runoff Ws 191	Runoff Ws 123
	mm			
1979	1124	92	3.81	140.0
1980	1175	80	4.90	313.0
1981	1057	88	0.14	142.0
1982	889	137	0.00	113.0
1983	1027	174	0.00	--
1984	909	198	2.31	--
1985	929	139	0.01	--
Total	7110	908	11.17	708.0
Avg.	1016	130	1.60	177.0‡

† Rain falling at intensity >50 mm/h.
‡ Four-year avg. Not measured after 1982.

After the surface was photographed, the camera support frame was set aside and the rectangular hole was successively deepened to 7.5-, 15-, and 30-cm depths where cleaned surfaces were photographed as above. All photos (four depths at eight locations) were taken in October 1984.

The slides were scanned with a Leitz TAS-plus Image Analyzer[1] at 10× magnification. The holes appeared dark enough that they were discriminated from the soil matrix which was light in color and well illuminated by the flash attachment.

At the magnification used, 1 pixel had an effective diameter of 0.2 mm. Computer software eliminated from the evaluation pores <2 pixels in diameter, so 0.4 mm in diameter was the smallest pore size included in this characterization. The pores were grouped into 20 diameter classes over the 0- to 5.0-mm range (ie. 0–0.25, 0.25-0.50, . . . 4.75–5.00 mm). All pores >5.0 mm were lumped into a single additional class.

RESULTS AND DISCUSSION

Infiltration

Rainfall and runoff data for 1979 through 1985 for Watershed 191 are given in Table 1. No-till corn has

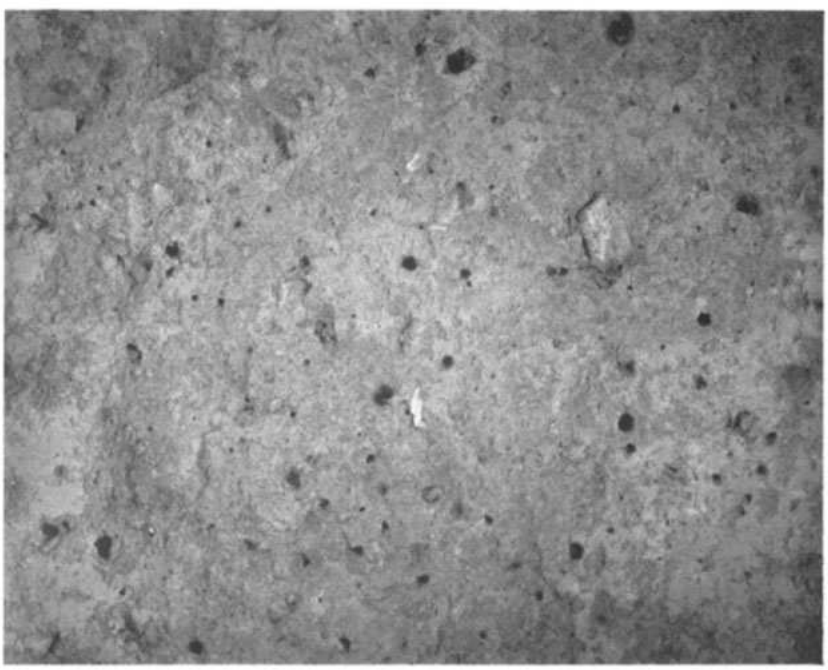

Fig. 3. Picture of surface at site 5, 30-cm depth.

Table 2. Number of pores 0.4 mm–5.0 mm in diameter per m².

Site	Depth (cm) 2.5	7.0	15.0	30.0	Avg.
1	21 151	18 632	18 729	16 760	18 818
2	9 225	8 170	12 605	26 533	14 133
3	15 199	15 134	16 447	20 699	16 867
4	3 369	1 959	2 530	5 673	3 380
5	3 477	1 270	4 090	9 731	4 639
6	16 814	19 429	27 879	28 966	23 272
7	10 753	21 428	22 195	16 555	17 685
8	9 698	15 317	21 065	25 177	17 814
Avg.	11 205	12 648	15 694	18 762	14 576

been produced in this watershed each year since 1964, but runoff was not measured from 1973 to 1979. Corn grain yield since 1979 has averaged 9600 kg/ha.

