Soil Aeration:

Introduction and Characterization Of Greenhouse Soils

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With few exceptions, the root system of every plant in a greenhouse bench has undergone one or more periods of insufficient oxygen supply. However, these periods are usually too short to cause a measurable crop response. Deficient aeration may be due to any combination of long or short periods of oxygen deficiency, and the dividing line between what constitutes deficient and sufficient aeration is obscure.

It is essential that we understand what factors influence oxygen supply in soil and learn what we can do to manipulate them in our cultural practices. Crop response must be the deciding criterion, since a well-aerated root medium does not mean that its use will invariably result in a satisfactory product.

Basis for research—The uptake of oxygen by roots is a continuous process (5), hence measurement of oxygen concentration in a soil is not enough (4). In addition, the rate of flow of oxygen to the root must be determined. This rate is directly regulated by the thickness of the water film which surrounds the root and across which oxygen molecules must diffuse (6, 8). Where the soil is waterlogged or possesses a very low porosity (less than ten per cent), the rate of supply may not always be controlled by film thickness (1, 8, 11). More often, oxygen concentration and supply is a function of moisture content and is related to the physical attributes of the soil (e.g. porosity, aggregation, pore-size distribution, etc.), its depth, the method of irrigation, amount of water applied, the plant, temperature and light intensity (6, 10, 12, 18, 20).

An inter-relationship exists between aeration and available moisture, both of which influence growth of the plant. There is little use in reducing moisture content to a point where wilting occurs for the purpose of improving aeration. Variations in moisture and oxygen supply either alone or in conjunction may drastically influence plant response. In the final analysis, the only definitive method by which a soil may be truly characterized is by growing a plant in it.

Main lines of research—The present investigation is long range and is purposely oriented toward an integrated approach to soil moisture and its effect on aeration as typified by crop response. The main divisions might be listed as: 1) characterization of greenhouse soils, 2) water requirements of floricultural crops and 3), experi-

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ments on methods of culture (e.g. effect of depth, method of irrigation, etc.). All three are proceeding concurrently; all are overlapping and difficult to separate. The authors wish to present in these reports some of the background supporting the investigation and an explanation of methods.

Definition of terms—Throughout this and following articles, terms will be used about which there may exist doubt or differences of opinion as to meaning. To avoid confusion, the authors include in each publication a short glossary of the more important terms encountered for the first time. (See page 10).

Characterization of greenhouse soils

Control of soil moisture—What factors determine the moisture content of a greenhouse soil? How may soil moisture content be regulated? There are two principal methods. One is to select a medium with a tilth such that sufficient water will be available for growth yet will allow rapid air renewal. A second method is to manipulate the depth of the soil.

Assuming for the moment that a root medium has been selected, what has depth to do with determining the moisture-holding capacity of a soil? In order to emphasize a point that people often forget, L. A. Richards (14) suggested that the "outflow law" be regarded as one of the basic laws of soil water. This "law" states that water will not flow out of a soil, wick or piece of blotting paper unless the pressure in the water is slightly greater than zero or atmospheric pressure. This is illustrated by a wick hanging over the edge of a vessel of water (Fig. 1). When the free end of the wick hangs slightly below the surface of the water in the container, water will drip from the end. When the wick's free end is slightly above the water level, the lower end will be quite wet, but will not drip. The critical point occurs when the two levels are the same.

As applied to a soil, the "outflow law" means that water will not drain from the bottom of a column (or bench) of soil into the atmosphere unless the water table in the soil is *above* the bottom of the soil column. Thus, a soil layer which has been thoroughly wetted and allowed to drain reaches a condition that simulates a water table at the base of the soil and remains that way unless further water losses ensue as a consequence of evaporation or removal by plants. In a small soil volume, evaporation losses may be relatively fast so that water content may continue to decline rapidly after drainage ceases.

