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THE INFLUENCE OF SOIL POROSITY
UPON ROOT BEHAVIOUR

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THESIS

THE INFLUENCE OF SOIL POROSITY UPON ROOT BEHAVIOUR

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INTRODUCTION

Farlier root investigations conducted by the author¹ with the Concord grape in the Niagara Peninsula of Ontario and with the McIntosh apple in the Okanogan Valley of British Columbia have revealed many facts for which an adequate explanation has not always been possible. It has been observed, for instance, that there was poor development of grape roots, even in the surface horizon, wherever the soil was heavy and compact, while in other soils of lighter texture there was a luxuriant development of roots at all depths. Also in the case of apple trees on a heavy silty clay loam soil, roots have been found in abundance at depths of 6 and 7 feet, while in nearby locations with somewhat different soils, most of the roots penetrated only $2\frac{1}{2}$ to 3 feet.

It is known that the supply of moisture, nutrients, and oxygen, the presence of toxic constituents, and physical impenetrability, are the most common factors limiting root growth, but the relative importance of each factor has not been definitely known in explaining root behaviour in specific soils.

Purpose of the Investigation

The purpose of the investigation was to determine the reason for the failure of roots to penetrate certain horizons of compact soil, and some Montmorency cherry trees in the orchard of Michigan State College growing in a soil characterized by a dense compact subsoil, provided some

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Unpublished material

convenient material with which to work.

Realizing the impossibility of studying all factors relating to this phenomenon, it was decided to give particular attention to the influence of soil porosity upon root behaviour. Such an approach to the problem demanded the introduction of a study of soil aeration, since the influence of soil porosity on root development is exerted largely through its control of moisture and air relationships.

REVIEW OF LITERATURE

There are in the literature many statements of a definite effect of aeration in influencing root behaviour. Such conclusions have been reached from the effect of waterlogging and compaction of the soil on root and top responses both in the field and greenhouse, from the results of aeration studies, and from gas and other analyses.

It has been reported by Robbins (14), that tramping and packing of a heavy orchard soil by cattle resulted in the killing of the fruit trees, and it is reported that deficient aeration was directly responsible for the death of the trees. Likewise, Baver and Farnsworth (3) have found that the failure of sugar beets on some of the heavier soils of Ohio in seasons of heavy rainfall is to be attributed to deficient aeration of the soil, since the losses were most severe where the larger pores had been largely destroyed through a system of continuous cultivation.¹

Symptoms of aeration deficiency have been even more pronounced in waterlogged soils than in those where such a condition has been produced by compaction, doubtless because aeration becomes even more restricted. Schuster and Stephenson (17), have shown from studies made in the Willamette Valley that roots of nut trees do not penetrate to any degree into waterlogged horizons because of the small amount, or absence, of air space. There was an absence of roots in soil cores taken from such horizons, and it is concluded that deficient aeration rather than the high moisture level was the direct cause of root restriction. Boynton and Reuther (4) and Heinicke (12) report similar observations in New York.

¹

Continuous cultivation reduces soil porosity largely through its destruction of organic matter.

Dean (9) reports that aeration of waterlogged horizons caused the roots to develop in such soil, even though the moisture content was well above the optimum for plant growth, and it was also observed that the densest root growth occurred in the neighborhood of the aerating coils. Tisdale and Jenkins (21) believe that the rice plant makes better growth and is more resistant to certain diseases when the soil is allowed to dry out for 2 to 3 weeks during the growing season, thus permitting the entrance of oxygen, and Coville (8) states that even cranberries and blueberries, which endure submergence for months when inactive, are harmed by waterlogging of the soil for only 3 to 4 days in summer.

Whether deficient aeration is induced by compaction and high moisture content, or by waterlogging of the soil alone, it is probable that the volume of air space becomes the limiting factor to root growth. Air capacity is usually represented by the volume of non-capillary pore space, i.e. the voids or spaces not filled with water. It is noteworthy that the volume of non-capillary pore space is a direct function of moisture percentage at high levels of soil moisture, since the volume of large pores decreases as the soil becomes filled with water. Eventually at the point of complete saturation both air capacity and air exchange are reduced to zero. Schuster and Stephenson (17) are of the opinion that soils with less than 5 or 6 per cent air space are not favorable to the penetration of fruit tree roots, and Bayer and Farnsworth (3) believe that non-capillary porosities of 7 to 10 per cent are necessary to produce large tonnages of sugar beets on heavy soils of Ohio.

Bayer (2) reports that soils with high non-capillary pore space have usually been found to favor a rapid rate of gas exchange, although Buehrer (6)

has shown that "not all of the void spaces between the particles contribute to the flow of gases through such assemblages, and that an appreciable proportion of them either terminate in stagnant estuaries or they are so small that they offer a much greater resistance to the flow of air than the larger pores." It is therefore probable that a soil with a considerable proportion of larger pores, but with little or no continuity between them may be less favorable to air exchange than a soil with a smaller proportion of larger pores, but with minute channels, root and worm holes, cracks and cleavage planes to act as connecting channels between at least a part of the pores. Schuster and Stephenson (17) believe that such are the principal means of effecting interchange of gases and drainage of water, and Buehrer (6) has found these channels of great significance in determining the rate of flow of air through soil.

There is some disagreement concerning the exact manner in which air exchange occurs in soil, but regardless of the nature of this phenomenon, it is generally agreed that continuous free pore spaces are normally essential in effecting this process. Although it is conceded that diffusion occurs in pores of smaller diameter equally as rapidly as in those of larger diameter, still under optimum soil moisture conditions, it is the large or non-capillary pores only that are important in air movements, for, in most soils, the small or capillary pores are filled with water.

It is probable, in the case of many soils of low non-capillary pore space, that rate of exchange may be equally as important, if not more important, than air capacity or volume of large pores in determining the suitability of a soil for root growth, since it has been demonstrated by Cannon (7) that slow artificial streaming of the soil atmosphere permits root development

(6)

to occur in soils of relatively low non-capillary pore space and low oxygen tension.

ROOT STUDIES IN THE ORCHARD

Method of Study

Three cherry trees were selected for root studies, two of which were in a decidedly poor state of vigor, while the other represented more nearly the average of the orchard.

A trench was dug along one side of the tree so that one half of the root system was exposed for root studies. No attempt was made to record quantitatively either the extent of spread of the roots or the degree of branching in each profile, since there was an almost complete absence of roots wherever compact horizons occurred. A photographic record was therefore considered more satisfactory.

Results of Orchard Studies

Even from casual observation, it was apparent that certain horizons were definitely unfavorable for the growth of cherry roots, as is illustrated in Figs. 1 and 2. There was almost a complete absence of roots



Fig. 1. Response of cherry roots to compact horizons.
(Note how roots have avoided compact soil on each side of trunk)



Fig. 2. Results of unfavorable subsoil for root growth.
(Note how all roots are on left side of trunk)



Fig. 3. Red cherry roots in favorable soil.
(Note large trunk and free distribution of
roots throughout profile)

wherever compact horizons appeared in the profile, while in those areas where the soil was loose and friable, there was considerable development of roots, both laterally and vertically as shown in Fig. 3.

Considerable root killing was evident in the surface horizon wherever compact subsoils were encountered. Later studies of pore space of the surface soil in such locations showed only a small volume of non-capillary pores owing in part to admixture of fine textured materials from the compact subsoil and also to cultivation. In loose, friable surface soils, such as those of Fig. 3, the amount of root killing was small. Such trees as those in Figs. 1 and 2 were therefore dependent upon a root system restricted largely to the subsoil. Examination of weather records for the fall of 1939 and early winter of 1940 showed a light snowfall in the fall with a minimum temperature of -11° F on January 11, and it is reasonable to attribute the root injury to the occurrence of such extreme cold at a time when the soil was free from snow. It is emphasized that this injury was of slight extent wherever the soil was friable and open, and although there are many factors influencing penetration of frost into soil, it is believed that the absence of air spaces in the surface soil has been responsible, at least in part, for the occurrence of root injury.

GREENHOUSE STUDIES

ProcedureGeneral Remarks

By studying the growth of roots of some indicator plant in soils of varying compactness in the greenhouse, and supporting these observations with an investigation of root growth in several soil-sand mixtures in which aeration studies were made, it was believed that a more complete determination of the suitability of soils for root development could be obtained than by limiting the study to what could be observed in the orchard.

Alfalfa was selected as the plant for greenhouse studies, primarily on account of its fairly rapid growth under short day conditions. As was shown later in the investigation, however, the outstanding advantage of this plant for such a study is its high oxygen requirement, in which, according to Gourley and Howlett (11), it may resemble many of our tree fruits. Alfalfa has the further advantage that it is adaptable to growth under greenhouse conditions.

Removal of Soil Cores

In order to provide soil conditions for the alfalfa plants in the greenhouse approximating those in the cherry orchard, it was necessary to remove undisturbed cores of soil from the field. This was considered especially important, since any disturbance of the natural field structure makes radical changes in soil characteristics, especially in their structural properties.

In removing the cores from the profile, it was found necessary to surround each core completely with a trench, since a slight strain was often

sufficient to split the core along the well-developed cleavage planes. Cores were approximately cylindrical in shape, and were 8 to 10 inches in height and 6 to 8 inches in diameter. Cans of approximately 5-gallon capacity were prepared with about 2 inches of coarse sand in the bottom for drainage, and the cores were transferred to them directly in the orchard. Sand was tamped lightly into the space around the cores, and about 1 inch of sand was added to the surface to prevent desiccation in the greenhouse between irrigation periods.

Cores were taken in duplicate from different parts of the profiles to represent both favorable and unfavorable soils for rooting, ranging from an A horizon to dense and compact B and C horizons. Two cores were taken from a dense sticky silty clay in the vicinity of East Lansing in order to have a soil of a distinctly different type for comparison with the cores from the orchard.

Importance of Moisture Control

As was stated earlier, the volume of non-capillary pores depends on the moisture content of the soil in the higher range of soil moisture values. In these compact subsoils with a small volume of large pores, a slight excess of soil moisture above field capacity may be sufficient to displace all the air from the few larger pores, and conditions for root growth are definitely unfavorable especially when the tree is making rapid growth. Under these conditions any roots which have penetrated such horizons will be existing in an anaerobic environment. The absence of well-developed cleavage planes, minute pores and other natural channels would seem to be sufficient evidence that the air capacity of compact subsoils in spring is quite small or nil, so that even without considering the influence

of physical impenetrability, conditions for root growth have become unfavorable.

It was not attempted to have alfalfa roots in the cans exposed to the same conditions of moisture and aeration as were cherry roots in the orchard, but rather to have uniformly high soil moisture conditions throughout the period of investigation. It was assumed that conditions were similar to those which prevailed in these soils in spring. As was shown later in this investigation, all cores were maintained at approximately field capacity, which probably represents a critical moisture level in soils such as those used in this study with a small volume of large pores.