Although 13% of the precipitation from 1979 through 1985 fell at an intensity greater than 50 mm/h, only 11.17 mm (<1% of the total precipitation) left the watershed as surface runoff (Table 1). In comparison, runoff from a nearby Watershed (no. 123), where corn was produced with conventional tillage from 1979 through 1982, was >700 mm during that 4-yr period. The conventionally tilled watershed was plowed each April, had a silt loam Ap horizon with 35% clay in the Bt horizon, and had an average slope of 7%.

Macropores

Figure 3, taken at the 30-cm depth at site 5 (Fig. 1), is an example of the 32 photos used in characterizing size and number of macropores per unit area. The surface area represented in each photo is approximately 31 by 45 cm. To avoid possible pore-sizing errors due to distortion near the edges of the photo, frequency and diameter analyses were confined to a 30.5- by 30.5-cm square portion in the center of each photo. Numbers detected were multiplied by 10.764 to convert to the number of holes per square meter.

The size-frequency distribution of macropores, generated by the image analyzer from Fig. 3, is shown in Fig. 4. In this case, the total number of pores detected in the 0.4- to 5.0-mm size range was 9731/m² (Table 2, site 5, 30-cm depth). In addition, at that site and depth, there were 301 pores/m² >5.0 mm in diameter (Table 3). The pores >0.4 mm in diameter accounted for 1.8% of the surface area at the 30-cm depth at site 5 (Table 4).

The pore size distribution of Fig. 4 is typical of the entire data set. The arithmetic mean diameter of this

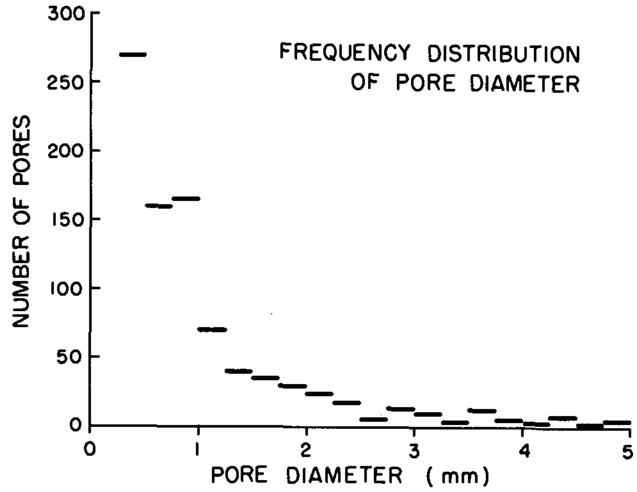

Fig. 4. Distribution of pores from site 5, 30-cm depth.

distribution is 1.588 mm with $s = 1.24$. Skewness was highly significant in each case.

Over 80% of the total number of pores counted were <1.0 mm in diameter. Since most earthworm holes are in the 1- to 10-mm diameter range (Lee, 1985), most of the pores detected by the image analyzer are not worm holes. Tippkoetter (1983) compared diameters, branching, and tapering of 0.1- to 1.0-mm diameter pores in Hapludalf subsoil horizons (1- to 2-m depths) with similar features of plant roots sampled at similar depths. He concluded that most pores <1-mm in diameter were made by plant roots.

By visual inspection, however, nearly all of the >5-mm diameter pores (Table 3) were made by surface-feeding worms (*Lumbricus terrestris*). Many of the other pores in the 1.0- to 5.0-mm diameter range also appear to have been made by worms. Many *Aporrectodea trapezoides, Lumbricus rubellus*, and immature *Lumbricus terrestris* were also identified in topsoil samples.

The number of 0.4- to 5.0-mm pores varied widely (Table 2). Using the F test (Snedecor, 1956) and considering the four depths at each site as replications, site-to-site differences were statistically significant ($P = 0.001$). The increase in number of pores as a function of depth was significant at the 90% probability level ($P = 0.10$).