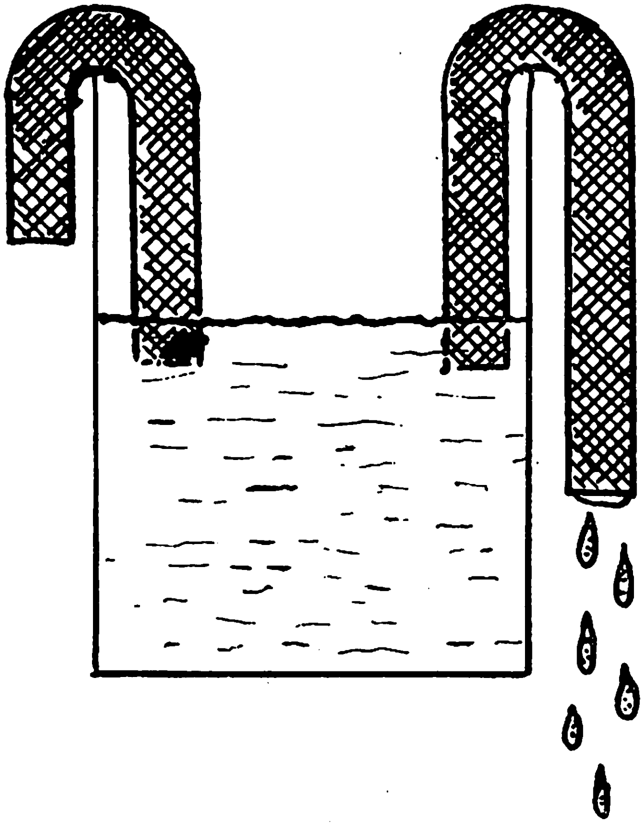

Fig 1: Demonstration of L. A. Richards's "outflow law." On the right side, the wick is below the water level in the container, and water drips from the free end. On the left, the wick is above the water level, and although quite moist, no water drips from the end.

In a greenhouse bench, there is an interaction between depth of soil and water content. When drainage ceases, the pressure in the soil water at the bottom is equal to the pressure in the atmosphere. An ordinary pressure gauge would record this as "zero" because it measures the difference between an unknown value and atmospheric pressure. Just as pressure *increases* with depth below the surface of the ocean, so it *decreases* with elevation of the soil water *above* the water table (i.e. the bottom of the soil). Hence, pressure of the water in a wick or in soil above the water table has a negative value, and this is often referred to as "soil moisture tension" or "soil suction" (10, 11) and avoids the use of negative terms that would be necessary if gauge pressure or hydraulic head are used. When a greenhouse bench has drained, the "tension" in the soil water at every point above the bottom of the column is equal to its height above the bottom of the column provided there has been no water loss from evaporation or removal by plants. In any freely draining soil, the water content will be at its maximum at the bottom and will decrease with elevation above the bottom. The deeper the soil; the lower will be the moisture content of the upper layers. L. A. and S. J. Richards (15), in the 1957 Yearbook of Agriculture, decribed a very effective demonstration for showing effect of depth. If a roll of cheesecloth is held up in the manner shown in Figure 2-A following saturation and until dripping has ceased; then allowed to hang free from one end (vertically) (Fig 2-B) drainage will resume.

Methods of relating water content, tension and depth—The relationship between water content and tension is called the *soil water characteristic curve* (13.). It is not necessary to use a long column to obtain this curve, in fact, it is much easier to do it with a small sample. The equipment used in this investigation (Fig. 3) is a modification of that employed by W. B. Haines (3), in 1930, and called the Haines apparatus.[1] Figure 4 illustrates the principle involved. Following standardized procedures, the soil sample to be studied is placed in a container, being supported by a filter permeable to water. The sample is filled with water from below. At the start, drip tube "A" is at "X" (Fig. 4), and the system is completely filled with water. Since the water meniscus at "X" is at

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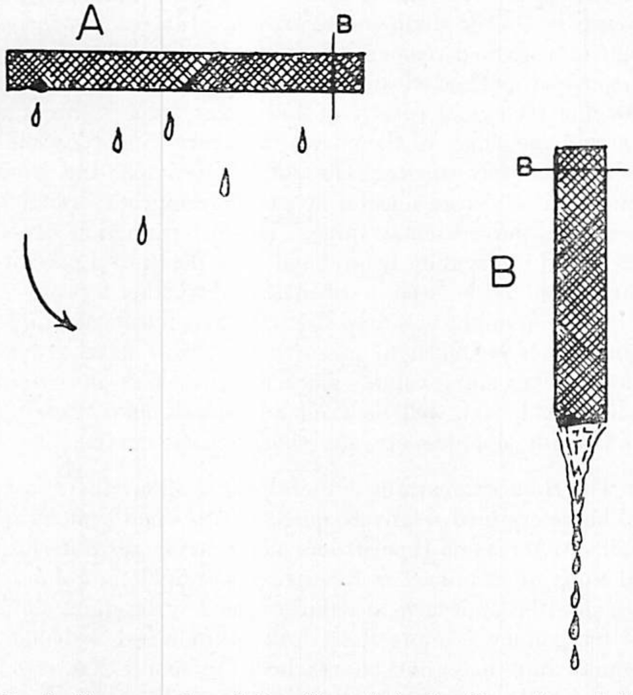

