MEASUREMENT OF THE SUCTION OF SOIL WATER BY PORTLAND STONE ABSORBERS CALIBRATED BY A NEW METHOD FOR DETERMINING VAPOUR PRESSURES NEAR TO SATURATION*·

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(With Four Text-figures)

SUCTION

The water in a soil that is not waterlogged is at a pressure less than the atmospheric pressure by an amount which it is convenient to call the *suction*. When water is withdrawn from a mass of soil the suction increases because of the increase in the curvature of the air-water menisci in the soil interstices. While suction is undoubtedly a factor of prime importance in determining the availability of soil water to plants, studies along these lines have been greatly hampered by the difficulty of measuring suction.

The freezing-point depression

In the years that followed the classical investigations of Briggs & Shantz (1912) on the wilting of plants, several attempts were made to determine the suction in soils at the wilting coefficient†; but reliable values were not obtained until the development by Schofield & Botelho da Costa (1935) of the freezing-point method. These authors turned to account the observation of Bouyoucos & McCool (1916) that soils when examined at moisture contents equal to or slightly in excess of their wilting coefficients exhibit freezing-point depressions of the order of 1° C. Thermodynamic reasoning involving the assumption that the ice is formed under atmospheric pressure (and not under the suction experienced by the water) yielded the relationship (Schofield, 1935)

$$pF = \log_{10} H = \log_{10} Lj/Tg + \log_{10} t = 4 \cdot 1 + \log_{10} t, \tag{1}$$

where pF stands for the logarithm of the free-energy depression expressed on a gravity scale as the height, H, in centimetres of a column of water.

Schofield & Botelho da Costa (1935, 1938) recognized that freezing dries the soil, and consequently that the pF calculated from the freezing-point depression corresponds to the moisture content at the time of reading the thermometer. It is necessary, therefore, to determine how much ice is formed and subtract this from the initial moisture content.

Depression of the free energy, and hence of the freezing-point, of soil water may be due to suction or to dissolved matter or to both. Botelho da Costa (1938) therefore determined, at a series of moisture contents, the freezing-point depression in several

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* This paper embodies the substance of a thesis submitted by the first-named author and approved for the degree of Doctor of Philosophy in the University of London.

† The moisture content of the soil (expressed as a percentage of the dry weight) when the leaves of plants growing in it first reach a stage of wilting, from which they cannot recover, in an approximately saturated atmosphere without addition of water to the soil. This stage of wilting is called permanent wilting.

soils that had been washed free of salts. Comparison with the values obtained for the unwashed soils showed that, even with ordinary non-saline soils, salts make an important contribution to the freezing-point depression at moisture contents in the neighbourhood of the moisture equivalent (the depression being then of the order of 0·1° C.). In the neighbourhood of the wilting coefficient the freezing-point depression was reduced by washing three decidedly saline soils, but was slightly increased by washing the soils of normal low salt content. The rise in water-holding capacity reflected in this increase must have been due to a partial dispersion of the clay, and this more than compensated for the decrease due to the removal of salts. Botelho da Costa concluded that if a soil, when saturated, has a freezing-point depression less than 0·07° C.,* the dissolved matter makes no important contribution to the pF at the wilting coefficient.

These investigations showed that the suction must be near the limit corresponding to permanent wilting if it is to be obtained simply by measuring the freezing-point depression. If we wish to determine suctions appreciably lower than this limit, but too large to be registered by a filter apparatus, we must either obtain a reasonably accurate measure of the contribution made by salts to the freezing-point depression and then obtain the contribution of the suction by difference, or we must adopt a different method. Washing out the salts appears to be ruled out as a feasible alternative owing to the risk of altering the soil structure. The contribution of the salts might be found by extracting some of the soil solution and measuring its freezing-point depression, but, apart from other considerations, the large sample of soil that would have to be extracted would make this at best an inconvenient procedure. The possibility of using calibrated absorbers was therefore explored.

MEASUREMENT OF SUCTION BY POROUS ABSORBERS

Historical

Xanthium seeds have a semi-permeable cuticle, and Shull (1916) calibrated a number of them by finding their equilibrium moisture contents in solutions of known osmotic pressure. He then brought them to equilibrium with soil samples of different moisture contents, and so deduced the curve connecting moisture content and suction. Unfortunately, he did not measure the wilting coefficient directly, but calculated it from the moisture equivalent by the formula of Briggs & McLane (1907), which is now known to be unreliable. The smallness of the value he obtained for the suction at the wilting coefficient is ascribable to his use of this formula and reflects no discredit on his experiments.