The low number of pores, especially large pores, at sites 4 and 5 was noticed in the field at sampling time, but a reason for the decrease was not apparent. Sites 4, 5, and 6 were between the same two adjacent corn rows and adjacent sites were about 10 m apart. Un-

[1]Company and product name is used for information only, not as a guarantee or endorsement by USDA.

Table 3. Number of pores >5.0 mm in diameter per m².

Site	Depth (cm) 2.5	7.0	15.0	30.0	Avg.
1	258	258	172	129	205
2	355	108	151	301	228
3	97	215	151	140	151
4	118	54	65	194	108
5	22	75	86	301	121
6	118	140	215	205	170
7	151	108	172	86	129
8	43	151	194	280	167
Avg.	145	139	151	205	160

Table 4. Area of pores >0.4 mm in diameter (%).

Site	Depth (cm) 2.5	7.0	15.0	30.0	Avg.
1	3.8	2.0	2.7	1.1	2.40
2	2.4	0.7	1.5	2.3	1.72
3	1.2	2.0	2.1	1.3	1.65
4	0.8	0.4	0.5	1.4	0.78
5	0.4	0.4	1.0	1.8	0.90
6	1.4	1.3	1.9	1.8	1.60
7	0.8	1.1	1.6	1.1	1.15
8	0.4	1.2	1.3	1.7	1.15
Avg.	1.40	1.14	1.58	1.56	1.42

usually high pesticide concentration due to application overlap or other unknown mishap in earlier years may be suspected, but such could not be verified at sampling time. Although surface color and structure didn't indicate recent physical disturbance at sites 4 and 5, the increased number of >5.0-mm diameter pores below the plow sole at these sites indicates that a topsoil disturbance obliterated large worm channels in the upper three depths that at one time were continuous with those large pores found at the 30-cm depth (Table 3).

Using the same assumptions and statistical analyses with the data of Table 3, we found no significant site or depth effect on number of pores >5.0 mm in diameter. Nearly all of these pores are burrows of *Lumbricus terrestris* and are continuous, nearly vertical channels that do not branch or interconnect with other large macropores. At different times of the year, they may be more or less plugged at or near the soil surface by worms using the holes, by other biological activity in the topsoil, or by man's activity associated with crop production. With the lack of soil-disturbing tillage, some of these large channels remain open for years after the resident worm has died or been removed.

In this soil many of the large worm holes could be continuously traced from the surface to the sedimentary bedrock boundary which is approximately 1 m below the soil surface. Water containing dye that had been sprinkled on the surface at low, moderate, and high simulated rainfall rates, lined many of these channels after earlier macropore flow studies (Germann et al., 1984).

Average bulk density in the 5- to 15-cm depth in this soil is 1.6 Mg/m^3. Assuming a particle density of 2.65 Mg/m^3, total porosity is 40%, 5 to 10% less than that of nearby conventionally tilled topsoils (Edwards, 1982). If total porosity alone controlled infiltration, runoff from the no-till watershed should exceed that of the conventionally tilled watershed. However, runoff data (Table 1) indicate that this was not the case, even when the storms were heavy and of high intensity. The presence of dye in the worm holes in the subsoil and the lack of storm runoff from the dense, no-till watershed indicate that the large, continuous worm holes are important pathways for rapid infiltration during intense storms.

The extent to which water movement in these vertical continuous macropores is important during infiltration under natural storm conditions and the extent to which the macroporosity can be characterized will greatly influence our ability to model not only infiltration but the movement of chemicals into and through the soil. The method presented here may be widely applicable for characterizing macroporosity, especially as influenced by different reduced tillage management practices.

SUMMARY

The rainfall-runoff record on a long-term, continuous, no-till corn watershed shows sustained high infiltration rates. Dye studies with an artificial rainfall simulator show that under some conditions, macropores, and especially large worm holes, are important channels for the rapidly infiltrating water.

A technique was developed whereby 35-mm slides, taken in the field, could be automatically evaluated by image analysis to count and size macropores that may be involved in rapid infiltration. The technique is described and the distribution of macropores in the soil of this watershed is characterized. In the example presented, the frequency distribution of pores in the 0.4- to 5.0-mm diam. range and the number of pores >5.0 mm in diameter were determined, as were considerable variabilities from site-to-site and with depth.

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