Fig. 2: Demonstration of the affect of depth with a cheesecloth. The cloth should be between 12 and 18-inches long and loosely rolled. At "A", the tube is supported at both ends with the fingers, saturated thoroughly in a pan of water, and held until dripping ceases. At "B", the end furthest from "b" is allowed to swing free.

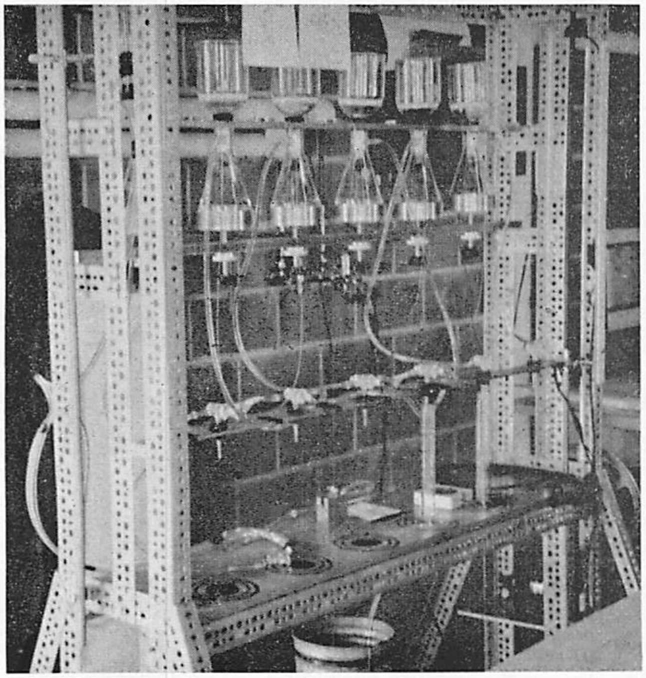

Fig. 3: The Haines apparatus for obtaining the soil water characteristic curve. Built for the Department of Floriculture with funds furnished by the Kenneth Post Foundation. The large beakers in the upper part contain the soil sample. The drip tubes can be seen projecting below the adjusting bar in the lower part of the photograph.

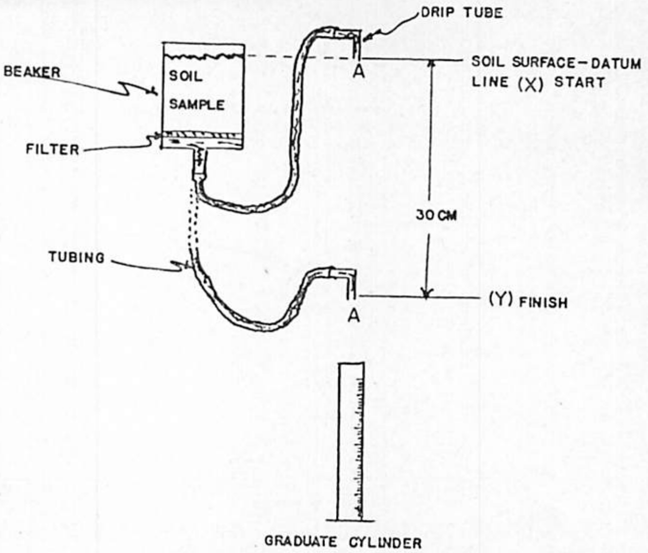

Fig. 4: Principle of operation of the Haines apparatus. At the start, the system is filled with water from drip tube "A" to the top of the soil sample. Lowering the drip tube increases the tension on the soil sample, and the water removed is measured in the graduate cylinder.

the same level as that in the beaker, the pressure is equal and no water flows from the drip tube. When the drip tube is lowered, the weight of the column of water literally "hanging" from the soil sample is increased and the amount removed at each increment in tension is measured in the graduate cylinder. The range of this apparatus is 0 to 65 centimeters, the latter being considered as representative of the arbitrary dividing line between non-capillary and capillary pore space in the field (2, 11, 16). Sixty-five centimeters is equivalent to 25.6 inches, far greater than any depth to be encountered in greenhouse benches.

