by Gerald M. Aubertin

Nature and Extent of MACROPORES IN FOREST SOILS and their Influence on Subsurface Water Movement

U.S.D.A. FOREST SERVICE RESEARCH PAPER NE-192
1971

NORTHEASTERN FOREST EXPERIMENT STATION, UPPER DARBY, PA.
FOREST SERVICE, U. S. DEPARTMENT OF AGRICULTURE
WARREN T. DOOLITTLE, DIRECTOR

The Author

GERALD M. AUBERTIN, research soil scientist at the Timber and Watershed Laboratory, Parsons, West Virginia, joined the Northeastern Forest Experiment Station's subsurface stormflow project, located in Ohio, in 1965. There he devoted his attention to the pathways water takes in moving through the soil. Upon termination of the project he transferred to his present position, in which he deals with the water quality of forested watersheds. He received his bachelor's and master's degrees in agronomy from the University of Illinois in 1958 and 1960, respectively. In 1964 he received his doctoral degree in agronomy from The Pennsylvania State University, after which he spent a year in post-doctorate study of soil physics at the Riverside campus of the University of California.

MANUSCRIPT RECEIVED FOR PUBLICATION 24 DECEMBER 1969

Nature and Extent of MACROPORES IN FOREST SOILS and their Influence on Subsurface Water Movement

CONTENTS

Macropores

RAIN, falling on a sloping forested soil, may enter the soil quickly and move considerable distances through the soil by way of macropores. A macropore is a large pore, cavity, passageway, channel, tunnel, or void in the soil, through which water usually drains by gravity.

Large quantities of water can move through the soil by way of these macropores—without appreciably wetting the soil mass. This phenomenon complicates the study and management of forested watersheds.

A series of studies was undertaken to provide information about the nature, extent, and influence of macropores, as an aid to future studies and management of forest soils. This is a report on those studies.

Background

Macropores occur extensively in forest soils. They serve as drainageways through otherwise impervious soils; they improve subsoil aeration; and they often serve as favorable sites for root growth.

In terms of macropores, most forest soils are extremely heterogeneous, in both vertical and horizontal directions; and the macropores frequently are concentrated in certain horizons and in particular areas of the forest.

Most macropores develop from old root channels or from burrows and tunnels made by insects, worms, or other animals. Some result from structural pores and cracks in the soil. Our studies dealt mainly with macropores resulting from biotic activity.

ROOT CHANNELS

Root channels are formed in place by decomposition of roots. The channels are first filled or partially filled with porous organic material derived from the roots themselves. Depending on their location with respect to the forest floor surface, additional organic residues from the litter horizons may be added to the channels.

As soil material moves into the channels, the mixture comes to resemble the A1 horizon. Eventually, as the organic matter is oxidized, the contained materials take on the appearance of an A2 horizon. During normal processes of soil development, clay particles become dispersed and move into the channels and are deposited as clay skins on the sides of the channels. This layered material is different in color, depending on its source in the profile, its age, the time of filling, and the conditions of aging.

The physical entrance and expansion of a root in the soil compresses the soil adjacent to it and locally changes the soil's porosity and bulk density. As a result, the percent of pore space near the root channel-soil boundary is lower than that a distance from the root's former influences *(Blevins 1967)*. This is accompanied by a shift of pore-size distribution toward the smaller capillary-size pores. In addition, a higher percentage of clay and mineral grains oriented tangent to the roots' surface is to be found adjacent to the root-soil interface than in the soil mass. These factors, along with the residues remaining from organic decomposition, promote a relatively stable conduit for the rapid conductance of free water, air movement, and new root growth.

Different tree species have different types of root systems. Thus, as the roots decay, they leave different types of root channels. Macropores resulting from the decay of plant roots are usually tubular and dendritic, and they range widely in diameter *(Johnson et. al. 1960)*. The roots of some plants leave a thick, tough, resistant bark lining around the root channels. Others tend to leave scale-like bark, which readily breaks apart. As far as I know, no one has yet undertaken a comprehensive study of the nature of root bark and its persistence in the soil.

The root channels within the forest floor form a network of relatively large, continuous, interconnected, open or partially filled channels that serve as pathways for the rapid movement of free water into and through the forest soil profiles. Due to variation in the vertical extent of the channels, after precipitation the lower boundary of the wetted zone is often extremely irregular. Water may thus move downward to the water table through these channels or move laterally through the soil mass, which, in part, remains unwetted *(Lutz and Chandler 1946)*. In fine-textured soils, the root channels from deep-rooted tree species favor vertical drainage while those from species having long lateral roots favor lateral subsurface water movement.

Soil texture seems to affect the persistence of old root channels. In coarse-textured soils, persistent channels are not normally common. In fine-textured soils, old root channels are abundant and persist for a long time. In coarse-textured soils, "sand pipes" — thought to be the remains of old root channels, now filled with coarse whitish sand — can often be observed. These "sand pipes" have been observed to conduct a substantial amount of water.

Root channels can be numerous. For example, in a hardwood site in southeastern Ohio, over 4,000 vertical root channels were found per acre *(Gaiser 1952)*. Although most were partially filled, they were relatively permeable and served as a network of interconnected channels to freely move water through the forest soil profile. Where shortleaf pine has been cut in the Southeast and the roots have had time to decay, open or partially filled root channels, several inches in diameter and 4 or more feet deep, are found *(Kittredge 1948)*.

ANIMAL PASSAGEWAYS

Insects, worms, and burrowing animals also form macropores in forest floors. Their burrowing activities promote good structure, good aeration, and good penetration of water. In addition, their tunnels often provide avenues for the growth and development of plant roots into and through tight layers of soil.

Earthworms *(Lumbricidae)* are the most conspicuous group of animals in most forested soils. Their activity is usually greatest in the A horizons, where they are largely responsible for the soil's porous nature. In all profiles of a forested Bellefontaine silt loam soil in Wisconsin, regardless of the resistant nature of the B horizons, earthworms and their burrows were found in the C horizons at depths of 3 to 3½ feet *(Scully 1942)*. The burrows were fairly perpendicular, deviating where rocks blocked the path. Nielsen and Hole *(1964)* found earthworm burrows having an average diameter of 5/16 inch were spaced at about 6-inch intervals and extended nearly vertically to a depth of 3 to 6 feet. They said that earthworms are responsible for making tubular extensions of the A1 down into the A2 horizon, which increases the interface of these two horizons and augments the permeability of soil to water and tree roots.

Cicada *(Magicicada septendecim)* burrows are also abundant in soil. On 30-meter quadrats sampled at random, Scully *(1942)* found an average of 14 cicada mounds per square meter, with open burrows extending almost perpendicular to varying depths.

Small burrowing animals are abundant in most forests and have a pronounced influence on soil conditions. Ground squirrels, moles, mice, and shrews often produce a labyrinth of interconnecting tunnels that allow ready penetration of air and water and facilitate their distribution within the soil body *(Lutz and Chandler 1946)*. Hamilton *(1940)* indicated that the looseness of the surface layers in many forests in the Northeastern States is due in part to the scores of burrows made by mice and shrews. The magnitude of animal burrows can be very great: Eadie *(1939)* found 220 surface tunnels of the hairy-tailed mole *(Parascalops breweri)* exposed along a newly cut road bank within a distance of 492 feet, making an average of one tunnel every 2.2 feet. These surface tunnels formed an irregular branching network, with main surface tunnels often extending beside or under some surface structure for 100 yards or more.

NONBIOTIC MACROPORES

Other agents, such as freezing and thawing, are also responsible for the formation of macropores in forest soils. Freezing the soil increases its porosity because the growth of ice crystals causes displacement and bulking of the soil *(Krumbach and*

White 1964). These pores may persist under undisturbed forest floor conditions and be preserved by the covering of litter *(Auten 1933)*.

Cavities formed by leaching and dissolution of pebbles of limestone or dolomite have been found to form as much as 10 percent of the B22 horizon of Howard gravelly loam in Bradford County, Pennsylvania *(Denny and Lyford 1963)*.

The Study

SITE

The study site was 1.2 miles north of Dover Dam in Tuscarawas County, Ohio, on land made available through cooperation of the Muskingum Watershed Conservancy District. A moderately steep south-southwest slope, covered by a mixed deciduous hardwood forest, was selected for study. Dominant trees were primarily white oak, beech, and hickory; diameters averaged about 18 to 24 inches. Six study locations were used. The soil type at the upper location, approximately 150 feet from the ridge, was a Dekalb sandy loam; the soil types at the five lower locations — on a line parallel to the slope — were characterized as variants of Clymer silt loam. The lowermost location was near midslope, approximately 500 feet from the ridge. The slope ranged from about 20 percent near midslope to about 25 percent at the upper location.