Setting the Plants

One-year old alfalfa plants were dug from the orchard in October while the leaves near the ground were still green. Only those plants which had developed uniform well-branched root systems were used, the tap root being pruned back to about 6 inches. The soil was removed by washing, and five plants chosen at random were set in each can. The manner of setting the plants is illustrated in Fig. 4. Conditions were such that

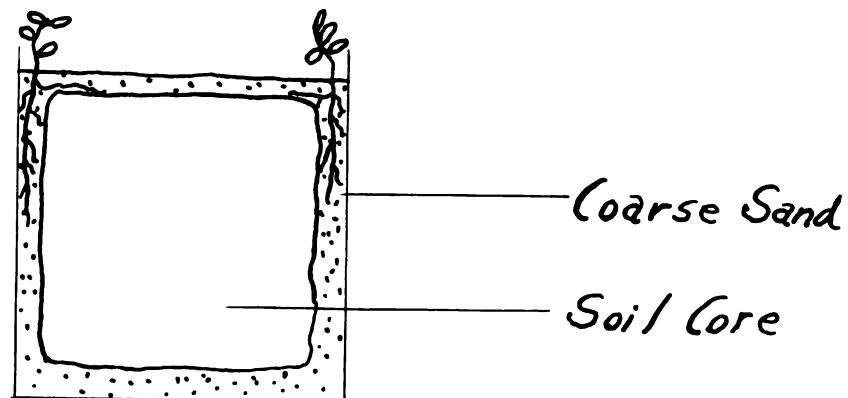


Fig. 4. Position of soil core and method of setting plants.

the roots could penetrate the core if the soil was favorable, but in the event that the soil environment was unfavorable, the plants would produce their roots in the coarse sand, obtaining their nutrient requirements from the nodules, and from the surface of the soil core. The plants were allowed to grow for a period of 7 months, in which time it was considered that there was ample opportunity for the roots to penetrate the cores.

Moisture Control

In controlling soil moisture, advantage was taken of the great tension exerted by heavy soils on water; it was therefore possible for the cores to extract moisture from the sand surrounding them, but the reverse process would not occur under the conditions of this study. The moisture content of the cores seemed favorable for plant growth at the time the cores were taken, but in all cases they absorbed water from the sand until approximately field capacity was reached, and since the periods during which free water appeared in the sand were not more than 30 minutes in duration, it is not likely that the moisture level in the cores rose much above field capacity. At every irrigation, sufficient water was added to cause drainage through holes in the bottoms of the cans, and it was attempted to have the sand continually moist. Usually this was possible by applying water every 2 or 3 days.

Artificial Soil-sand Cores

Un-aerated Cores

Owing to variations in nutrient level, compactness and other factors, it was decided to construct artificial cores using finely ground soil, taken from compact horizons, and coarse quartz sand in different proportions by weight; by mixing these components in the dry state and then adding water and

mixing until a puddling consistency was reached, it was hoped that a series of cores could be constructed varying only in different amounts of pore space of a non-capillary size. Mixtures containing the higher proportions of sand were expected to have the greater percentage of larger pores.

Cores were moulded in an 8-inch pot, jarring each pot several times to reduce the size of pores, and consequently the volume of pore space. It appeared later in the study that considerably more care should have been given to the matter of puddling since a small variation in degree of puddling was sufficient to offset the influence of the soil-sand ratio upon pore space relationships.

Plants were set as in the case of the undisturbed cores. Moisture control was obtained in the same way as mentioned above, and from data in Table 2, it is evident that variations in soil moisture greater than 1 per cent did not occur between duplicate samples of the same mixture.

Cores of the following soil-sand mixtures were constructed in duplicate:

$1/2$	soil	-	$1/2$	sand
$5/12$	"	-	$7/12$	"
$1/3$	"	-	$2/3$	"
$1/4$	"	-	$3/4$	"

Aerated Cores

Essentially the conditions of this series were similar to those mentioned above, excepting that all cores received daily aeration. Only one soil-sand mixture ($5/12 - 7/12$) was used in this series of cores, the constituents being mixed and puddled as in unaerated cores. Aeration was provided in three of these cores by running an air tube through the base

of the cans (Fig. 5a) into a layer of sand, the soil-sand mixture being placed in the can like a horizon of a soil profile, with sand above and below it. Air was removed through the tube in the base of the can, thus causing a movement of gas within the core (the volumes of air removed were 300, 600 and 900 ml. daily, with each core receiving a different treatment). The method of creating a flow of air is illustrated and described below.

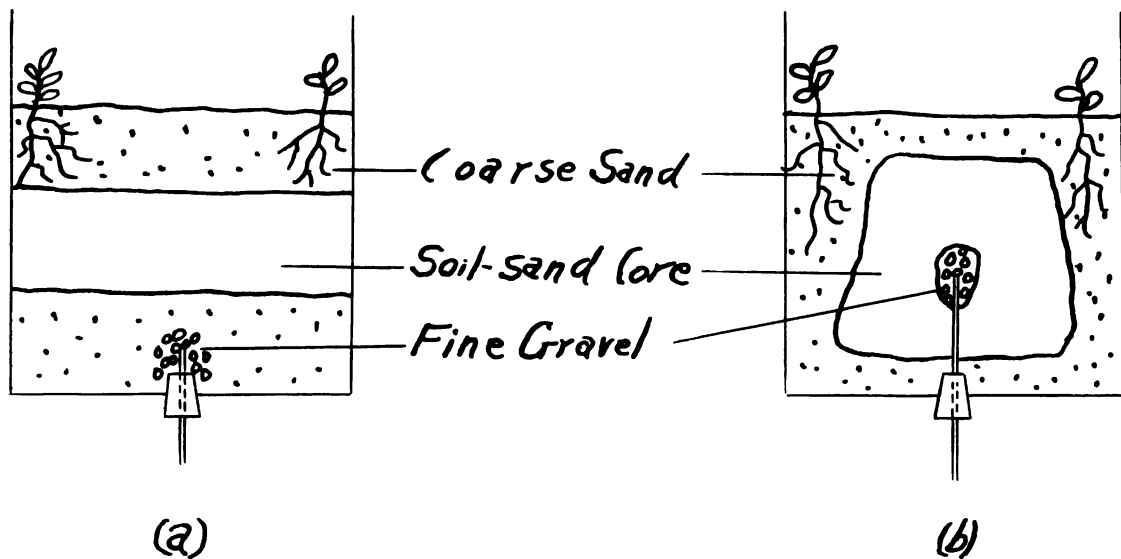


Fig. 5. Method of aerating soil-sand mixtures

The other three cores of this series were moulded and placed in the cans in the same manner as in the unaerated cores excepting that an air tube (Fig. 5b) was run through the base of the can into the center of the soil core. The ends of the glass tubing were covered with a small sack of fine gravel to prevent clogging of the mouth of the tube with soil and also to provide a more uniform distribution of air throughout the cores.

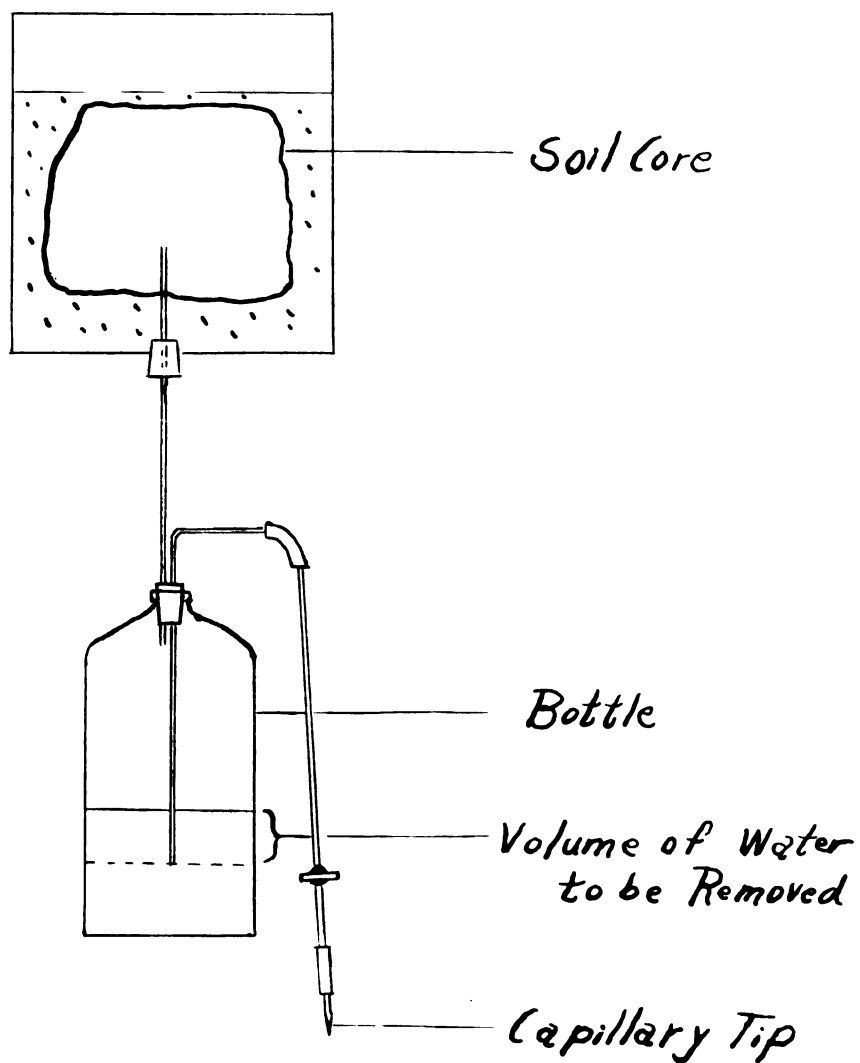


Fig. 6. Sketch of apparatus for aerating soil cores.

Air was removed at approximately the same rate from all cores in the aerated series, but the duration and amount of daily removal were varied. Under each of the aerated soil cores, an apparatus was constructed (fig. 6) to create a uniform flow of air, through reduction of air pressure, over a considerable period of time. It consisted essentially of a large bottle (the greater the diameter, the more uniform the flow of air) connected by means of an air tube to the soil core above, and with a siphon ending in a capillary glass tip to regulate the flow of water from the bottle. It was found that a stop cock was required as well as the capillary tip in order to reduce the flow of water to the rate of 2 to 3 drops a second. To adjust the apparatus to remove 300 ml. of air daily from a core, it was only required to have this volume of water removed from the bottle, the larger volumes being obtained by raising the water level in the bottle. Hence both amount and duration of daily aeration treatments were varied with rate of aeration constant.