Data obtained with three soils using the Haines apparatus are shown in Figure 5. In Figure 6, a different method of plotting for the 1-1-1 mixture shows more clearly the removal of free surface water, and the effect of tension on maximum water removal. The curves in Figure 5 simulate the relationship between water content and distance above the bottom of a soil column that would be expected if the soils were thoroughly wetted and allowed to drain without evaporation. These same data have been replotted to show the expected air content of the columns as a function of distance above the base in Figure 7. Note, that at the bottom the samples are practically devoid of air. A bench filled with the coarse sand to a depth of 6 cm, or with the fine sand to a depth of 16 cm, would remain essentially saturated even though the water was free to flow out of the bottom! By contrast, the 1-1-1 mixture would contain appreciable air all the way to the bottom for any depth of filling. However, if 10 per cent is taken as the minimum free pore space required for sufficient aeration, then a depth of 13 cm would be required. Ideally, to completely drain the 1-1-1 mix to a point where there is 20 per cent free pore space at the bottom of a 6-inch layer the depth would have to be increased to 16-inches—on obviously impractical suggestion.

The slope of the curves in Figures 5 and 7, and particularly Figure 6 for the 1-1-1 mix, shows that the majority

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[1] Funds for the construction of the Haines apparatus were provided by the Kenneth Post Foundation. In addition, the authors wish to emphasize, as well as express their appreciation of, the role played by Professors R. D. Miller and W. W. Gunkel (Departments of Agronomy and Agricultural Engineering). Dr. Miller originally suggested the use of Haines' method and has made substantial contributions to this article. Dr. Gunkel suggested the modifications incorporated in the present model.

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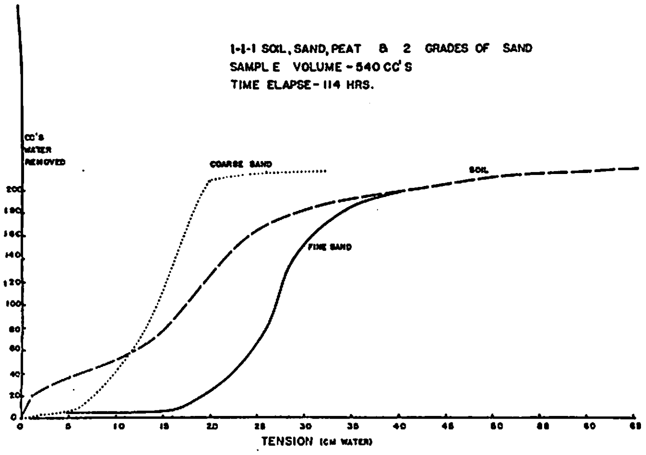

Fig. 5: Soil water characteristic curves for three media obtained with the Haines apparatus.

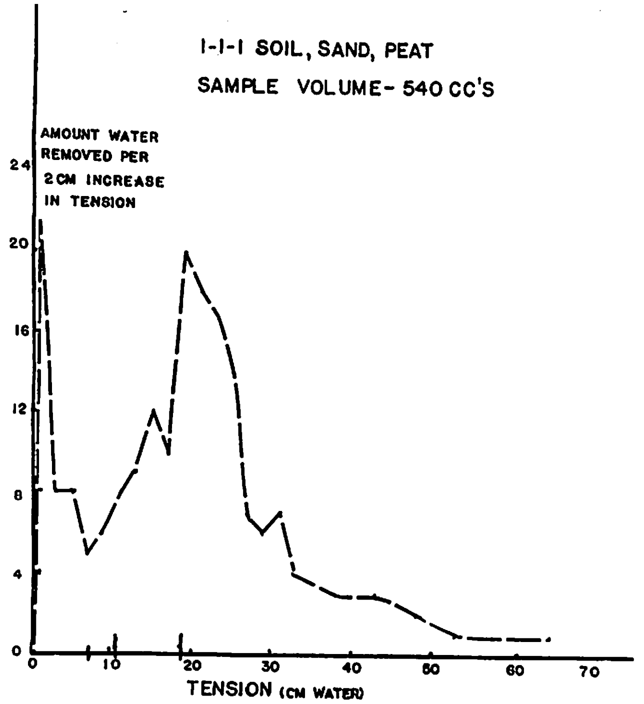

Fig. 6: The same data as shown in Figure 5 for the 1-1-1 mixture only plotted to show rate of water removal. The peak at 1 cm tension is the free surface water removed. The high peak at 19 cm indicates that a majority of pore spaces are of similar size.