METHODS

Outflow Pits

Observation pits, approximately 4 feet deep and extending approximately 10 feet across the slope, were dug at the uppermost and lowermost locations. The sandy loam here was underlain by a layer of moderate to coarse sand at about 40 to 45 inches. The silt loam graded at about 36 inches into a silty clay, which graded into a clay at about 44 inches.

Artificial rain, containing fluoresceine dye, was applied to the undisturbed surface of the forest floor immediately upslope from the pit faces at the rate of 1 inch per hour. An area 16 feet in diameter was wetted above each pit. Time and location of outflow from each pit face were recorded. Volume of outflow was measured from a selected number of outflow spots.

Hydraulic Conductivity

For evaluating hydraulic conductivity, a specially designed core sampler *(Aubertin 1969)* was used to obtain a large number of relatively undisturbed soil samples 6-inches in diameter and 3, 6, 9, 12, 15, and 18 inches deep. These samples included small stones, roots, old root channels, animal passageways, and other macropores in their natural state.

A sufficiently large number of samples was collected so that at each of the six locations at least 20 relatively undisturbed samples were obtained for the 0-6-, 6-12-, and 12-18-inch depths, and at least 10 similar qualitative samples were obtained for the 0-3-, 3-6-, 6-9-, 9-12-, 12-15-, 15-18-, 0-12-, and 0-18-inch depths.

The samples were placed in water and allowed to soak for about 24 hours before establishment of a constant head of about 15mm. via the overflow method *(Klute 1965)*. As soon as the constant head was established, outflow measurements were begun and were recorded every 2 to 5 minutes throughout a total lapsed time of 100 minutes. Hydraulic-conductivity values were calculated, then plotted against lapsed time on semilogarithmic paper.

Upon completion of the outflow measurements, but without allowing air to enter the sample, a 0.1-percent malachite green dye solution was passed through the sample. The amount of dye solution used per sample varied according to the rate of flow. This dye solution stained the major flow channels, making them readily visible when the samples were dissected. In addition, dye staining along the sample-cylinder wall interface revealed if and where flow occurred between the sample and the cylinder wall.

The samples were allowed to drain approximately 24 to 48 hours, then were dissected. Data from samples exhibiting evidence of sample-wall flow were not included in the analyses. As dissection proceeded, qualitative and semiquantitative remarks were noted on flow passageways, old root channels, animal passageways, macropores, and evidence of soil disturbance such as filled root channels or animal passageways, in an attempt to correlate their presence with the hydraulic-conductivity value obtained for each given core.

Block Study

To further evaluate the nature of the macropores *in situ,* a large free-standing block of soil, 8 feet wide by 20 feet long by 6 feet deep, was exposed by trenching around the four sides with a backhoe. This block corresponded to the lower part of the active portion of a previous subsurface stormflow plot *(Whipkey 1965)*. The downslope face (front) of the block was coincident with the outflow face of the former plot.

After the block had been trimmed and shaped by hand, all four sides were gridded into 6-x-6-inch squares, characterized, and sampled; and the soil horizons were mapped. All major features such as roots, stones, old open root channels, old filled root channels, filled and unfilled animal burrows, evidence of taproots, worm and other macro-organism passageways, and structural cracks were mapped to scale for the front, back, and one side. Unfortunately, because of wet weather, a portion of one side sloughed down before its features could be mapped.

After the external features had been mapped, the front or downslope and the back or upslope portions of the block were systematically dissected by carefully removing 6-inch cubes of soil one at a time. All major internal features, such as listed above for the external faces, were carefully traced and mapped on three-dimensional drawings.

A powerful industrial vacuum cleaner with a hurricane nozzle was used for cleaning up the loose material from the faces and for removing the loosened soil from the cube being dissected. The soil was loosened most efficiently with the point of a stiff knife blade, then was removed with the vacuum nozzle. A curved linoleum knife was found to work very well in loosening the soil with a minimum of disturbance to the roots and root channels. With careful work, very few roots were cut or removed, and it was possible to easily trace the roots from one point to another. Root channels were also easy to trace by using this method of soil removal, but because of their fragile nature many of them were obliterated as the soil was removed. Consequently all root channels and other open channels had to be continually mapped as the cube was dissected.

Results and Discussion

OUTFLOW PITS

A comparison of the faces of the observation pits showed marked differences in the presence of biotic macropores. Outflows from the pit faces also differed markedly in timing, rate, and distribution.

Qualitative observations showed a substantially greater number of old root channels in the finer textured soils. In these soils the root channels were distinct, well-preserved, generally open or only partially filled, and were ramified throughout the upper portion of the soil profile, with many extending below the 4-foot depth of the pit. Evidence of old taproots was clearly visible. Many old root channels were lined with persistent root bark. The mineral soil immediately surrounding the channel in the lower B horizons frequently had a pronounced gray color, indicating a gleyed condition.

These old root channels formed a network of pipes through the soil profile. Though we did not specifically study the areas immediately surrounding the root channels, evidence indicates that the dense zone of high clay content, and oriented particles reinforced by residues from decomposition of organic matter, were practically impervious to penetration by water.

Artificial wetting of the forest floor immediately upslope from the pit face revealed to a limited extent the influence root channels have on rapid subsurface movement of water in medium to moderately fine textured forested soil. In all cases numerous outflow sites were present in the pit face, many flowing pipe-like or faucet-like. However, there was little, if any, evidence that the soil mass proper was wetting up.

In a typical instance, applying artificial rain at the rate of 1 inch per hour to the finer textured soil (having approximately

20 percent initial moisture by weight) resulted in dye seepage coming up from the heavy, mottled clay pit floor, 18 linear feet from the center of the wetted area and 48 inches below the soil surface, within 15 minutes after starting to wet the area. Within 18 minutes after the start of the rainfall 3 additional small root channels located in the clay zone at a depth of 44 to 48 inches began seeping. In general, a depth/time-of-wetting relationship appeared to exist, and the deeper positions seeped first.

Sixteen positions (12 definitely old root channels, 1 from around a stone, 1 from an unidentified type of channel filled with dark spongy material, and 2 of undetermined nature) were seeping from the pit face within 1 hour. Seepage rates were generally moderate to rapid; four old root channels flowed pipe- or faucet-like. After continued application of artificial rain, 26 positions were seeping at the end of 2 hours. The soil mass proper did not appear to be wetting up, although at the end of 2 hours some evidence was noted that the soil surrounding some of the channels was becoming wet.

In another instance, from an approximately 1/4-inch-diameter old root channel, partially lined with bark, at a depth of 23 inches, outflow began approximately 9 minutes after wetting of the surface was begun. This particular root channel yielded an outflow volume of 1,127 ml./min., measured between the 10th and 11th minutes after start of the rainfall. In all cases at least one and usually several old root channels flowed pipe- or faucet-like from the finer textured silt loam soil.

At one location in the silt loam soil, in addition to outflow from the immediate pit face under observation, flow was observed coming from channels in another pit about 30 feet obliquely downslope from the wetted area, commencing between 30 and 45 minutes after starting to wet the forest floor above the observation pit. Outflow volume, although not measured, was substantial. This points up the fact that a substantial amount of water may rapidly enter into and move a considerable distance downslope through old root channels.

The data and observations bring up an interesting question: How does the water enter into and move through the soil so rapidly and in the quantities observed? First, the rapid movement through the soil has been demonstrated to occur through old root channels. The question of rapid entry and concentration of the rainfall has not been completely answered.

Qualitative observations have shown that the surface of undisturbed forest soils is highly porous and sponge-like. Additional observations revealed that the surface of the mineral soil is not smooth but has considerable microrelief variation. In addition, there are numerous depressions, filled with porous spongy material, which are the remains of old taproots.

Thus it appears probable that rainfall rapidly penetrates the highly porous forest floor surface, moves along the mineral surface interface, and collects in the depressions formed by decayed taproots. The water is then funnelled downward and combines with that coming from similar nearby sites through the interconnected network of channels. This subsurface water is then transmitted via paths of least resistance to the channel opening in the pit face. This may explain why overland flow seldom, if ever, occurs on sloping forest-covered soils.