Livingston (1906), Livingston & Koketsu (1920), Wilson (1927), and Wilson & Livingston (1932) used tapered tubes of porous porcelain (soil points) to measure the 'water-supplying power' of soil. No attempt was made to calibrate these in terms of suction, or to bring them to a state of equilibrium with the soil. Similar measurements were made by Mason (1922) and Hardy (1923, 1928) using lead pencils.

Gardner (1937) calibrated filter papers by leaving them for several months in evacuated desiccators over sulphuric acid of different concentrations. The calibration at low suctions was obtained by using a moisture equivalent centrifuge. The curve connecting suction and moisture content was obtained for small samples of soil interleaved between calibrated filter papers.

* 0·03° C. is perhaps a safer limit.

Schaffer, Wallace & Garwood (1937) determined the suction/moisture content relationship for three Portland stones for suctions up to about 0·6 atm. Independent measurements were made by centrifuge and by hydrostatic suction and the results compared. These authors were not concerned with the measurement of suction in soil.

Portland stone plates as absorbers

The porous absorbers used in the present investigation were small rectangular plates of Portland stone measuring $7 \times 4 \times 0.5$ cm., and weighing about 30 g. These were cut from the same three stones A, B and C that had been used by Schaffer, Wallace & Garwood, and were supplied to us from the Building Research Station, Garston, where the investigations of these authors were carried out. Portland stone was chosen because it is an insoluble and imperishable material having a rigid, unchanging pore-space. There was the additional advantage that data on these particular stones already existed.

Conditions for a stable relationship between suction and moisture content

The possibility of using the stone plates for measuring suction in soil depends in the first place on the existence of a stable relationship between the suction and the amount of water held in the stone. It was to be expected from the work of Haines (1927, 1930) that there would be hysteresis in this relationship; so that a stone originally saturated and then subjected to a given suction would retain more water than would be taken up by a dry stone supplied with water at the same suction.

Measurement of the weights of stones after contact for various lengths of time with soil, both in the field and in the laboratory, showed that, starting from saturation, a stone attains nearly constant weight after 2–3 hr., whereas starting dry it continues to take up water for several days. Moreover, in successive experiments with the same stone, there was a much greater variation in the final moisture content when the stone started dry.

From these trials it was evident that the stone should be calibrated in the *drying condition*.

Calibration by direct application of hydrostatic suction

The form of apparatus used in calibrating the stones by the application of direct suction is sketched in Fig. 1. The filter consisted of an earthenware dish with unglazed base into which a glass funnel, selected to make a snug fit, was inserted. The gap between the funnel and the cylindrical side of the dish was sealed first with a little paraffin wax and then with a thick layer of 15–20 % gelatin containing a little $HgCl_2$. The paraffin wax prevented the gelatin from soaking into the unglazed base of the dish, and the gelatin, if not allowed to get too dry, provided a strong seal.

As the porous base was slightly curved, and had a small rim, it was built up with several layers of filter paper, forming a flat surface that made good contact with the stone. The filter and stone were enclosed in a waxed carton with a hole in its base to admit the stem of the funnel. The screw lid prevented evaporation and pressed the stone firmly on to the filter. The filter was thoroughly soaked with water before each experiment, in which condition it did not allow the passage of an appreciable amount of air even under an atmospheric suction. Water was poured into the bottom of the carton to maintain a saturated atmosphere.

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In practice it was convenient to attach a number of these filters to one manometer and so to bring several stone plates to equilibrium under the same suction. The suction was applied by connecting the filters and manometer through an X-joint to the junction of two capillary tubes through which air was drawn by a suction pump. By adjusting the relative resistance of these tubes the suction could be maintained at any desired value.