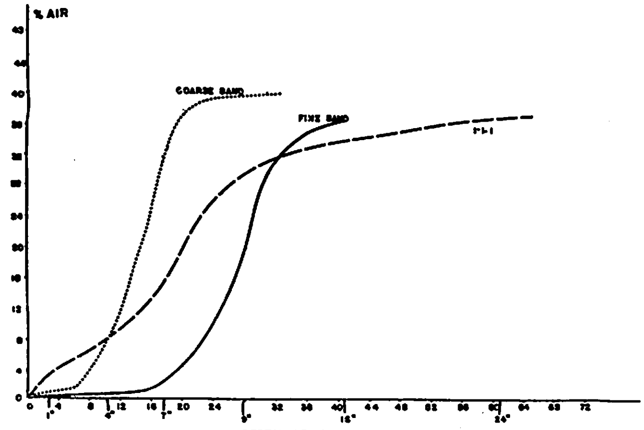

Fig. 7: Expected air content of three media as a function of distance above the bottom (depth).

of pore spaces in these media are concentrated about an average size, indicating that below a certain value of depth or tension the mixture will remain saturated or nearly so. Very slight increases above that value will result in a marked removal of water. If it were possible to remove all entrapped air from the sample, and to correct for the change in depth of the water level within the sample, the slopes of the curves in Figures 5 and 7 would be more nearly vertical. The authors designate the minimum soil moisture tension at which significant drainage occurs as the "air-entry value." This determination serves as an aid in deciding beforehand what depth of a particular soil should be used in a bench, and whether a problem of aeration might be solved by slightly increasing depth. It should not be taken to mean that all soils have a well-defined "air-entry value," since the pore sizes in certain soils could very well be randomly distributed, resulting in a gently sloping soil water characteristic curve.

The Haines apparatus is useful, for it allows these facts to be determined relatively quickly with small samples of soil. At the same time it does not provide accurate predictions of drainage as it might occur in long columns because the approach to equilibrium may be quite slow. If the column is more than three or four feet in length, equilibrium may not be reached for months, or even years, with some soils. In the meantime, evaporation losses are likely to become more important, and these cannot be anticipated by the Haines apparatus. Losses of water when plants are established in either a shallow or deep soil are highly dependent on the environment (12) and the stage of growth of the plant.

Some of the relationships of depth and evaporation are illustrated in Figure 8 and Tables 1 and 2. For these experiments, two depths of soil were used and three different mixtures. One plot was shallow, being only 6-inches deep (15.2 cm), while the other was 43.3-inches deep (110 cm). Both were wetted and allowed to drain. Tensiometers were inserted to observe the progress of drainage. Figure 9 is a photograph of the deep plot while Figure 10 indicates the depths at which the tensiometers were placed. In Figure 8, the curves show that equilibrium (i.e. tension=depth) was reached in a very short time in the bottom tensiometer. The depth was actually reduced 2-3 centimeters at the start of the constant water table, and this is indicated by the increase in pressure to 14 cm. which is equal to the height of the tensiometer above the water table. By contrast, those tensiometers more distant from the bottom took longer, and the top tensiometer had not reached equilibrium (106 cm) ten days after the start of the experiment. Table 1 shows that at the time of sampling, equilibrium had not been attained in any of the samples higher than 14 cm above the water table. Nevertheless, the relationship between depth, tension, moisture and air can be easily seen. In Table 2, the two different depths of soils are compared. The tensiometer readings are for those 106 cm from the bottom in the case of the deep plot (110 cm deep) and approximately 11 cm in the shallow plot (15 cm deep). Note that in the shallow plot evaporation in each case caused tension to exceed depth. But in two of the three mixtures the soils contained virtually no air. However while the deep plot had not completed drainage at the time of sampling all three mixes contained