This question can be raised: Does digging a pit that intersects the root channels create an artificial system? In many if not most forested areas the soil mass is honeycombed with a complex network of intricately interconnected old root channels, animal passageways, and other microvoids. Strong arguments can be advanced to support the contention that, under these conditions, the complex network is always open to the atmosphere at numerous points and that truly dead-end isolated channels, or macrovoids, are rare and of little consequence.

Studies on the sandy loam produced similar but less pronounced results. First, the number of old root channels was considerably smaller than in the finer textured soils. Second, those present did not appear to be as distinct and as well preserved. Most channels were filled or partially filled with dark sandy material. Root-bark linings were present but fewer and usually more discontinuous than those found in the finer textured soils. Although this was not studied, qualitative observations indicated a general lack of particle orientation or clay concentration near the root channels.

In the coarser textured soils, seepage was not restricted to old root channels. At approximately 40 to 44 inches in depth, the sandy layer overlying a heavier sandy clay zone wet up rather uniformly and began to seep within 35 to 45 minutes after wetting of the soil was begun. The most noticeable difference between the coarse and fine textured soils was that, in the coarse textured soil, the soil itself appeared to wet up and the initial time of outflow from the root channels did not appear to be related to the depth of the channel. Also, the volume of outflow from individual root channels was usually considerably less in the coarser textured soil than in the finer. Apparently the less-well-preserved old root channels and relatively large textural macro-voids allow the rainfall to readily enter and permeate the soil mass as a whole instead of being restricted to subsurface channels.

HYDRAULIC CONDUCTIVITY

Determining the true hydraulic conductivity of sloping forested soils is beset with a multitude of obstacles. Because of the high porosity of the surface layers, the abundance of roots, macropores, and channery fragments, hydraulic conductivity cannot be determined by means such as Bouwer's double-tube method *(1961, 1962)*. For the same reasons, attempts to obtain satisfactory and relatively undisturbed soil samples with the 3-inch Uhland sampler proved futile. Those 3-inch samples that could be obtained would not adequately represent the configuration of the old root channels, animal passageways, and other macropores found within the soil.

Consequently, a specially constructed core sampler *(Aubertin 1969)* was used to obtain a large number of 6-inch relatively undisturbed soil samples that included small stones, roots, old root channels, animal passageways, and other macropores. Though the results obtained from these samples are better than those from small samples, they still do not provide all the information needed.

However, there seems to be a close correlation between the presence of old root channels and overall conductivity, The data strongly suggest that with our forested soils, the overall conductivity is made up of two parts. The first is the hydraulic conductivity through the soil matrix itself. The second is essentially the inner-mass flow through old root channels, cracks, and macroorganism pathways. In our studies, the matrix conductivity was often found to be completely masked by inner-mass flow, which may be several hundred times more rapid.

Through-flow was found to be extremely variable in rate and magnitude for both supposedly replicated and unrelated samples. This variability was shown, by sample dissection, to be due mainly to the presence or absence of continuous old root channels and/or animal passageways that intersected both the top and bottom surfaces of the sample. A 50-fold difference between the initial through-flow rate for the slower and faster flowing samples was not at all uncommon.

Sample dissections revealed that vertical channels or passageways were absent in those samples having a low through-flow rate while those samples having high through-flow rates always had continuous vertical channels or passageways that intersected both the top and bottom surfaces of the sample. Samples exhibiting intermediate through-flow rates were found to contain varying numbers of, and usually smaller, continuous and/or discontinuous vertical channels or passageways. Our data indicated decisively that even one continuous but small old root channel that intersected both the top and bottom of the sample transmitted a tremendous volume of flow compared to that conducted through the sample matrix.

Channels or passageways that were cut by the top surface, but not by the bottom surface of the sample, normally had their upper portion dye-stained, indicating some flow, but lacked staining throughout the majority of their length. Channels or passageways that were cut by either the bottom and a side, or by the sides only, rarely showed signs of staining. Branched channels or passageways normally had staining only on those branches that were connected directly to both the top and bottom sample surfaces. Dead-end macropores, such as cicada tunnels and cavities, seldom exhibited signs of staining.

Sample dissection also revealed that flow occurred down and around live roots. The root-soil interfaces of all roots cut by both the top and bottom of the sample were normally stained continuously throughout the full length of the root. Staining, although always continuous, not infrequently occurred on only a portion of the root-soil interface circumference. For example, it was common for a given root to have portions of the entire root-soil interface stained and interspersed with portions that had only a relatively small segment of the root-soil interface circumference stained.

Our observations suggested, inconclusively, that there was a tendency for the partially stained portions to be spiraled around the root. This phenomenon, if found to be an actuality, will shed considerable light on root growth and root-soil void relations.

Roots cut by the top surface of the sample, but not by the bottom surface, normally had a portion of the root-soil interface, occurring near the top surface of the sample, stained for varying distances into the sample. Roots cut by either the bottom and a side or by the sides of the cylinder rarely showed signs of staining. These observations indicate that a void or space often exists between the root and the surrounding soil.

The through-flow differences found in replicated samples from a given site, brought about by the presence or absence of channels, logically raise the question as to the value of finitely bounded, relatively small diameter samples. Without question the flow through bounded samples is affected by boundary conditions. However, this through-flow difference is in itself a relevant factor that illustrates the nature and variability of macropores in forest soils.

Because of the complex interconnected network of old root channels and other macropores, many of which may rapidly conduct free water in a pipe-like manner, it is probable that the conductivity values determined on finitely bounded cores having open channels is not representative of that occurring *in situ.* In fact, such cores may actually underestimate the real conductivity rate, because only a limited number of open channels can flow in a finitely bounded sample. Those channels passing through the sample at an angle and not cut by the top and bottom surfaces do not directly contribute to the overall flow in bounded cores, but would do so *in situ*.

The data from our 6-inch diameter samples reveal a number of trends. Only three locations will be discussed: a silty clay loam over clay (site A), a sandy loam (site B), and a silt loam (site C) that contained an exceptionally large number of old root channels. General comments apply to all locations.

The plotted curves of calculated hydraulic conductivity versus time (figs. 1 and 2), show two trends. First is the difference between depths at a given location and between locations for the same depth. Second is the marked decrease in conductivity with time. This decrease is most marked in those samples having initially high through-flow rates. The rate at which the decrease occurred was much greater for samples from the upper portion of the soil profile, which had a high overall conductivity, and

Figure 1.—Average conductivity curves for undisturbed 3-inch-thick soil samples 6 inches in diameter taken from the depths indicated at site A (a silty clay loam over clay) and site B (a sandy loam).

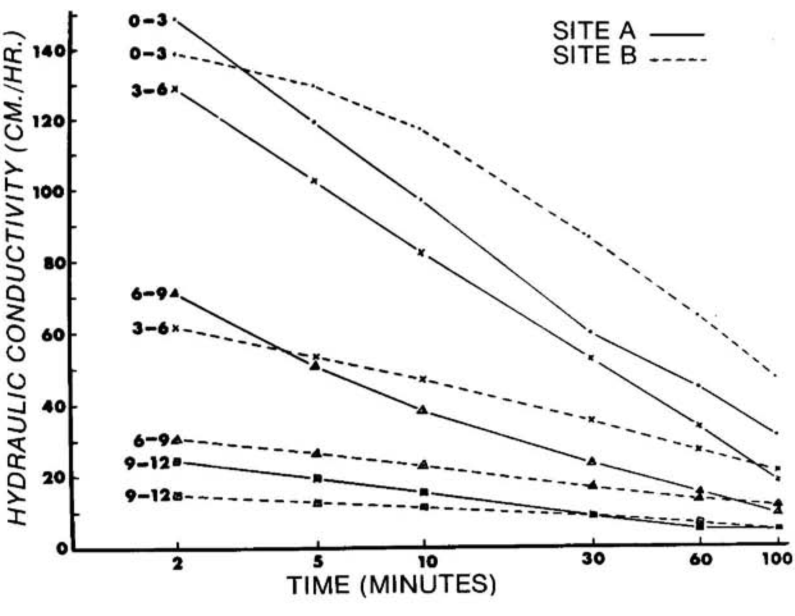
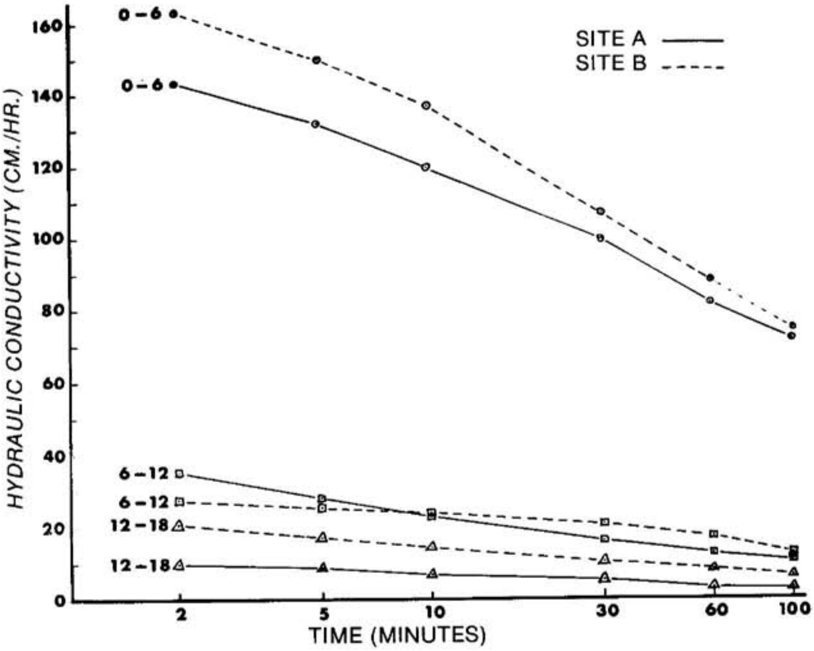