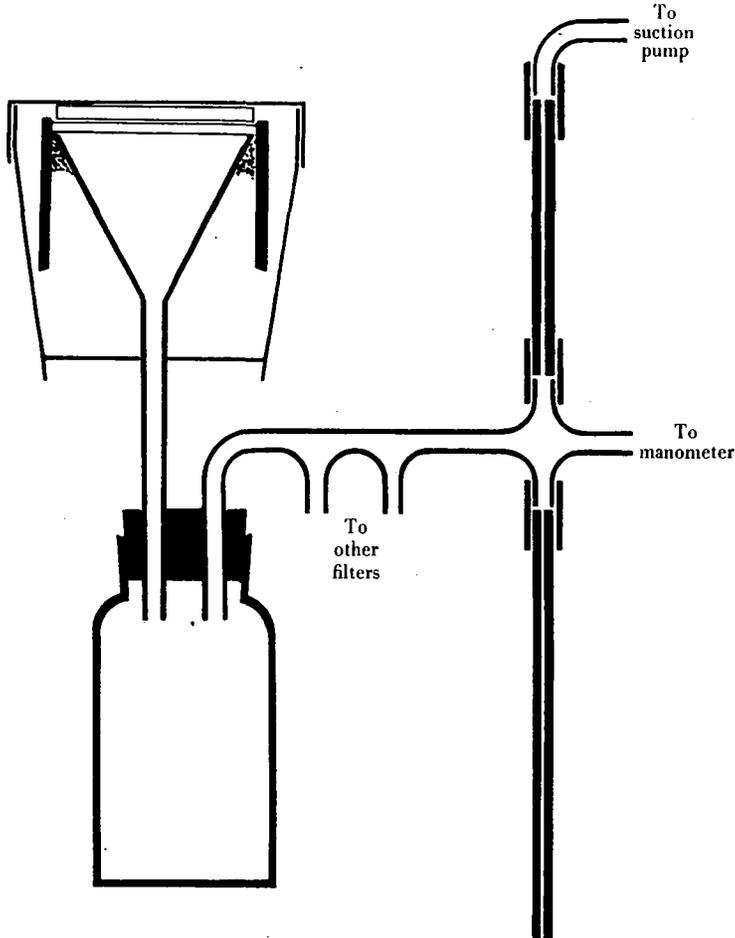To suction pump

To manometer

To other filters

Fig. 1

It was necessary, in order to obtain reproducible results, to get the stone plates completely saturated with water before applying suction. The safest way was to place them, when dry, in a vessel that could be evacuated and wet them with boiled distilled water in vacuo. Simply soaking in boiled water for 24 hr. did not always expel all the air.

The time taken for the plates to reach a constant moisture content, while a steady suction was applied through the filters, varied considerably from one filter to another. With the most permeable filters the time was under 2 hr. As much as 8 hr. was needed with the least permeable filters.

Calibration by vapour pressure

Since no suction greater than 1 atm. can be applied through a filter, another method must be used to extend the calibration to suctions greater than 10^3 cm. of water. It

was inadvisable to apply the freezing-point method direct to the stones owing to the risk of damaging them. The freezing-point method could have been used to determine the suctions in a series of salt-free soils with which stones had come to equilibrium. It appeared preferable, however, to adopt a method which could be applied direct to the stones. In an unpublished investigation by one of us (R. K. S.) in collaboration with C. R. Marshall, a technique had been worked out for obtaining the vapour pressure of honey, and this was adapted to the present purpose.

The substance with unknown vapour pressure and a material with known vapour pressure are placed close to one another, but without liquid contact, in a closed vessel. If, as a result of distillation during a sufficiently long period, the material gains weight, it has the lower vapour pressure of the two; if it loses weight, it has the higher vapour pressure. By carrying out several tests, using materials with different known vapour pressures, a close estimate of the unknown vapour pressure can be made by interpolation. The accuracy of this estimate can be tested by further experiment with materials closely bracketing the estimated vapour pressure.

The vessels used were circular 3 oz. size tobacco tins, 10·8 cm. in diameter and 2·5 cm. deep with air-tight lids. Two such tins were used for each measurement. Three steel hooks were soldered to the inner side of one lid near its rim so as to form an equilateral triangle. The insides of the tins and lids and the hook were then covered with a thin layer of paraffin wax.