Method of Studying Roots in Soil Cores

Owing to wide differences in types of rooting in different soil types investigated, and it was frequently observed that this phenomenon occurred even in different parts of an individual core, it was considered that quantitative studies of root growth in the different cores would not give significant results, even though all the roots from a core were removed and measured. By making macroscopic observations on such characters as amount of branching of roots, location of branches and penetration, and supplementing these with binocular studies of certain minute details such as the formation of root hairs, it was believed that some conclusions could be reached concerning the suitability of a given type of soil for root development.

Results of StudyRoot Growth in Undisturbed CoresPear Orchard (32 - 40 inches)

Under field conditions, few roots were found penetrating the cores from this horizon since they were taken from a depression where water frequently remained for considerable time in spring and also following torrential rains in summer. It is probable, however, that the moisture content of this horizon is lower than in that immediately above, since there was no reason to expect poor drainage conditions in a soil with the development of cleavage planes and large pores that this soil possessed, although the presence of a compact horizon below might create such a condition. The soil was a pale yellow-brown silty clay loam containing gravel of various sizes admixed. The pH was 7.4 to 7.6.

Cores broke readily along cleavage planes, which were most pronounced in this soil, the horizontal planes being much better developed than those running vertically. Many pores of various sizes and shapes were detected, some of them being as large as 0.4 cm. in diameter. It was of interest to note the small deposits of organic matter in some of these pores, and since many of these were isolated, it is hardly possible that they represent residues of old roots.

For the most part, roots followed planes of natural cleavage, as shown in Fig. 7, with root hairs appearing clearly wherever root tips entered a large pore, and it was also noted that there was little penetration into the soil beyond the cleavage planes. Constrictions were noted near some of the root tips where they penetrated the spaces between particles; these tips usually enlarged again when resistance to their progress decreased. This



Fig. 7. Root growth in core from subsoil of pear orchard.
(Note luxuriant root growth on plane of cleavage)

phenomenon is similar to that noted by Taubenhaus et al (19) in the case of roots of the cotton plant which developed normally as long as the soil was moist, but became strangled later in the season in a subsoil horizon of hard, dry clay which prevented enlargement in diameter.

Cherry Orchard (16-24 inches)

The horizon from which these **cores** were removed was almost impenetrable to cherry roots under orchard conditions. The soil was a pale yellow-brown silt loam containing some gravel admixed, varying from prismatic columnar structure and somewhat friable consistency to cloddy structure and compact granules. The pH was 7.2 to 7.5. Cleavage planes were well developed vertically as is illustrated in Fig. 8. Minute pores could be observed with the naked eye, and excepting where the consistency was somewhat friable, root development was largely restricted to planes of cleavage, a few root

channels and the minute pores.

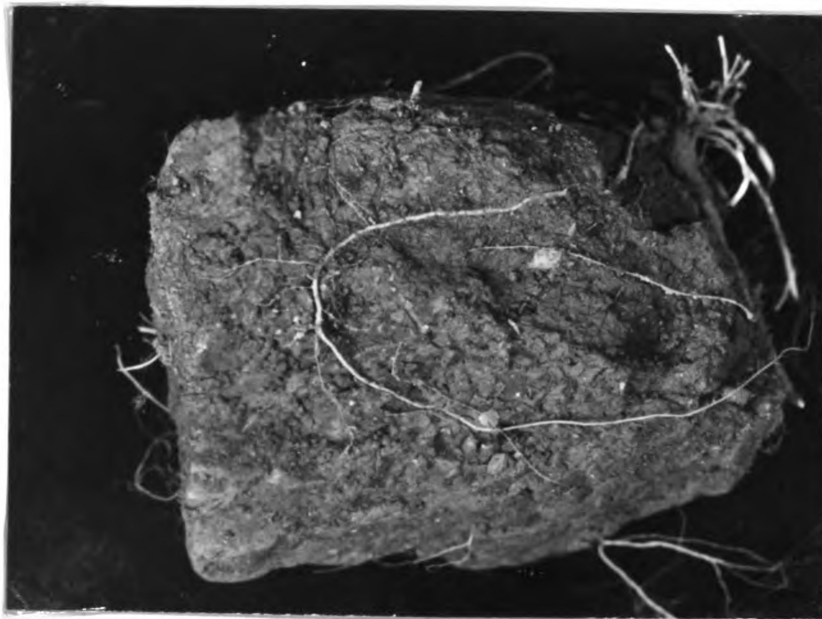


Fig. 8. Root growth in compact core from cherry orchard.
(Note lateral branching and nodulation on cleavage plane contrasted with relatively unbranched condition in lower part of core)

Lateral roots developed freely along cleavage planes, and even a few single nodules were noted as shown in Fig. 8. The thread-like character of the lateral roots and presence of nodules on roots in the cleavage plane are illustrated in Fig. 9.



Fig. 9. Dissected roots to illustrate (above) nodulation and thread-like lateral branching on cleavage planes and (below) large diameter and abundant branching of roots in outer layer of cores from A horizon.

A Horizon from Cherry Orchard

This soil is a dark gray-brown sandy loam containing considerable coarse sand, with a friable consistency and compact structure. No organic residues or fibrous materials were detected in October when the core samples were taken and this was not unexpected since the amount of organic material added to the soil annually through cover crops has been quite small. It is believed that the compact structure or absence of large pores is to be attributed to the effect of continuous cultivation with only small returns of organic materials, and there are many reports in the literature of such degradation of pore space (4), (5).

It is entirely possible that following cultivation in spring, conditions for rooting in this horizon are much more favorable in the orchard than later in the season when the temporary effects of cultivation upon non-capillary porosity have largely disappeared.

Few root or worm channels, or large pores were observed either with the naked eye or with the aid of binoculars, and cleavage planes were entirely absent. The pH of this horizon was 6.8.

In the outer layer of the cores, conditions were apparently favorable for root development, as shown by the dissected root in Fig. 9, but the number of roots penetrating the interior of the cores was comparatively few. Those roots which followed old root channels were characterized by their thread-like form and free branching habit, while those which penetrated the cores were whiter in color, larger in diameter and sparsely branched, especially in the interior of the core.

It should not be inferred from these observations that roots would not develop in such horizons in the field. It is probable that the moisture content under field conditions is somewhat lower than under the conditions of this investigation, so that rooting might occur in the orchard, while under such experimental conditions as these, there would be little or no development. Further, it should be mentioned that under orchard conditions the cherry roots had no alternative horizon from which they might obtain moisture and nutrients more easily, while in the case of alfalfa roots in cans in the greenhouse, a loose and open rooting medium was provided by the surrounding sand. Apparently the alfalfa roots were able to obtain all their requirements from the sand and from the outside of the cores.



Fig. 10. Root growth in weathered core of heavy silty clay.
(Note minute pores throughout exposed surface and
rooting on planes of cleavage)



Fig. 11. Root growth in unweathered core of heavy silty clay.
(Note absence of minute pores and of roots on most
of exposed surface)

Heavy Silty Clay (24 - 32 inches) and (32 - 40 inches)

Observations are reported on both a weathered and an unweathered core, since the response of roots is quite different in each. The core illustrated in Fig. 10 was taken at a depth of approximately 24 - 32 inches, representing a core of weathered soil, as indicated by the reddish-brown oxidation color, the considerable development of horizontal cleavage planes, the platy structure, and the presence of minute pores. The lower horizon (32 - 40 inches) evidenced little weathering, showing little development of cleavage planes, and in most of the core, not even the smallest of pores were visible as is shown in Fig. 11. It is significant that in both the unweathered and weathered cores, there was no indication of impenetrable properties such as existed in the orchard subsoils studied. The pH was about 8.0.

The differences in root distribution of the alfalfa between the two cores is shown in Figs. 10 and 11. In the weathered core, there were many roots ramifying through the core, and especially along cleavage planes. No nodules were noted along the cleavage planes, but, as in the case of the other cores, they appeared in profusion just beneath the surface of the cores. In most of the unweathered core, there was a complete absence of roots, and only where a slight degree of weathering appeared was there any development of roots. The white color of the roots in these cores was characteristic, which is an indication that toxic conditions did not exist.

Nutrient Studies of Soil Cores

In order to assist in the interpretation of root distribution of the alfalfa plants in the different soil cores, some studies were made of the nutrient level of the different soils under investigation. Results are presented in Table 1.

Table 1. Nutrient Studies of Soil Cores*

Soil	P ₂ O ₅ ppm.	CaO ppm.	Carbonate	pH
A Horizon	0.5	60	No test	6.8
Heavy Silty Clay	0.5	200	Very high	8.0
Pear Orchard (24-32")	0.5	125	No test	7.2
" " (32-40")	0.5	100	No test	7.4
Cherry Orchard (16-24")	1.0	100	No test	7.4
" " (24-32")	1.0	100	High	7.8
Artificial Cores	0.5	100	No test	7.4

*

All tests for available nutrients made by Simplex Rapid Method

In interpreting the results of such studies, it is necessary to decide whether or not there is an adequate supply of available nutrients, and also whether any nutrient element or toxic constituent appears in excess. It was considered that the test for phosphorus was especially important, in that soluble arsenic shows up in the test for phosphorus, and instances of arsenic toxicity have been reported in the surface horizon of orchard soils. As far as the test for arsenic is concerned, it is of little significance whether a low test for phosphorus is to be attributed to either arsenic or phosphorus, or both, since in any case the arsenic content would be too low to be of any significance. It was considered that arsenic toxicity was most likely to occur in cores from the A horizon of the cherry orchard, but the low test for phosphorus of 0.5 ppm. immediately dismisses this possibility. It is not likely that phosphorus deficiency has been responsible for absence of rooting in any of the cores, since there was

no indication of this in the artificial aerated cores in which a test of 0.5 ppm was obtained.

The data for calcium are presented because of the high requirement of alfalfa for this element (19). It is significant that sufficient available calcium appeared to be present in all soils, and even when the pH value rose to 8.0 in the heavy silty clay, there was an abundant supply of calcium to meet the requirement of the plants.

High tests for iron were obtained in the most compact of the subsoils, and it is probable that these horizons have been cemented by depositions of iron and aluminum colloids.

Root Growth in Artificial Soil-sand Cores

Un-aerated Cores

Perhaps the most significant result of the entire investigation was the almost complete absence of root penetration in all un-aerated cores, regardless of the proportion of soil to sand. There was a considerable development of roots in the 0 - 1/2 inch layer on the outside of some of the cores, with many large compound nodules just beneath the surface where aeration conditions and nutrient supply were apparently quite favorable. In only one core (1/2 soil - 1/2 sand) was there any penetration beyond 1 to 2 inches. It is at once apparent from a study of Fig. 12 that only a few roots have penetrated inwards more than 1 inch, and no roots have reached the center of the core during the 6-month period of growth.