Figure 2.—Average conductivity curves for undisturbed 6-inch-thick soil samples 6 inches in diameter taken from the depths indicated at site A (a silty clay loam over clay) and site B (a sandy loam).



least for the deeper zones whose overall conductivity was relatively small.

The large decrease of conductivity with time raises several questions. What causes the rapid decrease? What time period or value should be considered as being indicative of the true conductivity? Since dissection of the samples revealed that the rapid through-flow occurred through old root channels and other macropores, can one validly calculate hydraulic conductivity values from the outflow data? It would seem logical to assume that, under the condition of rapid flow through irregular and crooked channels, turbulent flow occurred. Thus the calculated conductivity values obtained by application of Darcy's law are invalid *(Scheidegger 1957)*. However, the calculated values do have relative meaning in comparing the different sites and depths.

The cause of the rapid reduction in calculated conductivity, which ran as high as an 85-percent reduction within 100 minutes for samples from the 3- to 6-inch depth of site A, is unknown. Numerous researchers have noted reduction in the conductivity of core samples, but usually occurring over a longer period of time. In our case, we feel that, because the samples were soaked for about 24 hours, and because of the initially rapid throughflow through old channels and the relatively short flow time (100 minutes), it seems that the probable but no doubt not the only cause of the reduction noted was particle movement. However, it must be kept in mind that dissection indicated no evidence of particle movement or relocation, although evidence of particle movement was not specifically investigated.

In general, the initial hydraulic conductivity was greater for comparable depths from the silty clay loam than for the sandy loam; and the rate of decrease as well as the total percent of decrease in conductivity was greater for the samples from the finer textured soil (figs. 1 and 2).

Since a direct relationship appeared to exist between the presence of old root channels and the calculated conductivity, a site (site C) known to have an abundance of old root channels and a texture relatively similar to that of site A was sampled and the conductivity values were obtained.

The calculated conductivity values for the 0-to-3-, 3-to-6-, and 0-to-6-inch samples were high (fig. 3). These samples had a greater overall decrease in conductivity, accompanied by a greater rate of decrease, than comparable samples from site A. However, the percentage reduction was greater for the samples taken from site A.

Dissection revealed that the samples from the upper soil levels of site C were permeated with old channels. Although samples from the deeper zones of site C had more old root channels, those channels present in the comparable samples from site A tended to be more vertical and had approximately the same frequency of intersections both at the top and bottom of the sample.

On all sites the conductivity consistently decreased, usually significantly (despite the large variation between replicated samples), with the depth of sampling. The calculated conduc-

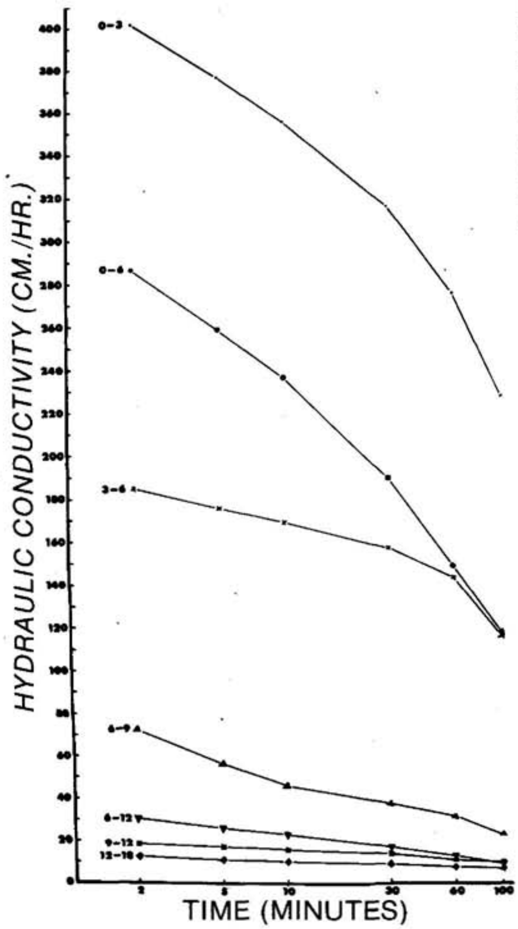


Figure 3.—Average conductivity curves for undisturbed 3- and 6-inch-thick soil samples 6 inches in diameter taken from the depths indicated at site C (a silt loam containing a large number of old root channels).

tivity at a given depth could be related directly to the soil texture and more specifically to the presence of macropores.

Qualitative and semiquantitative observations of the dissected samples revealed that the 0-to-3-inch zone was, in all cases, very porous and had a large mass of small roots. Although numerous partially decayed roots were to be found, few old open root channels were present. However, animal passageways were numerous. In general, this zone exhibited an open and highly porous network of interconnected macropores.

Between the 3- and 9-inch depths, the size and number of structural macropores decreased. In addition, evidence of animal activity became less noticeable. The number of larger roots increased while the number of smaller roots decreased substantially.

Old open root channels, generally angling downward at about a 30° angle and frequently bark-lined, increased in size and number and became largest and most numerous within the 6- to 12-inch zone. Large structural pores were seldom observed between 9 and 18 inches, while evidence of animal activity and passageways was infrequently observed and generally was localized. The number and diameter of old open root channels decreased with depth below 12 inches.

The data indicated that the presence of open channels has an overshadowing effect on the soil matrix conductivity. For example, the sandy loam had substantially fewer root channels in the 3- to 12-inch zone than did the silty clay loam. However, the conductivity of the 3- to 12-inch zone was greater for the silty clay loam than for the sandy loam.

In addition, values for replicated samples from site A varied greatly while those from site B were much more consistent. Those individual samples from site A, not having open channels, exhibited a much lower conductivity, usually in the slow to very slow category (less than 0.125 cm./hr.), than did corresponding samples (also without open channels) from site B whose rates were generally in the moderate to moderately rapid category (2.0 to 12.5 cm./hr.).

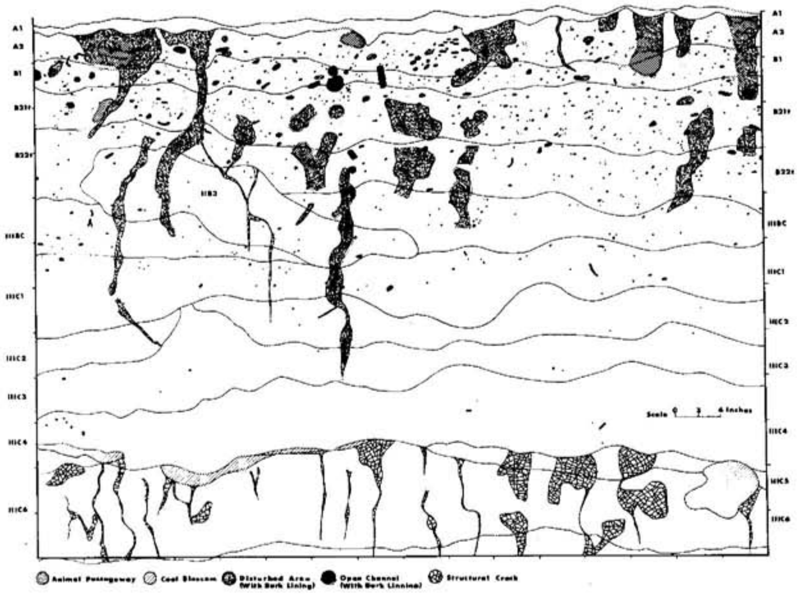
Thus, in considering the soil's conductivity in forested soils where old open channels abound, one must direct attention to the number, size, and orientation of open channels in addition to the soil texture.