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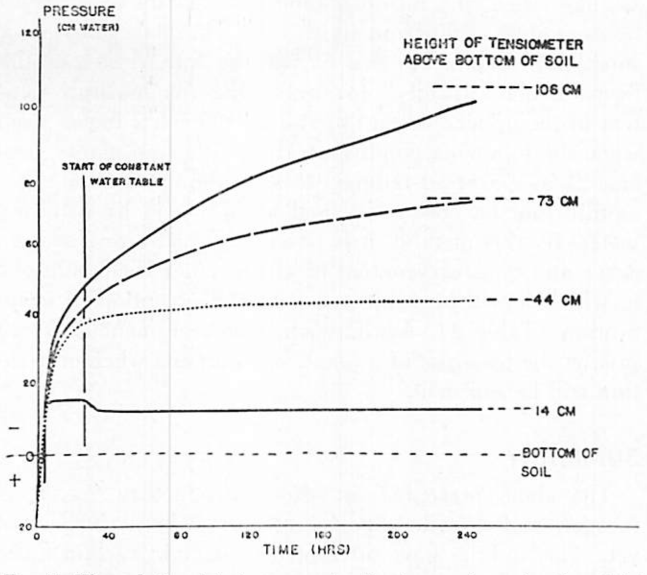

Fig. 8: The relationship between depth, time and tension in a 1-1-1 soil mixture 110 cm deep. Note that equilibrium (tension equals depth) is reached in a very short time for the lowest tensiometer. However, the top tensiometer (106 cm above the bottom) had still not reached equilibrium in 10 days after the start of the experiment.

TABLE 1. Relationship between depth, tension and air and water content in three soil mixtures each 110 cm deep.

Mixture	Distance above bottom (cm) at which sampled	Tension (cm of water) at sample depth.	Volume (per cent)[a] air	water
Soil	106	76	20	43
	73	49	13	47
	44	35	12	46
	14	14	7	51
Soil plus ¼ sand[b]	106	72	31	27
	73	36	23	30
	44	33	25	29
	14	13	10	52
1-1-1- mixture	106	49	43	25
	73	43	38	26
	44	39	33	33
	14	16	15	43

[a] Volume in all cases may be figured as cc's per 100cc.

[b] The sand is a locally obtained bank run, having considerable diversity in particle size as well as a high calcium content.

TABLE 2. The effect of depth of soil on drainage from the top four centimeters of three different soil mixtures.

Mixture	Depth of Mixture (cm)	Distance of tensiometer above bottom (cm)	Tension (cm of water) at time of sampling	Volume (per cent) air	water
Soil	110	106	76	20	43
	15	11	17	0	53
Soil plus ¼ Sand	110	106	72	31	27
	15	11	12	0	54
1-1-1 mixture	110	106	49	43	25
	17	13	14	22	39

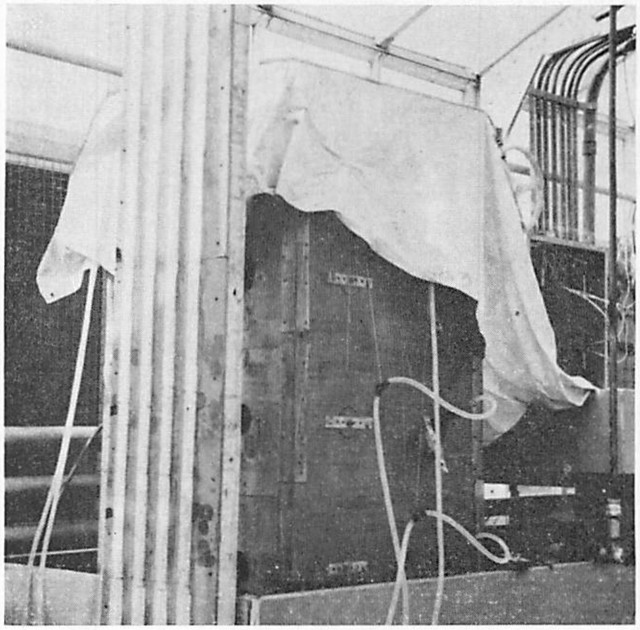

Fig. 9: The deep plot used for experiments in determining relationships of depth and drainage.