Penetration of roots appeared to be more extensive in those cores in which the pores were larger, the presence of the larger pores indicating less puddling than where only smaller sizes were present. It is notable that no relationship was to be found between proportion of soil to sand

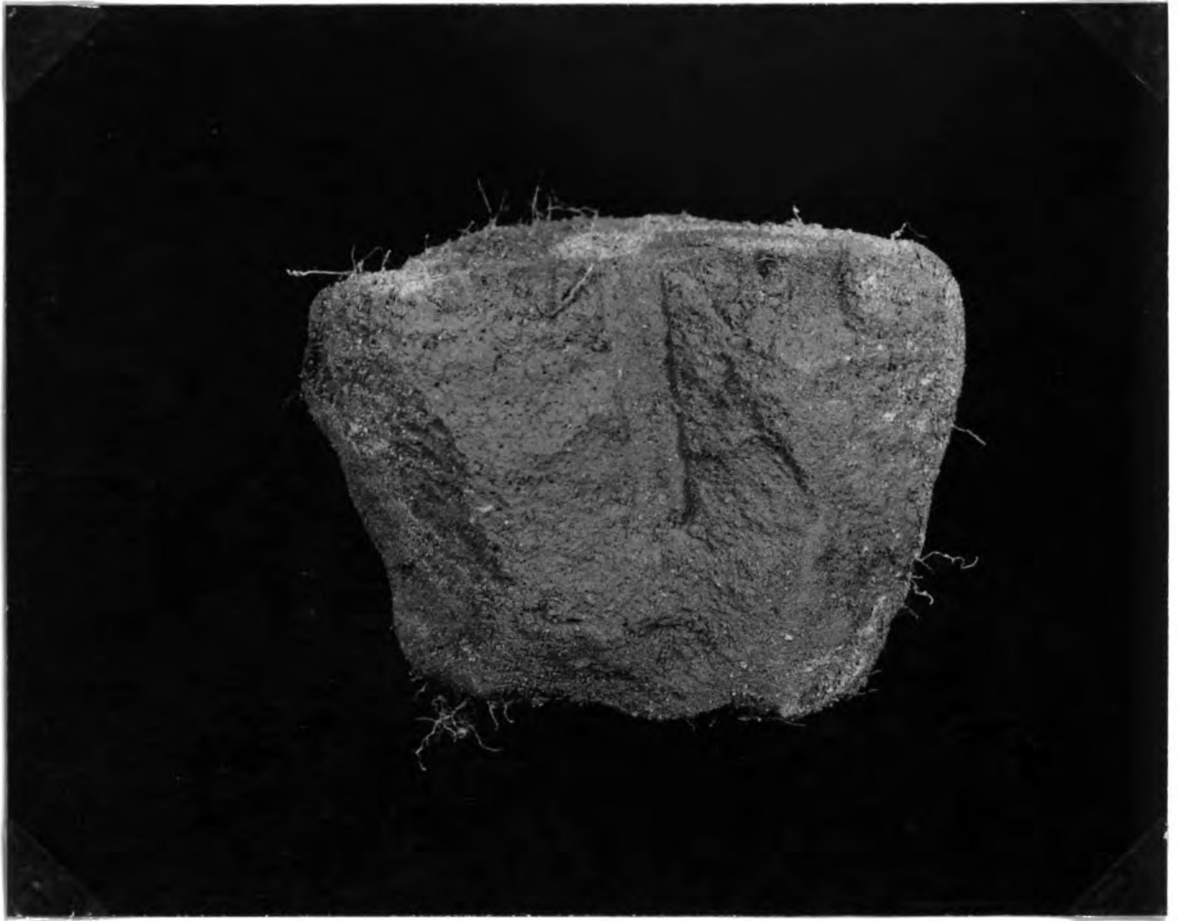


Fig. 12. Cross section of unaerated soil-sand core
(Note very shallow penetration of roots on
all sides of core¹)

¹ Alfalfa roots were permitted to grow in the sand on all sides of the cores so that penetration might occur anywhere on the surface.

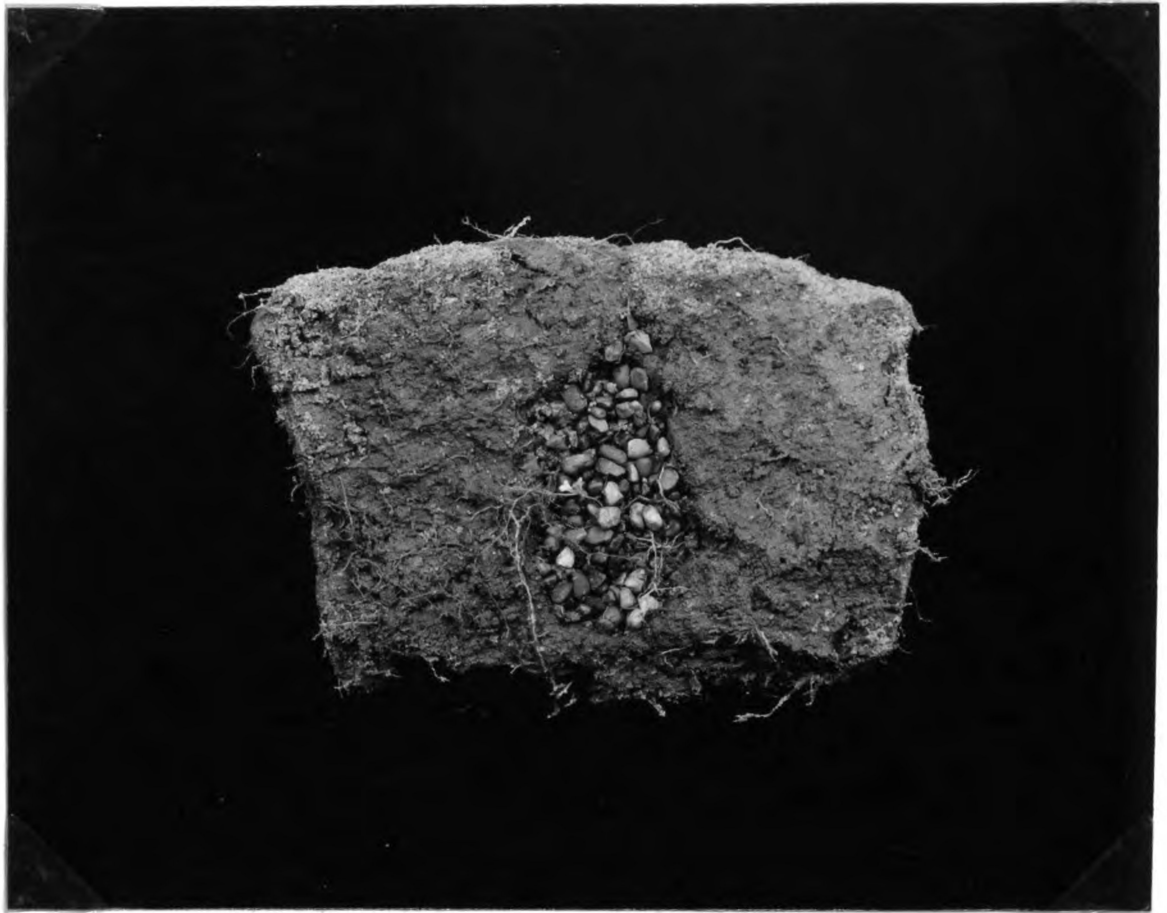


Fig. 13. Cross section of aerated soil-sand core
(Note nodule in coarse gravel in center)

and extent of rooting, but there was evidence to show that the effect of puddling was so pronounced that any influence of the constituents of these artificial cores was masked. It is assumed that aeration conditions were more favorable in those cores in which large pores were found.

In order to check the efficiency of the method of irrigating the soil cores, duplicate moisture determinations were made of the unaerated cores at the time of root examination, as was mentioned earlier. The

results of this study, together with the moisture equivalents of the same mixtures are presented in Table 2. With the exception of the 1/3-2/3

Table 2. Per cent moisture in artificial unaerated cores at conclusion of experiment

Mixture of soil-sand	Per cent moisture (by wt.)		Per cent moisture of moisture equivalent (approx.)
1/4- 3/4	10.9,	11.2	12.1
1/3 -2/3	11.3,	12.4	12.8
5/12-7/12	12.7,	13.7	12.3
1/2 - 1/2	12.9,	13.2	12.5

Moisture equivalent determined at pF 2.6

core, there was a tendency for high moisture values to be associated with higher moisture equivalent, but further data concerning this core (Fig. 21) have shown it to be somewhat abnormal. It is therefore believed that moisture conditions were maintained uniformly in all cores of this series, with approximately 1 per cent variation between duplicate cores.

Aerated Cores

In contrast to the absence of rooting reported in all unaerated cores, it was noted in all those receiving aeration treatment, that there was a luxuriant development of roots as is shown in Fig. 13. Since the only difference between this series and the unaerated series was the use of artificial aeration, it seems reasonable to conclude that the differences in rooting were associated with that factor. As far as it was possible

to determine, the puddling was similar to that in the unaerated cores. At no time during the course of the investigation was the sand surrounding the cores allowed to become dry, for, although water was applied less heavily than in the unaerated series, it was put on more frequently; hence it is not likely that the moisture content of cores in this series differed significantly from those in the unaerated series.

After making detailed observations of the extent and habit of rooting under the different aeration treatments, it was apparent that the lowest treatment (300 ml. daily) was equally as effective in stimulating the development of roots as were the higher degrees of aeration. Some conception of the ramification of fine roots can be obtained from Fig. 14.

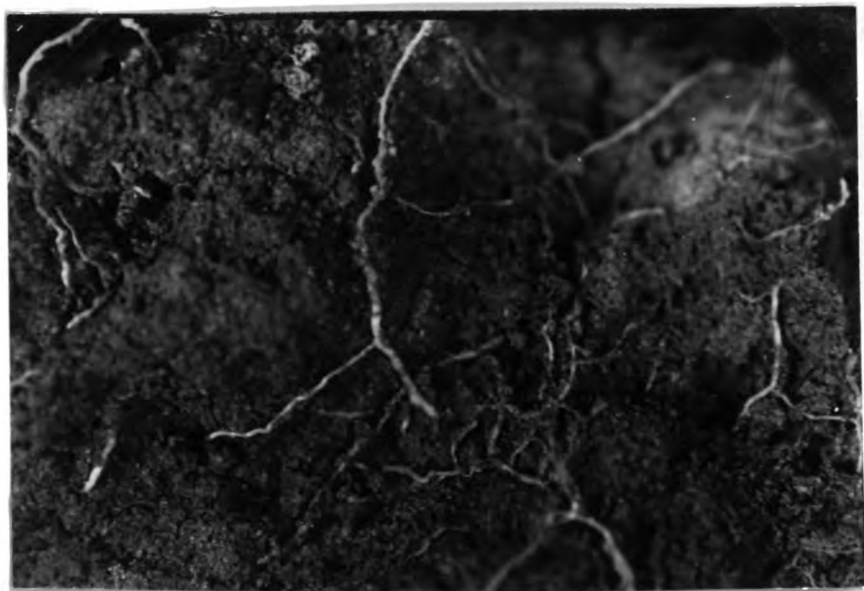


Fig. 14. Ramification of roots as a result of aeration

As compared with roots from unaerated cores, these were larger in diameter, more freely branched, and possibly whiter in color. There was an abundance of root hairs near the root tips wherever the roots entered one of the larger pores, which according to the investigations of Snow (18), is an indication of satisfactory aeration conditions.