BLOCK STUDY

To obtain semi-quantitative information about the number, volume, and interconnection of old root channels, animal passageways, disturbed areas, structural cracks, and roots — and how they vary with depth and/or horizons — a large free-standing block of soil, 8 feet by 20 feet, was studied.

The data representing the soil horizons were drawn to scale (figs. 4 and 5) and were assembled into a "box" model of the

Figure 4.—A scale model representation of the soil horizons, animal passageways, "disturbed" areas, open channels, and structural cracks observed on the *front* face of the root-study block.

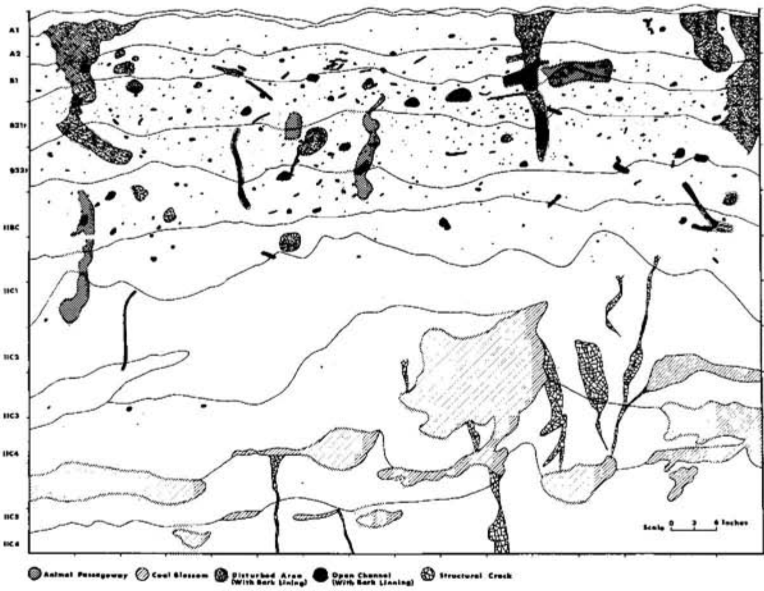


block. The results were revealing, especially the extent of variation in the different horizons. Although the A and B horizons varied somewhat in thickness from point to point, they paralleled the surface slope closely. However, the different C horizons were variable in thickness; and it was not uncommon for those horizons to thin out and disappear, only to reappear further along the face or on a different face.

The characterization data obtained from the free-standing block of soil, though not directly relevant to macropores, showed beyond question the variability of the soil profile. At this particular site the choice of a different location only a few feet along the block face often, sometimes drastically, changed the profile description. (See appendix for profile description of front and back faces.)

Mechanical analysis indicated that the top 9 to 10 inches, composing the A1, A2, and B1 horizons, was a silt loam for all four sides. Below 10 inches, although the actual percentages of

Figure 5.—A scale model representation of the soil horizons, animal passageways, "disturbed" areas, open channels, and structural cracks observed on the *back* face of the root-study block.



sand, silt, and clay (approximately 20, 40, and 40 percent, respectively) were similar, due to their borderline position, the textural class for a given horizon often varied all the way from a silty clay loam through a clay loam through a silty clay to a clay.

The horizons and macropore features found on the front and back faces of the block are shown in figures 4 and 5. The latter face was situated 20 feet upslope from the front of the block. The data shown in these figures are typical of those obtained from the side face and from the different dissected transects of the front and back portions of the block.

Examination of the faces represented in these figures revealed large areas that were unlike the surrounding soil matrix. These "disturbed" areas exhibited evidence of having once been old root channels or animal passageways that are now filled with a dark, highly porous, spongy material. Many of these filled root channels could be identified as taproot or semi-taproot sites and still had portions of root bark lining the channel.

Evidence of animal activity was extensive. Numerous open animal passageways were found in the upper horizons, generally in localized areas of the soil, usually within the upper 2 feet. Passageways often seemed to be concentrated near "disturbed" areas or stones and to follow large roots.

The number, sizes, and distribution of the open root channels were surprising. The majority of these open root channels were found to have a persistent bark lining throughout the major portion of their length. This lining was frequently persistent and often remained as a hollow tube after the surrounding soil had been removed.

Relatively few open root channels were found in the upper 6 inches of the profile (fig. 5). However, this area was thickly permeated with small, apparently live, roots. Its structure was open and porous, especially in the A1 horizon. The small number of persistent root channels in this area may be a result of more rapid biological decomposition or may be due to the fact that woody roots were not originally abundant in this zone. The presence of the large number of relatively large open root channels in the 9- to 24-inch zones and the lack of large roots in that area, along with the concentration of roots — mostly relatively small — in the upper 9 inches of the profile, suggests the possibility that larger and older trees or a tree species different from that now growing on the site formed the old root channels.

Although numerous roots and some root channels were found at 6 feet, most roots and root channels were found in the upper 2 to $2\frac{1}{2}$ feet. In the lower depths of the C horizon most of the roots and root channels were restricted to structural cracks while in the A and B horizons or the upper $2\frac{1}{2}$ feet, the roots and root channels freely permeated the soil mass.

A very common feature, especially in the denser horizons, was the presence of live roots growing within old root channels. It was not at all uncommon to find a live root growing in an old root channel which in turn had been formed in a yet older root channel.

Tables 1 and 2 show the percentages of total surface area of each horizon that was occupied by biotic macropores. "Disturbed" areas, those portions of the profile that were dissimilar in color, texture, and structure, are included, because of their highly porous nature and the evidence that they were the remains of old roots and animal passageways. In addition, dye studies showed that these "disturbed" areas often act like open channels that conduct water rapidly.

The effect of pH and bulk density on the persistence of biotic macropores is open to question. Because of the small variation in pH values between horizons, it seems likely that the soil pH did not determine the presence or absence of biotic macropores in a given horizon. Bulk-density values consistently increased with horizon depth while the number and the area percentage occupied by biotic macropores decreased. The data seem to indicate that the size and concentration of biotic macropores may be more a function of depth than of overall bulk density. In the denser C

Table 1.—*Surface-area percentages of biotic macropores exposed in the front face, as related to horizon, depth, pH, and bulk density*

Horizon	Depth	Total biotic macro-pores	"Dis-turbed" area[1]	Open root channels	Open animal passage-ways	pH	Bulk density
	Inches	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*G/cc.*
A1	0-1	—	—	—	—	5.0	0.94
A2	1-6	36.0	28.9	2.8	4.3	4.5	1.26
B1	6-9	11.4	5.8	3.8	1.8	4.5	1.49
B21t	9-16	16.6	13.3	2.8	.5	4.6	1.61
B22t	16-23	14.4	12.6	1.8	0	4.6	1.59
IIB3	23-31	10.8	9.8	1.0	0	4.6	1.34
IIIBC	31-36	5.8	4.8	1.0	0	4.7	1.63
IIIC1	36-42	2.1	1.6	.5	0	4.6	1.72
IIIC2	42-47	2.3	2.1	.2	0	4.6	1.82
IIIC3	47-56	.8	.6	.2	0	4.6	1.78
IIIC4	56-68	1	0	.1	0	4.6	1.79
IIIC5	(60-63)	0	0	0	0	4.3	1.81
IIIC6	68-74	<.1	0	<.1	0	4.3	1.80

[1]"Disturbed" area refers to those portions of the soil profile that were dissimilar in color, texture, and structure, from the bulk of the surrounding soil mass. These areas were always darker in color and highly porous. Frequently they contained bark linings.