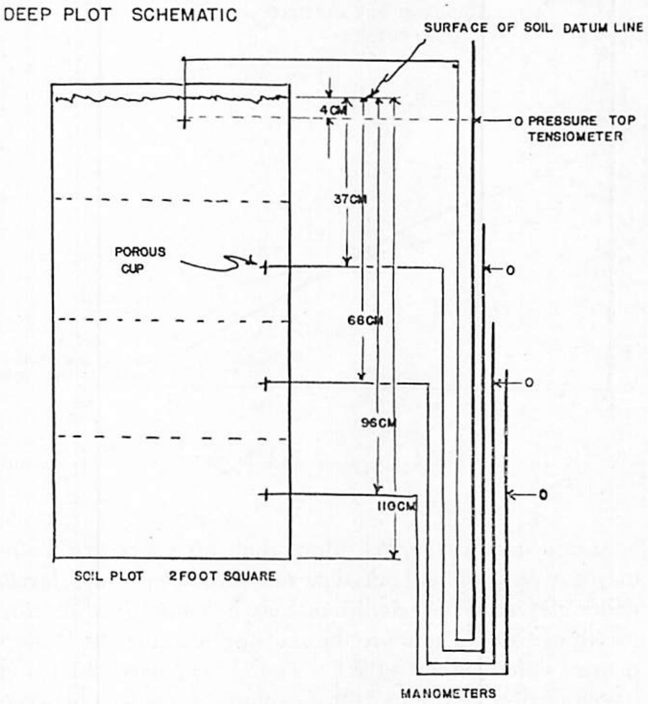

Fig. 10: Schematic of the deep plot to show placement of tensiometers and distances involved.

appreciable amounts of air. The added depth while retarding completion of the drainage period, caused air to displace water from the surface layer to a very important degree.

The importance of soil volume and depth in regard to the possible affect on aeration is further substantiated in Figure 11. In this experiment, a standard potting mixture was placed in two 7-inch clay pots, the only difference being that sufficient gravel was placed in the bottom of one to reduce the depth of soil from 16 cm to 12 cm. Equilibrium was reached approximately two hours after the start of the experiment as can be noted from the abrupt

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change in slopes. After 15 hours the shallow treatment increased in tension over the deeper due to evaporation. If plants had been established in the pots, reversal of curves would have probably taken place sooner, and the attainment of equilibrium might not have been seen. If the total moisture-holding capacity of the shallow soil had been increased (by substituting a different soil), without increasing volume, the reversal of curves might not have taken place until much later. The relationship of depth, volume and total water-holding capacity has led some individuals (9) to state that deficient aeration is not a problem under their environmental conditions, inasmuch as transpiration and evaporation losses prevent the continuance of deficient aeration in small volumes for any length of time. It is probably the reason why some soil mixtures have given trouble in benches but not in small containers (17). The authors are familiar with several examples in practice (e.g. small seedlings in a bench, overpotting, etc.) where the relationship of depth, volume and water content are critical.

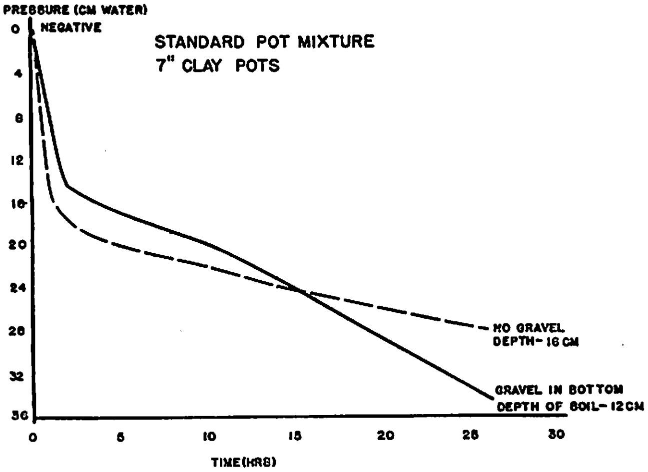

Fig. 11: The effect of evaporation and depth on tension in porous clay pots.

Significance of depth—More than 30 years ago Viehmeyer (19) pointed out that only three moisture levels under a given set of conditions may be *maintained* for any length of time. These are the moisture contents at 1) permanent wilting point (PWP) 2) field capacity (FC) and 3) saturation. If the moisture content of a soil is between PWP and FC, the water content will change continuously depending upon the rate of water removal by plants and evaporation. It is impossible, at the present time, to bring a soil in which plants are established back to a pre-determined moisture content between PWP and FC. The addition of water results in the wetting of the upper layers while the lower layers continue to dry. To bring a soil to a constant moisture level, it must be wetted thoroughly (saturated) and allowed to drain to FC. The permanent wilting point sets the lower limit of freely available water for transpiration (20, 21). It is a quantity that changes from soil to soil—a clay soil holding more water at its PWP than a sandy mixture. Thus, the PWP and FC determine the range over which moisture is available for plant growth for a particular soil, and these constants must be determined in attempting to characterize a soil.