Since no detectable differences were noted in root response to the different degrees of aeration, and since the sampling of roots for dry weight or length determinations seemed to present many possibilities for error, it was decided to resort to chemical measurements of the effect of aeration. Providing the lowest rate of aeration was insufficient to meet the needs of the plants, it seemed reasonable to expect that nitrification would be greatest under the higher aeration treatments. The data presented in Table 3 would seem to show that the higher degrees of aeration had caused

Table 3. Effect of Aeration upon Nitrification

Aeration from center of core (ML. per day)	Nitrates ¹ ppm.
300	6-12
600	10-15
900	10-20
Aeration from below	
300	6-10
600	10-15
900	15-20
Check (Unaerated)	5-10

¹ Nitrogen determinations made by Simplex Rapid Method

significantly large differences in nitrification to warrant conclusions concerning the effect of different rates of aeration. Although duplicate determinations were made, it is considered that the range of readings for each treatment is too great to indicate more than a tendency for nitrification to be related positively to degree of aeration. It can be stated, however, that higher degree of aeration has tended to stimulate microbiological activity more than the lower treatments, and it seems reasonable that there should be a similar relationship between aeration and root growth.

Moisture determinations were not made as in the unaerated series, and it can only be assumed from the results with unaerated cores, that there was no greater fluctuation than is shown in the moisture values in Table 2. It was realized, however, that a luxuriant development of roots in this series must have required a considerable volume of water, and it is not known whether or not the passage of water through the soil was sufficiently rapid to maintain moisture conditions relatively constant. This is an important consideration in view of the fact that lower soil moisture values within the cores would make conditions for rooting more favorable. At the time the experiment was in progress, it was considered that the maintenance of a continuously high moisture content in the surrounding sand would be sufficient precaution in moisture control.

DISCUSSION OF ROOT STUDIES

As far as root development in undisturbed soil cores is concerned, it appeared that penetration of roots was favored by well-developed cleavage planes, root and worm holes, minute channels, and other natural passages through the soil. It is valuable, in this connection, to compare the behaviour of alfalfa roots in soil with that noted by Thornton (35) with nodule bacteria in agar culture. It is reported that the most efficient nodules (those most active in nitrification) developed at the surface of the culture or at some point where shrinkage or cracking of the agar permitted free access of air. Plants with nodules embedded in agar grew very poorly and gained no nitrogen, but the same plants were apparently stimulated to new growth when cracks occurred in the agar, thus exposing the nodules to air. It is considered that similarly favorable aeration occurred in undisturbed soil along cleavage planes and other natural passages, while conditions within the soil clods, or in the poorly developed cleavage planes, were not suited to the growth of nodules.

In the more compact subsoils investigated, it is probable that deficient aeration has not been the only factor limiting root growth, since the gnarled and tortuous nature of roots found in such soil indicated that it was difficult for the roots to penetrate it. It should be mentioned, however, that white roots were found, even within the soil clods, in all but the most compact of the soils studied in the greenhouse (Cherry orchard 24-32 inches), but there was little penetration beyond 2 inches from a cleavage plane. It would be interesting and informative to apply aeration to some of the undisturbed soil from these compact horizons and also from

tight A horizons in future studies. It is noted that Heinicke and Boynton (12) by aerating the subsoil of a Dunkirk silty clay loam in New York obtained significant responses in tree growth, leaf area, shoot growth and in gain in cross section of trunk. It is not stated whether or not root development was improved by this treatment, but it can be inferred from the higher oxygen concentrations that there was an effect upon roots also.

When it is recalled that most of the non-capillary pore spaces of compact horizons found in nature appear to have been filled with colloidal material from the upper horizons, it is conceivable that aeration conditions may become definitely unfavorable for root development, especially under high soil moisture, since a slight excess of water above field capacity is sufficient to displace the air from the limited volume of pores that remain.

The influence of aeration in stimulating root development in artificial soil-sand cores is unquestionable. As was stated earlier, alfalfa plants have high oxygen requirements, in which they are believed to resemble certain of our tree fruits, and the profuse ramification of roots indicates a favorable response to such conditions. The fact that artificial aeration was necessary in order to obtain vigorous root development in these mixtures is strong evidence of the fundamental importance of aeration in permitting root penetration in the undisturbed soil cores studied. It is further indication of the general necessity for air exchange in the development of roots of other plants of similar oxygen requirements.

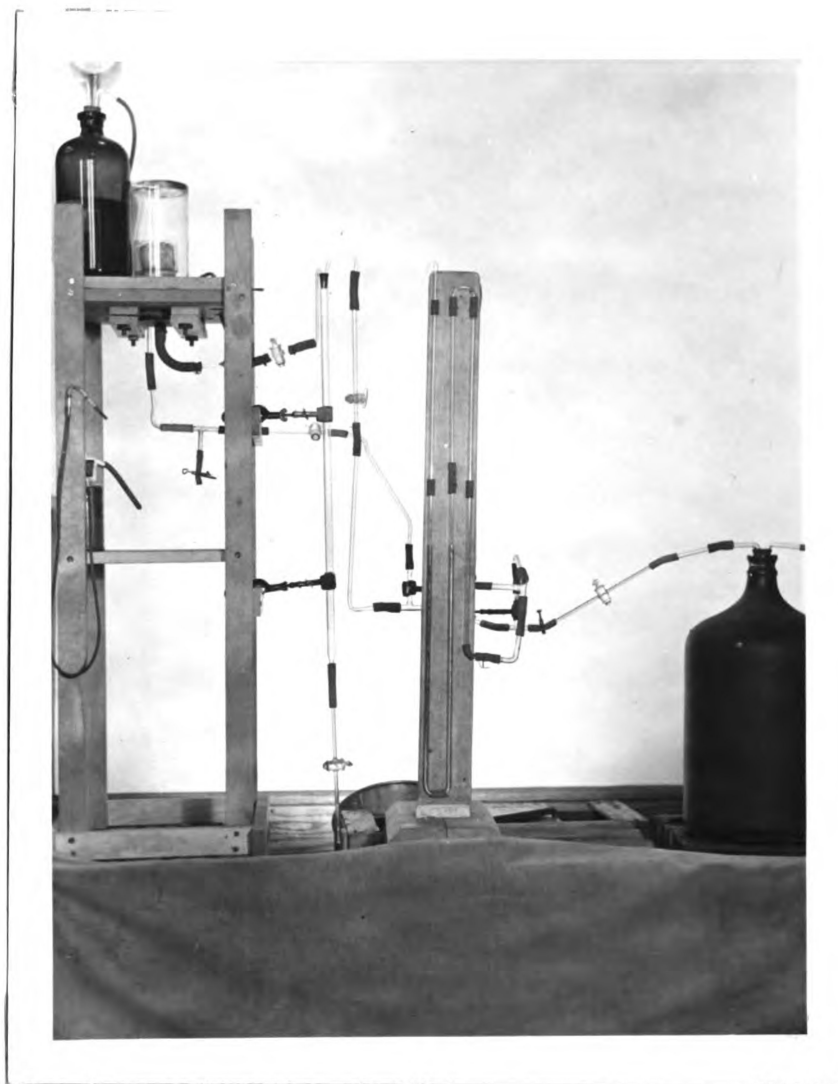


Fig. 15. Apparatus for measuring volume of pores evacuated at different tensions.

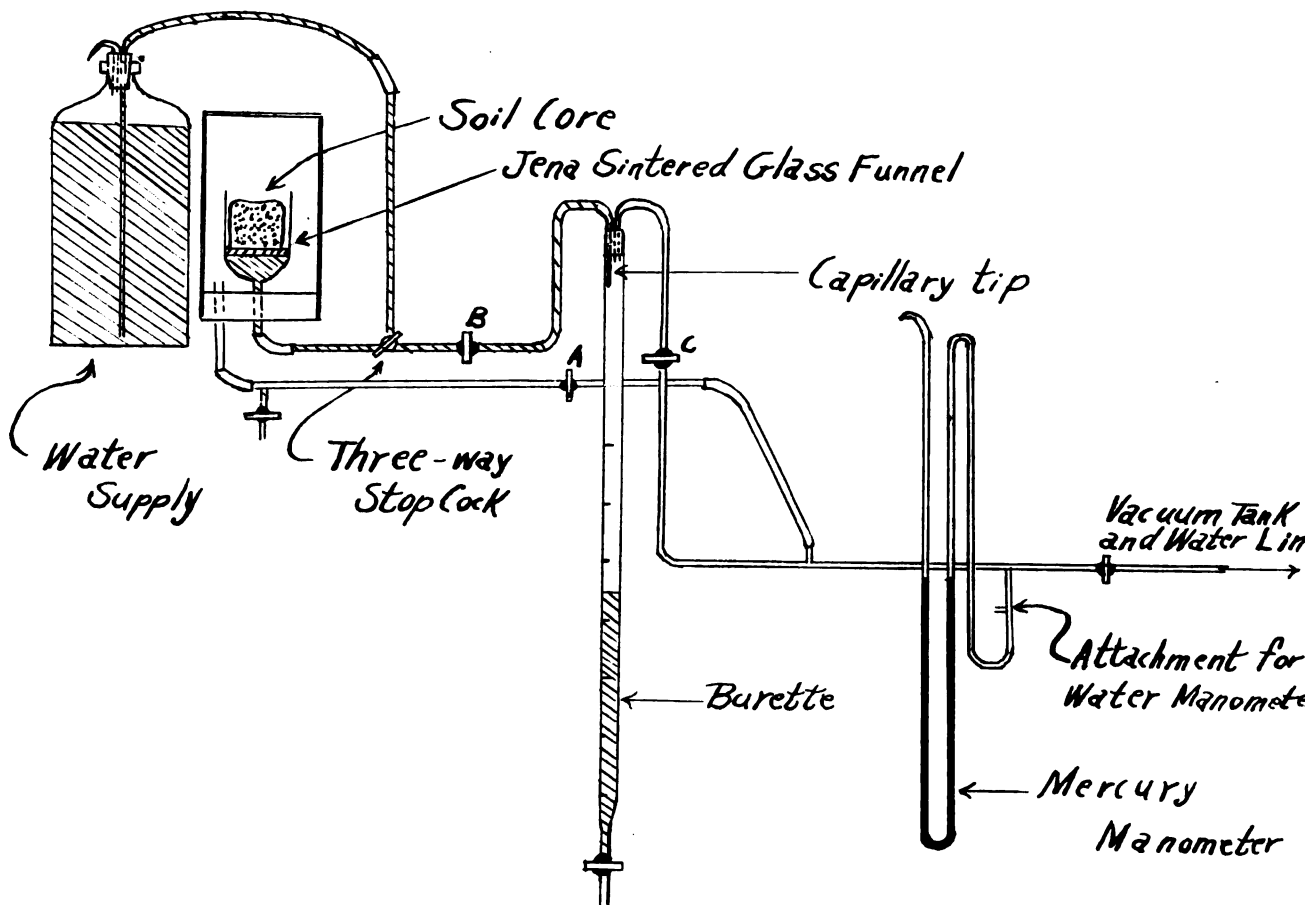


Fig. 16. Sketch of apparatus for measuring volume of pores evacuated at different tensions.