Table 2.—*Surface-area percentages of biotic macropores exposed in the back face as related to horizon, depth, pH, and bulk density*

Horizon	Depth	Total biotic macro-pores	"Dis-turbed" area[1]	Open root channels	Open animal passage-ways	pH	Bulk density
	Inches	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*G/cc.*
A1	0-1	—	—	—	—	5.6	0.98
A2	1-5	23.4	22.7	0.6	0.1	4.5	1.20
B1	5-9	17.0	9.9	3.4	3.7	4.5	1.45
B21t	9-16	17.4	8.9	5.5	3.0	4.5	1.62
B22t	16-24	12.0	6.2	3.5	2.3	4.7	1.70
IIBC	24-31	6.7	1.4	2.3	3.0	4.7	1.72
IIC1	31-37	2.8	1.3	1.0	.5	4.6	1.74
IIC2	37-47	1.4	0	.4	1.0	4.5	1.76
IIC3	47-51	.5	0	.5	0	4.5	1.76
IIC4	51-58	.1	0	.1	0	4.4	1.81
IIC5	58-64	0	0	0	0	4.2	1.80
IIC6	64-74	0	0	0	0	4.3	1.81
Coal bloss.	—	0	0	0	0	4.5	—

[1]"Disturbed" area refers to those portions of the soil profile that were dissimilar in color, texture, and structure, from the bulk of the surrounding soil mass. These areas were always darker in color and highly porous. Frequently they contained bark linings.

horizons, what little root growth and evidence of biotic macropores were found were restricted to structural cracks, old channels, or both.

The data in table 3 were derived from three-dimensional drawings of the features found within the 6- x 6- x 6-inch cubes from the first transect of the front face. Data from subsequent transects of the front face and the back face were similar. The calculated volumes for features within cubes varied considerably between cubes in the same layer. It was not at all uncommon for individual cubes in the B horizon to contain over 10 percent of the volume as open root channels, while the volume percentage of disturbed area often ran as high as 50 to 75 percent per cube in the A and upper B horizons.

In general, a relatively close relationship existed between the surface area percentages and volume percentages occupied by the major features. Our working experience and drawings enabled us to accurately predict the volume of roots, open channels, and

Table 3.—*Calculated root and root channel diameters, and average volume of roots, root channels, "disturbed" areas, and animal passageways found in the first dissected transect of the front face*

Depth of layers (inches)	Percent of layer occupied by —				Calculated average diameter of —	
	Roots	Channels	"Disturbed" area[1]	Animal passageways	Roots	Old root channels
	Pct.	*Pct.*	*Pct.*	*Pct.*	*Mm.*	*Mm.*
0-6	1.1	1.5	19.4	2.1	3.9	5.8
6-12	.9	1.8	5.3	.5	4.0	6.3
12-18	.4	.4	.7	.4	2.8	3.6
18-24	.2	.2	2.0	.1	2.0	2.5
24-30	.1	.2	.4	<.1	1.8	2.6
30-36	.1	<.1	.6	<.1	1.2	1.7
36-42	<.1	<.1	1.4	<.1	.9	1.8
42-48	<.1	<.1	.6	0	.9	.5
48-54	<.1	<.1	.2	0	.7	.8
54-60	<.1	<.1	.3	0	.6	1.1

[1] "Disturbed" area refers to those portions of the soil profile that were dissimilar in color, texture, and structure from the bulk of the surrounding soil mass. These areas were always darker in color and highly porous. Frequently they contained bark linings.

disturbed areas that we could expect to find in the front half in a given cube of soil from their percentage occupation of the surface face of the cube.

We are optimistic that after we obtain more data, we shall be able to establish surface area/volume correlations whereby an estimate of the volume of macropores in a given volume of soil can be made from the percentage of the surface area occupied by these features via application of a conversion factor.

Open root channels were predominantly concentrated in the B1, B21t, and B22t horizons lying between 6 and 24 inches in depth (figs. 4 and 5; tables 1, 2, and 3). "Disturbed" areas were most bountiful in the upper 6 inches or A horizons. These areas extended some distance into the soil and many had high concentrations of additional open root channels within their boundaries. Since in many cases the upper definable portion of these "disturbed" areas appeared to occur in slight depressions, filled with highly porous material, it is reasonable to speculate that water falling upon the surface of the forest floor rapidly enters these areas, which then act as funnels to transmit the water down into the profile and to interconnecting open or partially filled channels.

Since old root channels cannot be present in a soil profile unless roots were previously present, some brief mention of root distribution is in order. Live roots were very abundant in the A horizons and abundant in the B horizons. Although there generally were considerably more live roots than old root channels in these horizons, their larger number was compensated for by their smaller size; and consequently in the B horizons the percentages of the surface area and volume occupied by live roots were considerably smaller than those of the old root channels. Also, there were relatively few live roots that had diameters approaching those of the relatively abundant larger open root channels. No live roots were found that even began to approach the size of the "disturbed" area resulting from the filling of old root channels.

The differences noted between the number, sizes, and distribution of existing roots and old channels raises the question about the age of the persistent old root channels, their rate and time of formation, and by what age and species of tree. The present stand on the site is predominantly white oak, but evidence indicates that before World War I the area contained a heavy stocking of chestnut. The presence of roots growing in open bark-lined root channels within other similar open or partially filled channels raises the possibility that some of those persistent old channels may be of considerable age. No attempt was made in this experiment to determine the age of the root channel or the species that made it.

Macropores due to animal activity were found in the upper horizons, and they were generally associated with large roots or stones. These zoological macropores ranged all the way in size from small tunnels formed by insects up to relatively large passageways and chambers formed by mammals. Some chambers were found to contain stores of acorns.

The volume of the different cubes occupied by animal passageways varied from zero up to about 80 percent. The distribution of animal passageways was highly localized: certain areas were a maze of passageways while the majority of the soil layer was devoid of passageways.

The contribution of these zoologically formed macropores to the subsurface movement of water is open to question. While many such passageways were associated with "disturbed" areas or old root channels, the majority were essentially dead-end passageways. However, many passageways did intersect open or partially filled channels at various places along their length. Probably their major contribution to flow was the association between the larger passageways and roots and stones. Dye studies showed that some flow did occur along root-soil and stone-soil interfaces that were associated with the larger passageways. How or where the flow originally entered the system was undetermined.

Summary

The experiments reported here showed that under mixed hardwood forests in northeastern Ohio, macropores in the forest floor consisted of:

- Structural pores resulting from the texture and arrangement of the primary soil particles.
- Open channels formed by the passage through the soil of woody roots that have subsequently decayed. It was observed that these old root channels frequently retained a persistent root-bark layer lining the channels.
- "Disturbed" areas, formed by root growth or animal activity, which now contain a dark, highly porous, often spongy material. These "disturbed" areas exhibited evidence of bark lining.
- Animal passageways ranging in size from small tunnels formed by insects to relatively large passageways formed by mammals.
- Voids between roots and the surrounding soil matrix.
- Structural cracks between the soil structural units.

Qualitative and semiquantitative observations of outflow from the pit faces of soil masses receiving artificial rainfall containing fluoresceine dye showed that in fine textured soils many old root channels rapidly conduct free water through the soil mass without wetting the soil mass proper. Onset of outflow after the beginning of rainfall was normally rapid, often beginning within 10 to 15 minutes. Volume of outflow per location was frequently high, exceeding 1,000 ml./min.

That free water can rapidly move substantial distances through relatively dry soil was demonstrated by an observation of seepage occurring from a pit face some 30 feet obliquely downslope from the pit under study. The seepage commenced between 30 and 45 minutes after starting to wet the forest floor above the observation pit.

Site differences were noted. Outflow from the faces of coarse textured soils was usually considerably less than that from the finer textured soils. The coarse textured soil mass tended to wet up while the fine textured soil remained essentially unwetted.

Hydraulic conductivity determinations on 6-inch-diameter cores revealed a close correlation between the presence of old root channels and overall conductivity. The data obtained indicated that the presence of an open channel had an overshadowing effect on the soil's matrix conductivity. Finitely bounded cores from soils having an abundance of open channels may lead to an underestimate of the real conductivity rate because only a limited number of open channels can flow in a finitely bounded sample, whereas *in situ* most would flow. These data emphasize that in considering conductivity of forested soils where old open channels abound, one must direct attention to the number, size, and orientation of open channels in addition to the soil texture.