Field capacity as it is commonly defined for field use (10, 11, 20, 21) is meaningless for greenhouse soils. As we have seen, the moisture-holding capacity of a greenhouse soil— aside from its textural characteristics—is a function of depth. For this reason, the authors suggest the term "bench capacity" for indicating the moisture content of the upper 2-inches of soil in a bench 7-inches deep when the following conditions are met: 1) no plants present, 2) evaporation reduced to a minimum, and 3) after equilibrium has been obtained as indicated by a tensiometer. By this method, it is possible to measure free pore space and moisture content of a soil under the conditions to which it will be subjected with the exception of evaporation (Table 2). Again, such a measurement does not predict the response of a plant, but suggests whether aeration will be sufficient.

SUMMARY

The data presented in this introductory paper is meager, and definite conclusions cannot be arrived at as yet. The authors have attempted to explain certain basic principles which form the basis of their investigation on soil aeration, and to define terms that will enable you to understand and utilize the future experimental data in its commercial application.

In the next article, the authors will describe methods used in determining water losses and some results obtained in preliminary experiments with Snapdragons.

GLOSSARY

Sources of information for the definitions in this glossary are the literature pertinent to the particular subject under discussion as well as articles on terminology in volumes 16 and 20 of the Soil Science Society of America Proceedings, 1952 and 1956 respectively.

It should be emphasized that some of the definitions have been altered by the authors for application to the specific subject of greenhouse soils, and as more information becomes available further change may prove necessary.

Air entry value—The minimum soil moisture tension required in a soil to cause displacement of water by air in significant amounts.

Atmosphere—A unit of pressure, equal to the pressure exerted by the earth's atmosphere at sea level. One Atmosphere (A)=14.7 pounds per square inch (psi)=76.0 centimeters (cm) of Mercury=1.033 bar=1033 millibars, approximately 1000 cm of water.

Bench capacity—The moisture-holding capacity of the upper 2-inches of soil in a bench following drainage, analogous to field capacity, and when the following conditions are met: 1) 7-inches deep, 2) no plants, 3) evaporation prevented or reduced, and 4) when soil moisture tension equals the depth (7 inches).

Capillary pore space—Space within a soil which remains filled with water at a specified tension. The exact value may vary according to the authority quoted, but a tension of 65 cm of water is a representative figure.

Centimeter (cm)—A unit of length. 1 cm=0.394-inches, or 1-inch=2.54 cm, 100 cm=1 meter (M)=39.37 inches.

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Cubic-centimeter (cc or cm^3)—A unit of volume approximately equal to one milliliter (ml), 1000 ml=1 liter 3.78 liters (L)=1 U.S. gallon.

Drainage—As used in this paper, the process of discharge of water from a soil by sheet or stream flow. Drainage is completed in a greenhouse bench when the soil moisture tension in the upper layers equals the depth of the soil.

Field capacity—The amount of water held in a soil where the excess water has drained away and rate of downward movement has materially decreased.

Free pore space—Pore spaces within a soil which are filled with air following drainage.

Moisture content—The amount of water present in a soil expressed as per cent of dry weight. Determined by drying a sample to a constant weight at 105°C.

Non-capillary pore space—Pore spaces in a soil which are occupied by air at a specified tension. The exact value may vary according to the authority quoted, but 65 cm of water is a representative figure.

Permanent wilting point—Moisture content of a soil at the time when the leaves of a plant first undergo a permanent reduction in their moisture content as the result of a deficiency in the soil-moisture supply, and the leaves will not recover when the plant is placed in a saturated atmosphere.

Porosity—The total volume of pore space in a given volume of soil whether filled with air, water or both.

Saturation—The condition of a soil in which all pores are filled with water.

Soil—Any material or mixture of materials in which plants are grown.

Soil aeration—The process by which air and other gases in a soil are renewed.

Tension (Soil moisture Tension)—A measure of the affinity or attraction of soil for water. May be considered synonymous with negative pressure, pressure deficiency, suction or hydraulic head. In this paper, all data are given in centimeters of water (i.e. depth). A lark tensiometer reading of 30 corresponds to the pressure exerted by a column of water 300 cm high or a column of mercury approximately 9-inches high, except it is negative. It is a quantity measured by a tensiometer and represents the pressure of water inside a porous cup inserted in the soil.

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