POROSITY DETERMINATIONS

Procedure

The apparatus used for porosity determinations is similar to that described by Bradfield and Jamison (5), differing essentially in the method of controlling tension in the position of the burette. The apparatus designed for this study is represented in Figs. 15 and 16. Essentially it consists of a porous plate fused in the bottom of a straight-walled glass funnel, the lower face of the plate being in contact with a free water surface. The connection between the moisture in the

soil and this free water surface is continuous through the porous plate. Water removed from soil placed on the plate is allowed to collect in a burette where it can be conveniently measured. The partial vacuum is produced by a water pump connected through a vacuum tank to a sensitive manometer. In making water extractions at low tensions, it was found necessary to use water as the manometer fluid in order to adjust the tension accurately. It was found desirable to have the water manometer on the one side of the stand and a mercury manometer on the other.

The most important part of the apparatus is the porous plate or membrane in the base of the funnel. In this study, a Jena sintered glass plate supplied by the Coors Company was used. According to specifications, this plate consists of a thin layer of sintered glass of 5 porosity over a layer of 3 porosity, the pore diameters of the entire plate ranging from 1.0 to 1.5 μ . Water is held in these small pores with such great force that it is supposedly possible to exert tensions of 60 cm. of mercury (810 cm. of water) without air passing through the plate. It was not possible, however, even with prolonged boiling in water to use tensions above 36 cm. of mercury without leakage of air. Since a tension of 30 cm. was sufficient for the purposes of this study, the plate proved to be entirely satisfactory, and it had the advantage of permitting rapid percolation of water. Tensiometer cups were not found to be practical for this study on account of the extremely slow movement of water.

In conducting studies of pore space of sand or pulverized soil, a given volume, about 200 cc., is placed in the funnel and a tension of 20 to 30 cm.¹ is exerted in order to remove the air from the internal pore spaces.

¹ cm. refers to height of mercury column.

After extracting at this tension for 5 minutes, boiled distilled water from the reserve water supply is slowly drawn through the porous plate by opening the three-way stop cock, and stop cock A, and closing B and C. The tension is continued in order to insure complete wetting of the soil and filling of all air spaces with water. When the water has completely covered the soil, the flow of water is closed off, and after standing under tension for a few minutes, it is assumed that all of the pores have been filled with water.

When a determination of pore spaces evacuated under the force of gravity is to be made, drainage of water is checked by closing stop cock B at the moment the free water disappears from the surface of the soil, and a reading of the burette is made. A second reading is made when no more water drains from the soil under gravity, and it is considered that this volume represents the gravitational or free water. This extraction is probably of little significance when pulverized soil is being studied because the natural structure has been largely deranged and the volume of free water would be of no significance. With undisturbed soil cores, however, such a determination is of considerable significance because it is a measure of the volume of the larger pores, and it is these which are of most significance in aeration. It is probable that root and worm channels, natural fissures and cracks, and the major portion of the larger pores are at least partly drained in this extraction, and that they are almost completely drained under a tension of 1 cm. In the case of corundum and 40-20 mesh sand, it is noteworthy that the volume of pores drained at zero tension amounted to only 0.2 and 0.6 ml. respectively, as shown in Fig. 18, while in some of the undisturbed cores, it amounted to as much as 2 ml. The volume of the pores evacuated under the force of gravity has

been recorded in the moisture-tension graphs as a solid horizontal line just above the base line. In this study, the force of gravity has been represented graphically as zero tension, so that in making comparisons between these data and what have been obtained by other investigators, it is necessary to make a small correction since the tensions herein reported are about 0.2 cm. greater than the actual force of gravity. Bradfield and Jamison (5), for instance, place the graduated pipette on the same level as the upper surface of the soil; with such apparatus, it is necessary to exert a slight tension to remove the water which in this study was removed under gravity.

After extraction under gravity has been completed, successive tensions are exerted, and the volume of water evacuated at each increased tension is recorded. The width of the tension classes (0-0.4 cm., 0.5-0.9 cm., 1.0-1.4 cm., or 1.0-1.9 cm.) must be decided by the nature of the soil as is discussed below. Moisture-tension curves can be constructed more accurately when narrow tension classes are used, and this is especially important in plotting the horizontal portion of the curve, as illustrated in Fig. 18. It is unnecessary, of course, to make more than 2 determinations in order to plot a straight line, so that some conception of where the lines are likely to change direction is valuable. In the case of the 40-20 mesh sand, for instance, it was necessary to make extractions at tensions of 0.5, 0.8, 0.9, 1.0, 1.4, 1.8, 2.5 and 30.0 cm. in order to construct the curve accurately, while with some of the samples of finer texture, it was sufficient to make extractions at tensions of 1.0, 2.0, 3.0, 4.0, 5.0, 10.0, 20.0 and 30.0 cm.

In preliminary trials with the apparatus, some difficulty was experienced in determining whether or not extraction at a given tension was complete. The capillary tip at the top of the burette affords a rapid and simple test, for by exerting a slight pressure on the connecting rubber tube, and then releasing the pressure, a small bubble of air appears in the capillary glass tip. If equilibrium has not been reached, this bubble is soon forced out into the burette, and extraction must be allowed to continue further. The danger of incomplete extraction of water is especially great when heavy soils are being studied, since the rate of water movement is very slow owing to the minute channels through which the water must move.

Some important modifications of the above procedure must be introduced when undisturbed soils are under consideration, for it would be hardly possible to prepare a core which exactly fits the funnel. Bever (4) describes a core sampler which permits the insertion of a brass cylinder within itself; after taking the core, the cylinder containing the soil column is clamped onto the porous plate. Such methods of core sampling can only be used, however, when the soil is free from gravel, roots and other such coarse material. In the soils under investigation, small stones occurred frequently, so that it was necessary to shape the cores with a knife; such a procedure also eliminated the danger of compacting the cores during sampling, a precaution which is especially important in this study, since it is the larger pores that are most affected by such compaction.

In preliminary trials, undisturbed cores were used without covering of any kind. It was found, however, even when water was introduced quite slowly into the funnel, that slaking and erosion occurred on the surface of the cores, and an accurate measure of the volume of pores drained at each

tension was impossible. There was also the disadvantage that it was never possible to calculate the exact volume or weight of the core after material was lost from the surface.

It was found that, by covering the base and sides of the core with a single layer of cheesecloth with as little overlapping as possible, the error caused by slaking and erosion could be eliminated. Since a considerable amount of water is retained by the cheesecloth after saturation of the core with water, it is necessary to make a correction for the volume of water removed from the cheesecloth at each tension. This was done by covering waxed soil cores with the same piece of cheesecloth and making triplicate determinations of the water drained from the cheesecloth. By this procedure, it was found that an accurate correction could be made for water removed from the cheesecloth at tensions above zero, but there were variations of 0.1 to 0.3 ml. on draining under gravity. It is assumed that this variation is the error inherent in the method of measuring gravitational water and that no greater error is introduced when the undisturbed soils core is used. Further, it is not likely that the error involved in the use of the cheesecloth is as great as the error of sampling, since a single root or worm channel in the core could easily cause a variation of several times this amount.

In conducting a pore space determination of an undisturbed soil core, all changes in tension must take place gradually in order to prevent derangement of the natural structure. When air is removed suddenly from the core, there is danger of fracturing the walls of the pores owing to the sudden release of air from isolated pores. Likewise, water must be admitted slowly in order to prevent similar alterations in structure, especially in soils of unstable aggregates. Both the period of extraction of air preceding saturation with water, and the period of wetting must be extended

somewhat longer in the case of undisturbed cores than when pulverized soil is used, and especially when compact subsoil is being studied.

In order to measure the volume of the pores evacuated under the force of gravity, it is necessary to remove the water from around the core as quickly as possible so that any free water in the large pores or cracks in the soil does not drain into the funnel before measurement of water in the burette has begun. By connecting a rubber hose and drainage bottle to the tension line (illustrated in Fig. 15), it was possible to remove almost all the free water from around the core in less than 5 seconds. Determination of the volume of pores extracted at each increased tension was made as in the case of the pulverized soil.

After extraction of water was complete, all cores were weighed and a determination of volume was made by dipping the cores in melted parawax at 70° C. and then measuring the amount of water they displaced on immersion in water. The parawax was heated until soft, and it was possible to remove it without removing soil from the core. A determination of dry weight was then made by heating in the oven for 24 hours at 97° C. and all moisture percentages were based upon this oven dry weight.