The measurements were made in a constant temperature room running at 17° C. The procedure was as follows:

(1) A stone plate, which had been vacuum-saturated and then dried to the desired extent, was placed in one tin, which was closed with a lid. A flat pad of cotton-wool was thoroughly wetted with a solution of sodium chloride of known concentration and was then secured to the under side of the other lid by a rubber band stretched round the hooks. This lid was fitted to the empty tin. Both tins were then weighed. If the stone or solution had just been introduced into the constant temperature room it was left for some hours to reach temperature equilibrium before proceeding.

(2) The lids of the tins were rapidly exchanged. This placed the cotton-wool pad in the same tin as the stone plate, where they were separated from one another by an air gap of about 1·5 cm. Both tins were then weighed and placed in a metal cabinet (an old steam oven) to cut out any temperature gradient.

(3) After a period, usually 24 hr., the tins were again weighed and any small losses, which were usually less than 5 mg., were recorded.

(4) The lids were again rapidly exchanged, and the tins having now the same lids as in weighing (1) were reweighed.

Had no vapour escaped while the lids were being exchanged, the loss in weight of one tin would have equalled the gain in weight of the other. In practice there was usually a difference of some 10 mg. The error is practically eliminated by taking the mean as the measure of the vapour that distilled from the stone to the solution, or vice versa, during the time that they were in the same tin.

To obtain the percentage vapour pressure depression (v.p.d.) of a stone plate at a particular moisture content, several experiments were made. The concentrations of the sodium chloride solutions were so chosen that in some experiments the stone lost weight and in others it gained weight. Having used a constant time for the distillation (24 hr.),

and as nearly as possible a constant distance between the stone and the pad (about 1·5 cm.), a plot of the change in weight of the stone (increase as positive change, decrease as negative change) against the V.P.D. of the solution gives a curve which intersects the axis at the V.P.D. of the solution causing no distillation and, hence, gives the V.P.D. of the stone plate.

The portions of these curves for changes in weight not exceeding about ±50 mg. were found to be substantially straight. These portions were also found to have substantially the same slope independent of the V.P.D. of the stone over the range 0–1·5% V.P.D. The mean slope was 77 mg. per 1% difference in V.P.D. Using this figure, a value for the V.P.D. of a stone could be obtained from a single experiment in which the change in weight was small.

There appeared to be a slight discontinuity between the positive and negative parts of the curves, due to hysteresis, but the effect was scarcely greater than experimental error and consequently did not interfere with the determination.

Results of the calibration

The results for stones A and B are plotted in Figs. 2 and 3. The abscissae give the moisture content of the stones as a percentage of the dry weight. The ordinates give the pF obtained either as the logarithm of the suction applied through the filter, or from the V.P.D. by the equation (Schofield, 1935)

$$pF = \log_{10} H = \log_{10} 2·303 RT/MC + \log_{10} (2 - \log_{10} (100 - v))$$
$$= 6·5 + \log_{10} (2 - \log_{10} (100 - v)) \Big\}\ \ T = 293° \text{K.,}^* \qquad (2)$$
$$= 4·14 + \log_{10} v \text{ when } v < 2\%$$

where v is the V.P.D. %. As there is no contribution from salts, the pF calculated from V.P.D. is the logarithm of the suction.

There were, undoubtedly, small differences between individual plates cut from the same stone. Thus two plates cut from stone A had saturation moisture contents 10·17 and 9·92% respectively. Nevertheless, we felt justified in plotting the results for several plates on the same curve without distinction. The portions of the curves below pF 2·8 have been drawn to correspond to the curves published by Schaffer, Wallace & Garwood. As the range of suction in which a new method is principally needed is between 10^2 and 10^4 cm. suction (pF 2–4) the measurements were mainly made in this range.

The most important and satisfactory feature about Figs. 2 and 3 is the agreement, particularly evident in Fig. 3, between the moisture contents at pF 3 determined by the two methods. The agreement is, of course, a thermodynamic necessity and simply serves as a valuable check on the experimental accuracy of both sets of observations.

The form of the curves is interesting. It shows that the pore-space of these stones is divisible into two rather distinct parts having pores of different average size. The part with the larger pores is half empty at pF 2·1 in stone A, pF 1·9 in stone B and pF 1·6 in stone C. Taking the round figure, 70 dynes/cm., the corresponding mean radii of curvature of the meniscii work out at about 10μ in stone A, 16μ in stone B and 30μ in stone C. The radius of curvature, when the part with the small pores is half empty, is about $0·13\mu$ for stone A and about $0·1\mu$ for stone B.