Study of a large free-standing block of soil showed that biotic macropores freely permeated the A and B horizons, the greater percentage occurring in the A2 horizon. Calculated volume percentages showed that the distribution of root channels, animal passageways, and disturbed areas varied greatly throughout the profile, both horizontally and vertically. Root channels were most prevalent in the upper B horizons, where it was not uncommon to find over 10 percent of the total volume of a 6-inch cube occupied by open root channels. The volume percentage of disturbed areas often ran as high as 50 to 75 percent of cubes from the A and upper B horizons. Macropores due to zoological activity were highly localized, certain areas being a maze of passageways while the majority of the soil layer was devoid of such passageways. In general, macropores were associated with large roots, stones, or disturbed areas.

At the experimental sites, macropores appear to persist for a considerable length of time, as illustrated by live roots growing in an old open root channel that had in turn been formed in a still older channel. However, the persistence of old root channels appears to depend somewhat on soil structure or texture. Root channels were most prevalent in the finer textured silt-silty clay loams and least in the coarser textured sandy loams. Additional evidence suggests that tree species has a definite influence on whether its roots will leave open, or partially filled root channels.

Dye studies showed that macropores provide pathways or conduits for the rapid movement of free water into and through the soil profile. Evidence of flow around live roots was also observed. Water moving within the macropores may or may not contribute to wetting up of the soil mass proper.

Qualitative observations on the benefit of macropores indicate that macropores formed in zones of high mechanical resistance and low water permeability provide avenues for the ascending and descending movement of water through the zone of resistance. The decay of the root leaves organic matter distributed throughout the root zone. In addition, old channels provide favorable growing conditions and pathways for future generations of roots.

References

Aubertin, G. M.
1969. An Improved Technique for Taking Hydraulic Conductivity Cores from Forest Soils. USDA Forest Serv. NE. Forest Exp. Sta. Res. Note 92, 4 pp. Upper Darby, Pa.

Auten, J. T.
1933. Porosity and Water Absorption of Forest Soils. J. Agr. Res. 46:997-1014.

Baver, L. D.
1936. Soil Characteristics Influencing the Measurement and Balance of Soil Moisture. Soil Sci. Soc. Amer. Proc. 1:431-437.

Blevins, R. L.
1967. Micromorphology of Soil Fabric at Tree Root-Soil Interface. Ph.D. thesis. Ohio State Univ. 161 pp. (Diss. Abstr. 28 B (12, part 1: 4843-4) 1968.)

Bouwer, H.
1961. A Double Tube Method for Measuring Hydraulic Conductivity of Soil *In Situ* Above a Water Table. Soil Sci. Soc. Amer. Proc. 25:334-339.

Bouwer, H.
1962. Field Determination of Hydraulic Conductivity Above a Water Table with the Double-tube Method. Soil Sci. Soc. Amer. Proc. 26:330-335.

Coile, T. S.
1937. Distribution of Forest Tree Roots in North Carolina Piedmont Soil. J. Forestry 35:247-257.

Denny, Charles S., and Walter H. Lyford.
1963. Surficial Geology and Soils of the Elmira-Williamsport Region, New York and Pennsylvania. Geol. Survey Prof. Paper 379, 60 pp.

Diebold, C. H.
1941. An Interpretation of Certain Infiltration Values in Forest Areas Obtained with the Type F and Type FA Infiltrometers. Soil Sci. Soc. Amer. Proc. 6:423-429.

Eadie, Robert W.
1939. A Contribution to the Biology of *Parascalops Breweri*. J. Mammalogy 20(2):150-173.

Gaiser, R. N.
1952. Root Channels and Roots in Forest Soils. Soil Sci. Soc. Amer. Proc. 16:62-65.

Gaiser, R. N., and J. R. Campbell.
1951. The Concentration of Roots in the White Oak Forests of Southeastern Ohio. USDA Forest Serv. Central States Forest Exp. Sta. Tech. Paper 120, 13 pp. Columbus, Ohio.

Hamilton, W. J., Jr.
1940. Mammal Life of the Forest Floor. N. Y. Zoological Soc. Bull. 43:171-180.

Hursh, C. R., and M. D. Hoover.
1941. Soil Profile Characteristics Pertinent to Hydrologic Studies in the Southern Appalachians. Soil Sci. Soc. Amer. Proc. 6:414-422.

Johnson, W. M., J. E. McClelland, S. A. McCaleb, Rudolph Ulrich, W. G. Harper, and T. B. Hutchings.
1960. Classification and Description of Soil Pores. Soil Sci. 89: 319-321.

Kittredge, Joseph, Jr.
1948. Forest Influences. 394 pp. McGraw-Hill Book Co., New York.

Klute, A.
1965. Laboratory Measurement of Hydraulic Conductivity of Saturated Soil. *In* Methods of soil Analysis, Part I, Chapter 13, pp. 210-221. Amer. Soc. Agron., Madison, Wisc.

Köstler, J. N., E. Brückner, and H. Bibelriether.
1968. Die Wurzeln der Waldbaume. 284 pp. Verlag Paul Parey, Hamburg and Berlin.

Krumbach, A. W., Jr., and D. P. White.
1964. Moisture, Pore Space, and Bulk Density Changes in Frozen Soil. Soil Sci. Soc. Amer. Proc. 28: 422-425.

Kutschera, Lore.
1960. Wurzelatlas Mitteleuropäischer Ackerunkräuter und Kulturpflanzen. 574 pp. DLG-Verlags, Frankfurt am Main.

Lutz, H. J., and R. F. Chandler.
1946. Forest Soils. 514 pp. John Wiley & Sons, Inc., N. Y.

Lutz, H. J., and F. S. Griswold.
1939. The Influence of Tree Roots on Soil Morphology. Amer. J. Sci. 237:389-400.

Lyell, Charles.
1866. Elements of Geology: or, the Ancient Changes of the Earth and its Inhabitants as Illustrated by Geological Monuments. 6th ed., 803 pp. D. Appleton & Co., N. Y.

McCaleb, S. B.
1959. THE GENESIS OF THE RED-YELLOW PODZOLIC SOILS. Soil Sci. Soc. Amer. Proc. 23:164-168.

Nielsen, G. A., and F. D. Hole.
1964. EARTHWORMS AND THE DEVELOPMENT OF COPROGENOUS A1 HORIZONS IN FOREST SOILS OF WISCONSIN. Soil Sci. Soc. Amer. Proc. 28:426-430.

Reynolds, E. R. C.
1966. THE PERCOLATION OF RAINWATER THROUGH SOIL DEMONSTRATED BY FLUORESCENT DYES. J. Soil Sci. 17:127-132.

Rogers, W. S.
1939. ROOT STUDIES. VIII. APPLE ROOT GROWTH IN RELATION TO ROOTSTOCK, SOIL, SEASONAL AND CLIMATIC FACTORS. J. Pomology 17 (2):99-130.

Rogers, W. S., and G. C. Head.
1962. STUDIES OF GROWING ROOTS OF FRUIT PLANTS IN A NEW UNDERGROUND ROOT OBSERVATION LABORATORY. XVIth Internat. Hort. Cong. 16:311-318. Brussels, Belgium.

Scheidegger, Adrian E.
1957. THE PHYSICS OF FLOW THROUGH POROUS MEDIA. 236 pp. MacMillan Co., N. Y.

Scully, Norbert J.
1942. ROOT DISTRIBUTION AND ENVIRONMENT IN A MAPLE-OAK FOREST. Bot. Gaz. 103:492-517.

Shaler, Nathaniel Southgate.
1891. THE ORIGIN AND NATURE OF SOILS. U. S. Geol. Sur. 12th Ann. Rep. 1890-91. Part 1, Geology.

Smith, F. H.
1958. ANATOMICAL DEVELOPMENT OF THE HYPOCOTYL OF DOUGLAS FIR. Forest Sci. 4:61-70.

Voigt, G. K.
1960. DISTRIBUTION OF RAINFALL UNDER FOREST STANDS. Forest Sci. 6:2-10.

Whipkey, Ronald Z.
1965. SUBSURFACE STORMFLOW FROM FORESTED SLOPES. Bull. International Assoc. Sci. Hydrol: 74-85. Louvain, Belgium.

Whipkey, Ronald Z.
1966. THEORY AND MECHANICS OF SUBSURFACE STORMFLOW. *In* Internat. Symp. Forest Hydrol: 255-260. Pergamon Press. N. Y.

Wilde, S. A.
1958. FOREST SOILS. 537 pp. Ronald Press Co., N. Y.

Wollny, E.
1890. UNTERSUCHUNGEN ÜBER DIE BEEINFLUSSUNG DER FRUCHTBARKEIT DER ACKERKRUME DURCH DIE THÄLIGKEIT DER REGENWURMER. Forschungen Gebiete d. Agrikultur-Physik 13:381-395.