Expression of Tension

The relation of moisture content to tension can be plotted graphically without converting the tension values in centimetres of mercury or water to logarithms, but the space required for such a representation makes this method impracticable when a wide range of tensions is considered. By using the logarithm of the capillary potential, pF, it is possible to represent moisture-tension curves on one graph which covers a wide range of tensions. The term pF was introduced by Schofield (16) to express the logarithm of the height in centimetres of the column of water that is

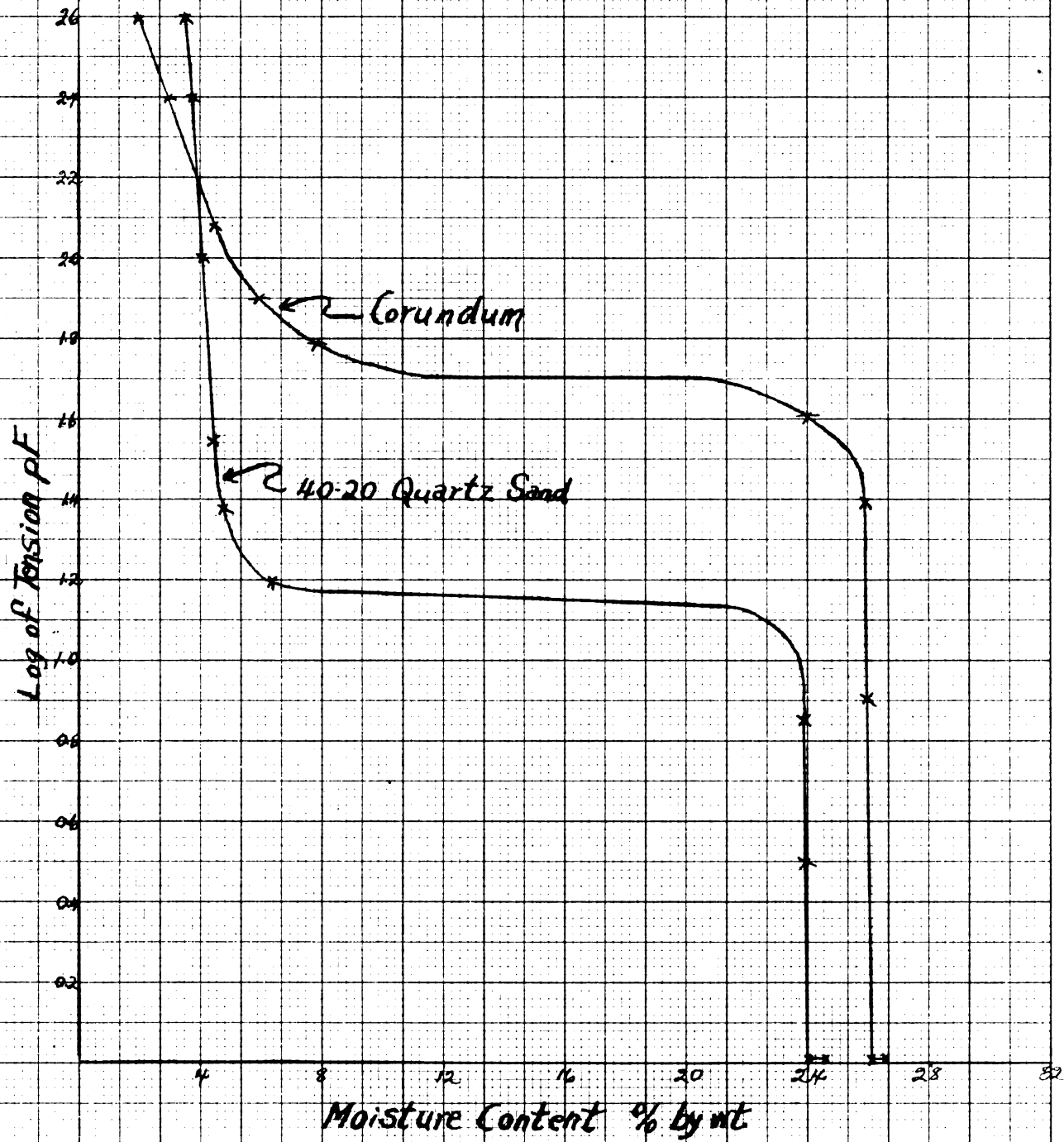


Fig. 18. Moisture-tension curves for corundum and sand.

necessary to produce the desired suction or tension. For example, a force which supports a column of water 1000 cm. high is said to have a pF of 3 since the logarithm of 1000 to the base 10 is 3. Similarly a column of water 10 cm. high must be supported by a force whose pF is 1, since the logarithm of 10 is 1. Forces measured by mercury columns can be converted to equivalent water columns by multiplying the height in centimetres of mercury by 13.54. The relationship of the height of mercury and water columns to pF is illustrated by the graph in Fig. 17.

The greatest tension at which water was extracted in this study was pF 2.6, which, according to Russell and Richards (15), is only slightly below the pF of the moisture equivalent.

According to Bradfield and Jamison (5), the diameter of pores evacuated at a given tension can be calculated from the formula $d = .30/h$, where h represents the tension in centimetres of water. For example, at a tension of 60 cm. of water, it is considered that all pores are drained which have effective diameters larger than 50μ . From the curves of Fig. 18, it is seen that pores in corundum are largely about 60μ in diameter, while those of the 40-20 sand are largely in the 270μ class.

Significance of Moisture-tension Curves

Curves for corundum and sand have been presented for the purpose of illustrating the significance of certain characteristics of moisture-tension curves. The short horizontal lines, to which reference has already been made, indicate that the volume of pores drained under the force of gravity is relatively small. The nearly vertical lines show that there are few pores in the corundum above 60μ and above 270μ in the sand, and a

large number of the pores fall within relatively narrow class limits. For the purposes of this study, the portion of the curve above the flex point (the more or less horizontal portion of the curve at the point where it begins to swing upwards) is not of much significance since it has already been well established (4) that it is only the non-capillary pores (those evacuated from zero tension to the pF of the flex point) that are instrumental in soil aeration. On the other hand, when soil moisture movement is considered, these small pores may have considerable significance.

As far as this study is concerned, the volume of the pores drained under the force of gravity, and from zero tension to pF 1.0 and perhaps the height of the flex point, are considered to have special significance in indicating or measuring the aeration capacity of soils. It is evident that the length of the horizontal line, together with the slope of the curve from zero tension to pF 1.0 is also a measure of the volume of pores which contribute towards aeration. Paver (1) has found that the tension of the flex point, and the volume of water removed from zero tension to the pF of the flex point, have considerable influence upon the rate of permeability of water. The lower the pF of the flex point, and the larger the volume of pores drained at low tensions, the greater was the permeability, and since aeration and rapid permeability of water are conditioned by the same or similar factors, it is quite possible that these characteristics of moisture-tension curves are also indicative of the aeration to be expected in a soil in which free drainage is permitted. In this study, special emphasis has been placed upon the volume of pores drained from zero tension to pF 1.0 since pores drained at tensions above this point are too small to influence aeration to any considerable extent, even when moisture conditions are optimum.

Owing to the length of time required to make pore space measurements by this method, it was impossible to make more than one determination with most of the soil cores. The characteristics of the entire moisture-tension curve are interesting, but it seems probable that the careful determination of that portion of the curve from zero tension to pF 1.0 by decreasing the interval between determinations, and representing this portion in detail on the graph, would give a better representation of the aeration characteristics of a soil; measurements at higher tensions could then be omitted.

Porosity Studies of Undisturbed Cores

The moisture-tension curve of the core from the A horizon (Fig. 19), is similar to that of the 1/3-2/3 soil-sand mixture. The small volume of pores drained under the force of gravity, the nearly vertical nature of the curve from zero tension to the pF of the flex point, and the high pF of the flex point, are all factors which would indicate that the structure of this soil is unfavorable for root development. As was mentioned earlier, an inspection of this core revealed very few root or worm channels, the absence of fissures and cracks, and very few pores, either large or small, and these observations were confirmed by the pore space measurements.

Moisture-tension curves of undisturbed cores from three soils are presented in Fig. 21. In the case of the cores from the 16-24 inch horizon of the cherry orchard, and the 32-40 inch horizon of the pear orchard, there was a considerable drainage of pores under the force of gravity, and from zero tension to pF 1.0. Further, the pF of the flex point was very low in both soils (about 0.9), all of which are believed to be favorable to aeration and root penetration.

The heavy silty clay soil has certain characteristics, notably the tendency to swell on wetting, which make this method of measuring pore space of questionable value for such soils. Soil pore space is a dynamic property, owing to a large extent to changes in moisture content. When such highly colloidal soils become saturated with water, either under natural or laboratory conditions, not only do the larger cleavage planes and pores become filled with water, but there is also a decrease in the volume of these spaces. Hence, on measuring the volume of pores drained at a given tension, it is found that the results are considerably lower than expected from observations made on the soil in the dry state or at the time of sampling in the field. It is the author's opinion, and likewise that of Bever (4), that a measurement of the volume of pores in a soil in the swollen condition more closely represents the conditions in the soil, especially in spring when moisture is high in the available range, and when most of the root growth occurs.

The small volume of pores drained under gravity and the vertical nature of the curve from zero tension to the pF of the flex point, are indications that this is a soil of poor internal drainage, yet the considerable degree of rooting observed (Fig. 13) would seem to show that this is not the case.

It is noteworthy that in this soil, a considerable time was required for equilibrium to be reached at each tension. In making the extraction at pF 1.4, for instance, it was necessary to continue the tension for $2\frac{1}{2}$ hours in order to obtain complete drainage of pores. The small size of the pores retards the rate of movement of water through the soil, so that it was found impracticable at tensions above pF 1.4 to attempt to obtain complete extraction at any given tension.

Porosity Studies of Artificial Soil-sand Cores

An inspection of the curves presented in Fig. 20 shows that there was considerable variation in the pore space relationships in the artificial soil-sand cores, and, as was mentioned earlier, it would appear that the degree of puddling has had more influence upon the amount of moisture held at all tensions, and upon the pF of the flex points, than have the relative proportions of soil to sand. The 1/2-1/2 and 5/12-7/12 mixtures, have lower moisture values almost throughout the range of tensions, than have the 1/3-2/3 and 1/4-3/4 mixtures, and the pF of the flex points show similar discrepancies. It is believed that the degree of puddling has contributed largely to these variations, although it is possible that failure to permit complete saturation of the cores with water before applying tensions has also had an effect.

No porosity studies were conducted of aerated cores.