■

Appendix

SOIL DESCRIPTIONS

Soil type.—Clymer silt loam over clay. County: Tuscarawas. Site: TU-F1 and TU-F3.

Location.—Fairfield township SE 1/4, NW 1/4, Sec. 5. About 1.2 miles north of Dover Dam. U. S. Forest Service hydrology plots.

Physiography.—Dissected plateau.

Parent material.—Surficial colluvium derived primarily from Freeport sandstone, Allegheny formation.

Topography and slope.—Moderately steep south slope. Site slightly below midslope. Gradient 20 percent at site.

Drainage.—Well drained.

Use or vegetation.—White oak, beech, and hickory.

Remarks.—Site was described and sampled for mechanical analysis in conjunction with a root study on a block opened on four sides.

South or Front Face of Root Study Block 1

Depth & Horizon	
2-1/2 inch 01	Litter, undecomposed, from oak, beech and hickory.
1/2-0 inch 02	Partially decomposed organic matter.
0-1 inch A1	Very dark gray (10YR 3/1) silt loam; weak, fine granular structure; very friable; roots abundant; thickness range from 1/2 to 2 inches; clear wavy boundary; pH 5.0; organic carbon 12.1 percent.
1-6 inch A2	Dark brown (10YR 4/3) silt loam; weak, fine, and medium subangular blocky structure; friable; roots abundant, few abandoned root channels; common fine pores; lower boundary gradual and smooth; pH 4.5; organic carbon 1.2 percent.
6-9 inch BI	Yellowish brown (10YR 5/4) heavy silt loam; weak, fine, and medium subangular blocky structure; slightly sticky when wet; numerous roots, pipings, or abandoned root channels are common ranging from 3 to 20 mm. in diameter; less than 5 percent coarse skeletal material; lower boundary gradual and smooth; pH 4.5; organic carbon 0.5 percent.
9-16 inch B21t	Yellowish brown (10YR 5/6) silty clay loam; moderate, medium subangular blocky structure; firm, sticky, and plastic when wet; roots common; thin, patchy clay films on ped surfaces; common fine pores; 3 to 5 percent coarse skeleton of sandstone fragments; lower boundary gradual; pH 4.6; organic carbon 0.4 percent.
16-23 inch B22t	Yellowish brown (10 YR 5/8) silty clay loam with common olive (5Y 5/3) and reddish brown (5 YR 5/4) variegations; moderate, medium subangular blocky structure; firm, sticky, and plastic; thin clay films on channel walls, and

	patchy on ped surfaces; roots common, but decreasing in number; 10 percent coarse skeleton of sandstone and shale fragments; lower boundary abrupt and irregular; ph 4.6; organic carbon 0.3 percent.
23-31 inch IIB3	Yellowish brown (10YR 5/4) loamy coarse sand with thin bands of gray (10 YR 6/1) sandy loam; weak, coarse subangular blocky structure that crushes to single grain; very friable; few roots observed, coarse skeleton material 40 percent; horizon is discontinuous; abrupt irregular lower boundary; pH 4.6; organic carbon 0.3 percent.
31-36 inch IIIBC	Gray (5Y 6/1) silty clay loam with many (25 percent) strong brown (7.5YR 5/6) mottles; moderate, coarse, subangular blocky structure; very firm; few small roots, weathered clay shale fragments common; ped faces have moderately thick clay films; lower boundary clear; pH 4.7; organic carbon 0.3 percent.
36-42 inch IIIC1	Dark gray (N4/) silty clay with strong brown (7.5YR 5/6) and gray (10YR 6/1) mottles; platy to massive; very firm; few small roots growing in structural cracks; lower boundary abrupt; pH 4.6; organic carbon 0.3 percent.
42-47 inch IIIC2	Brown (10YR 5/3) silty clay loam with strong brown (7.5YR 5/6) and gray (10YR 6/1) mottles; weak, coarse, subangular blocky structure to massive; firm, occasional small roots, thin lenses of coal blossoms; lower boundary clear, wavy; pH 4.6; organic carbon 0.8 percent.
47-56 inch IIIC3	Mottled grayish brown (10YR 5/3) and dark gray (N4/) silty clay loam; massive, firm, sticky, and plastic; thin coal blossom bands; lower boundary clear; pH 4.6; organic carbon 0.3 percent.
56-68 inch IIIC4	Mottled olive brown (2.5Y 4/4), light olive gray (5Y 6/2) and grayish brown (2.5Y 5/2) silty clay; massive; firm, sticky, and plastic; lower boundary clear; pH 4.6; organic carbon 0.6 percent.
68-74 inch IIIC6	Light olive brown (2.5Y 5/6) silty clay with many (30 percent) gray (10YR 6/1) mottles; massive; sticky when wet; pH 4.3; organic carbon 0.1 percent.

North or Back Face of Root Study Block 1

Depth & Horizon	
1-½ inch 01	Undecomposed litter from oak, hickory, and beech.
½-0 inch 02	Partially decomposed organic material.
0-1 inch A1	Very dark gray (10YR 3/1) silt loam; weak, fine granular structure; friable; roots abundant; thickness range from ½ to 2 inches; clear wavy boundary; pH 5.6; organic carbon 13.4 percent.
1-5 inch A2	Brown (10YR 4/3) silt loam; weak, fine subangular blocky structure; friable; roots abundant; lower boundary gradual smooth; pH 4.5; organic carbon 1.9 percent.

5-9 inch B1	Yellowish brown (10YR 5/4) silt loam; weak, fine to medium subangular blocky structure; firm; numerous roots; lower boundary gradual smooth; pH 4.5; organic carbon 0.8 percent.
9-16 inch B21t	Yellowish brown (10YR 5/6-5/8) clay loam; moderate, medium subangular blocky structure; firm, sticky when wet; few roots; occasional large sandstone cobbles observed; thin patchy clay films on ped surfaces; lower boundary clear smooth; pH 4.5.
16-24 inch B22t	Yellowish brown (10YR 5/6) heavy silty clay loam with few strong brown (7.5YR 5/6) pale brown (10YR 6/3) mottles; moderate, medium subangular blocky structure; firm, sticky when wet; few roots; thin patchy clay films on ped surfaces and channel walls; less than 5 percent coarse skeleton; lower boundary clear smooth; pH 4.7.
24-31 inch IIBC	Light olive gray (5Y 6/2) silty clay with few, distinct, strong brown (7.5YR 5/6) and yellowish red (5YR 4/6) mottles; weak, medium and coarse subangular blocky structure; firm, sticky and plastic; numerous abandoned root channels observed; discontinuous lenses of sandy material and sandstone fragments occur in this horizon; clay films on ped surfaces; lower boundary clear; pH 4.7.
31-37 inch IIC1	Light olive brown (2.5Y 5/4) silty clay with dark yellowish brown (10YR 4/4) coatings; massive to prismatic; firm, sticky and plastic; numerous soft brittle shale fragments (10 percent); lower boundary gradual wavy; pH 4.6.
37-47 inch IIC2	Grayish brown (2.5Y 5/2) (60 percent) and yellowish brown (10YR 5/6) silty clay; massive; firm, sticky and plastic; lower boundary abrupt smooth; pH 4.5.
47-51 inch IIC3	Yellowish brown (10YR 5/6) silty clay loam with grayish brown (2.5Y 5/2) mottles; relict platy to massive; firm, sticky; bands of very dark gray (N3/); coal blossom; pH 4.5.
51-58 inch IIC4	Light olive brown (2.5Y 5/4) clay with yellowish brown (10YR 5/6) mottles and bands of dark gray (N4/) coal blossom; relict platy structure; firm, sticky and plastic; lower boundary abrupt smooth; pH 4.4.
58-64 inch IIC5	Gray (5Y 6/1) clay with gray (10YR 5/1) coatings and yellowish brown (10YR 5/6) mottles; massive to prismatic structure; very firm, sticky and plastic; lower boundary abrupt; pH 4.2.
64-74 inch IIC6	Light olive gray (5Y 6/2) silty clay loam with yellowish brown (10YR 5/6) streaks; massive to prismatic structure; firm; pH 4.3.

THE FOREST SERVICE of the U. S. Department of Agriculture is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, and management of the National Forests and National Grasslands, it strives — as directed by Congress — to provide increasingly greater service to a growing Nation.