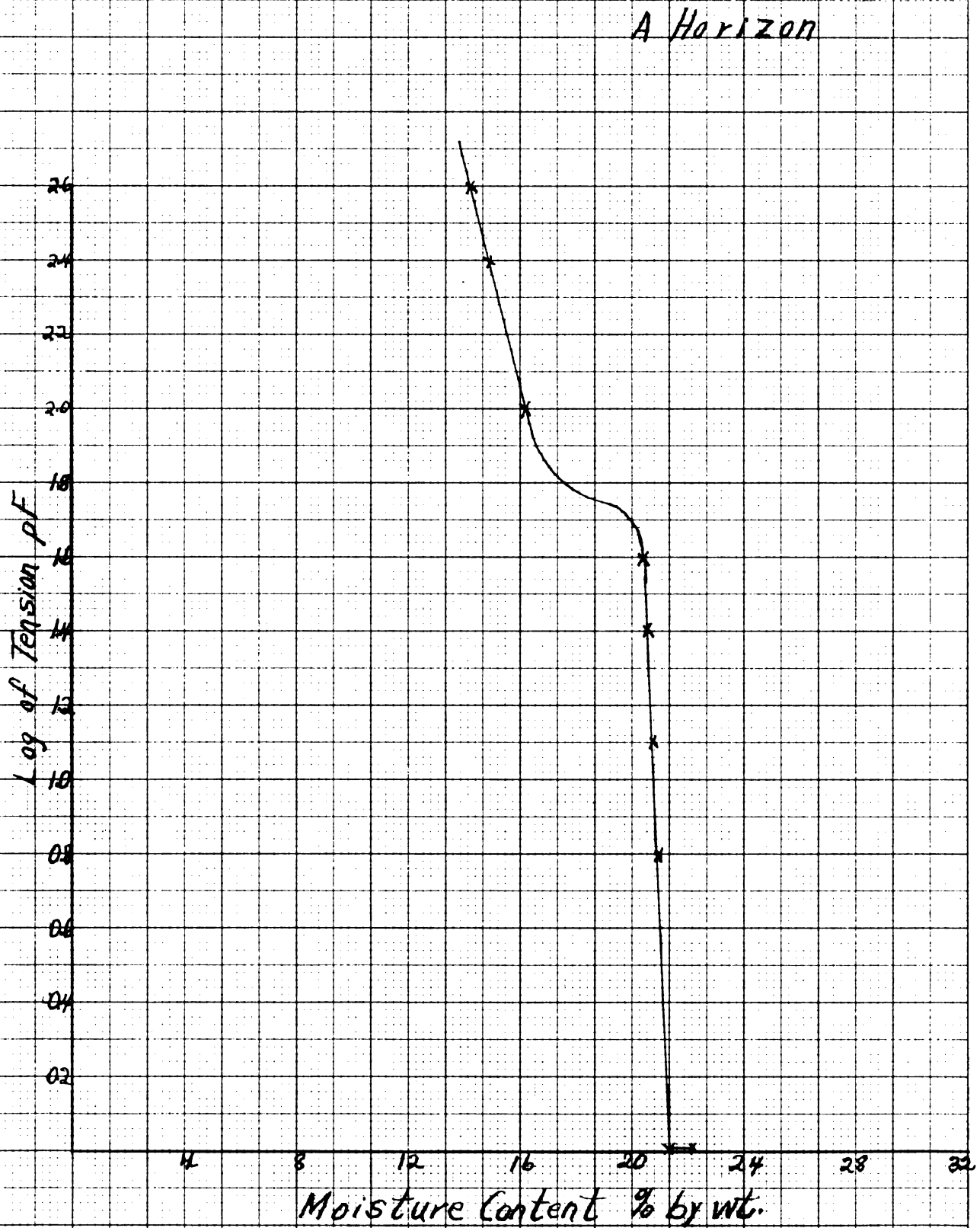
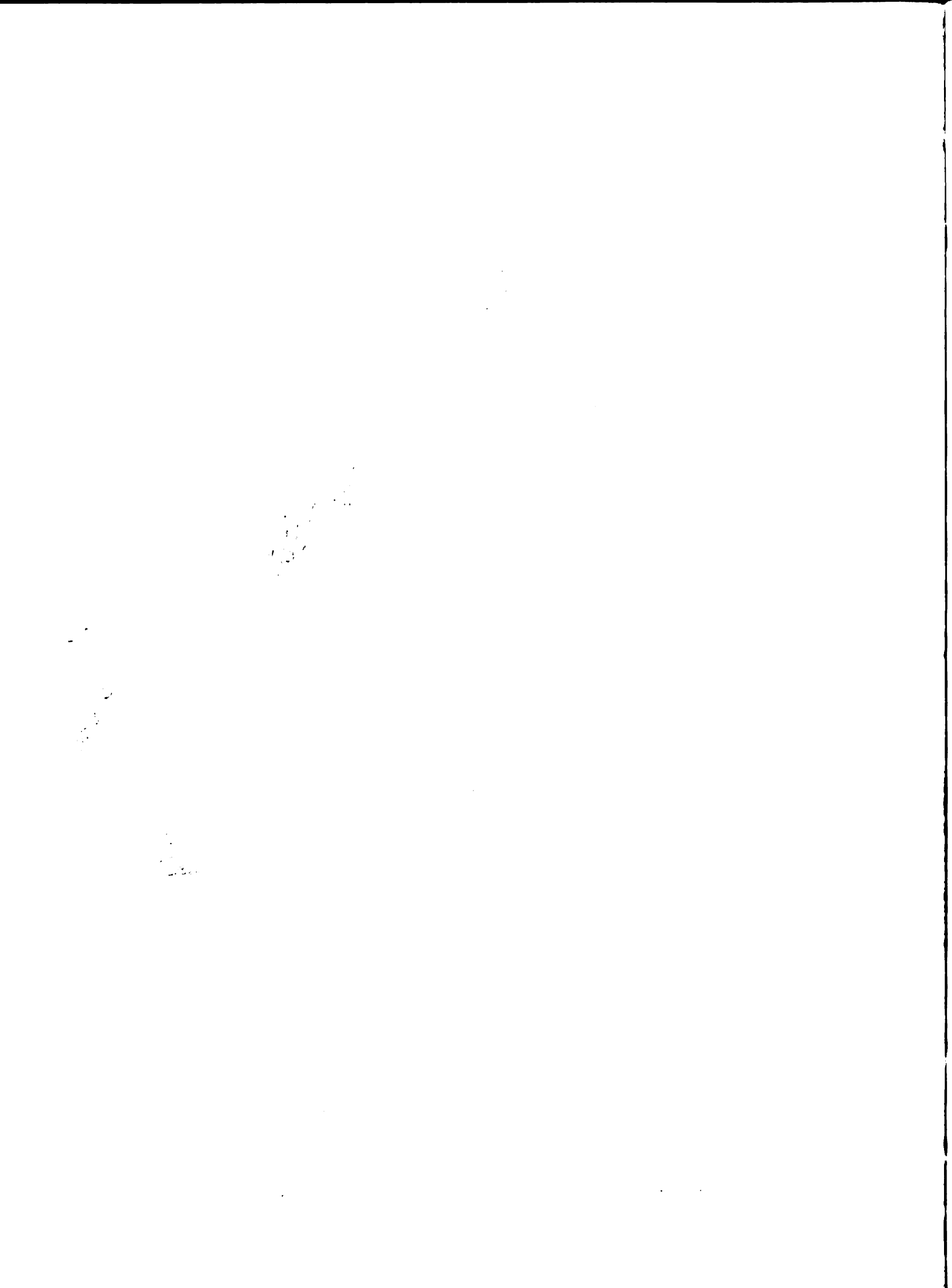


Fig. 19. Moisture-tension curve of A horizon.



DISCUSSION OF PORE POSITY DETERMINATIONS

Large differences were found in the total amount and size distribution of pores in the soils studied, as is shown in Table 4.

Table 4. Percentage of pores drained from zero tension to pF 1.0

Soil	Vol. of pores drained from zero to pF 1.0	Per cent of pores drained from zero to pF 1.0
Undisturbed		
A-horizon	1.9	6.8
Cherry orchard (16-24")	3.9	12.1
Pear orchard (32-40")	5.8	16.4
Heavy silty clay (32-40")	3.3	7.0
Artificial		
1/4 - 3/4	5.2	15.0
1/3- 2/3	4.2	9.2
5/12- 7/12	4.1	10.9
1/2 - 1/2	3.0	10.0

The small volume of the pores (6.8 per cent) drained from zero tension to pF 1.0 in the core from the A horizon, and the large volume of pores (16.4 per cent) of the same size from the 32-40 inch horizon of the pear orchard are noteworthy with respect to root response. When only undisturbed soils are considered, it is believed that differences between volumes of the larger pores were associated with differences in type and amount of rooting in the different cores. Although the small number of

cores studied does not warrant the statement of definite conclusions, still the differences between degree of rooting in the different types of soil and those illustrated in Table 4 concerning the volume of the larger pores would seem to be sufficient evidence for the existence of this association. Further, the absence of rooting in the unweathered core of heavy silty clay, and the very sparse development in the A horizon from the cherry orchard were associated with small volume of pore spaces of all sizes (as determined from observation), while in the weathered core of silty clay and in other cores in which minute pores and planes of cleavage could be detected, there seemed to be favorable conditions for rooting.

In the case of the cores from the A horizon, it is possible that the absence of connecting channels between the pores may be of even greater significance in determining root response than the small volume of large pores, since in this horizon only very few root and worm channels were observed, and there was a complete absence of cleavage planes. Owing to the fact that rooting in many of the other undisturbed cores was largely restricted to the natural channels in the soil, it is postulated that the presence of such connecting channels, by virtue of their effect upon water and air movements, may be of extremely great importance in determining the suitability of a soil for root growth.

In the light of this hypothesis, it is of interest to study the relationship between volume of pores drained from zero tension to pF 1.0 in the different artificial unaerated soil-sand mixtures and the absence of rooting in them. In the case of the $1/4-3/4$ mixture, there has been a drainage of 15 per cent of the pores which would seem to indicate that

aeration conditions were satisfactory for abundant root growth, yet this did not occur. Owing to the fact that the pores in the artificial soil-sand cores were largely isolated from one another, it seems reasonable to suppose that the absence of connecting channels between isolated pores has been responsible for relatively stagnant pockets of air. In all probability active microbiological development soon depleted oxygen supply of these pockets, and since there was no connection established with the atmosphere, the conditions for root development were decidedly unfavorable.

SUMMARY

Root observations of some Montmorency cherry trees growing in dense compact subsoil indicated that certain soil horizons were definitely unfavorable for root development. Freezing injury in January, 1940, was most severe where the surface soil was tight and somewhat compact, a condition which apparently allowed deep penetration of frost.

Rooting of alfalfa in undisturbed soil cores taken from these and other profiles showed considerable variation. Wherever cleavage planes or other natural passages were well-developed, conditions for rooting seemed to be favorable, as was indicated by the development of nodules and abundant lateral branching in such locations. Very sparse rooting was observed in the cores from the A horizon, and this is to be attributed to the small volume of non-capillary pores, and to the absence of connecting passages between pores.

Aeration was necessary, under greenhouse conditions, to enable alfalfa roots to penetrate artificial soil-sand cores, apparently on account of the high oxygen requirement of this plant, and the absence of connecting passages between isolated pores of the soil. Artificial cores had higher volumes of non-capillary pores than certain of the undisturbed soil cores, yet no rooting occurred without artificial aeration, apparently due to the lack of air exchange within these cores.

In many compact subsoils, lack of aeration in spring may be of greater significance in determining root behaviour of certain tree fruits than physical impenetrability.

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