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* These formulae are worked out for $T = 293°$ K., i.e. 20° C. The temperature of these experiments was 17° C., but a fall of temperature of 3° C. causes the constants 6·5 and 4·14 to decrease by 0·003—a negligible amount.

Measurement of suction in soil

An obvious consequence of the form of the curves is that stone A is rather insensitive to suctions below about 65 cm. (pF 1·8), stone B to suctions below about 40 cm. (pF 1·6), and stone C to suctions below about 20 cm. (pF 1·3). This does not matter much because there is no difficulty about measuring suctions of these magnitudes with a filter apparatus.

Next we see that stone A is particularly sensitive to suctions between about 80 and 200 cm. (pF 1·9–2·3), stone B to suctions between about 50 and 125 cm. (pF 1·7–2·1),
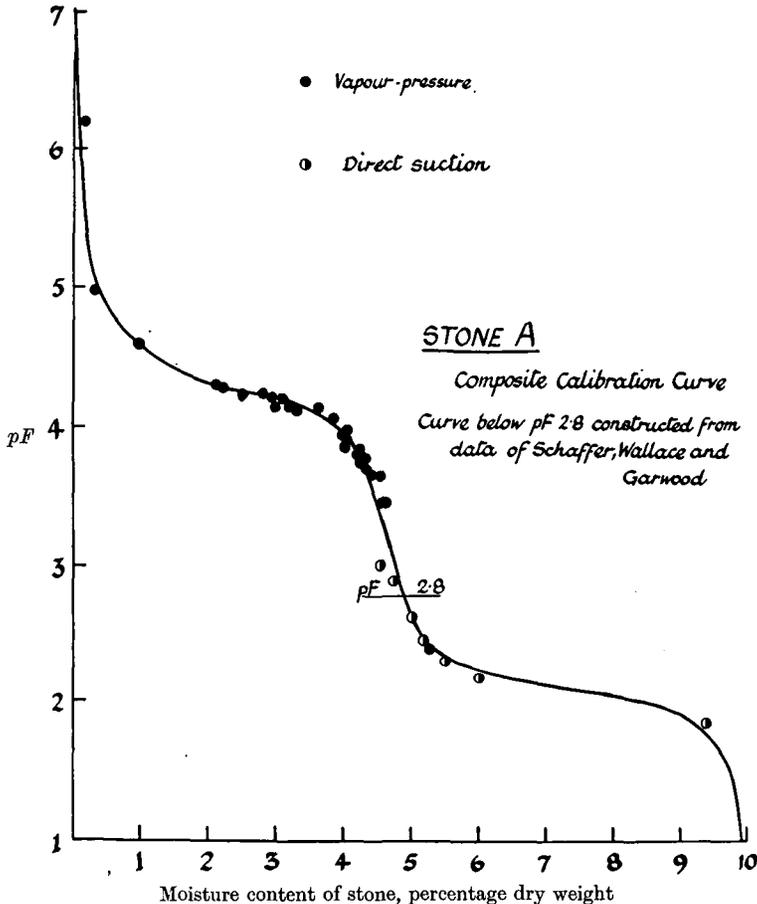

Fig. 2

and stone C to suctions between about 25 and 65 cm. (pF 1·4–1·8). Seeing that all these ranges are well within the capacity of any well-designed filter apparatus it did not seem necessary to carry out detailed checking of the values given by the stones under these conditions.

For suctions between about 400 and 4000 cm. (pF 2·6–3·6) the stones have a much smaller sensitivity. This is the range in which a new method of measurement is most needed. The low sensitivity of Portland stone in this range is a distinct drawback, because there goes with it a greater difference in suction between individual stones at the same

moisture content than in the ranges of high sensitivity. There is, however, an advantage in low sensitivity which, as the following considerations show, partly offsets this disadvantage.

It will be clear from the way in which the stones were prepared for calibration that they must first be vacuum-saturated and then dried. When suctions greater than about 200 cm. (pF 2·3) are to be measured it is desirable to effect most of the drying before placing the stones in contact with the soil in which the suction is to be measured, thereby
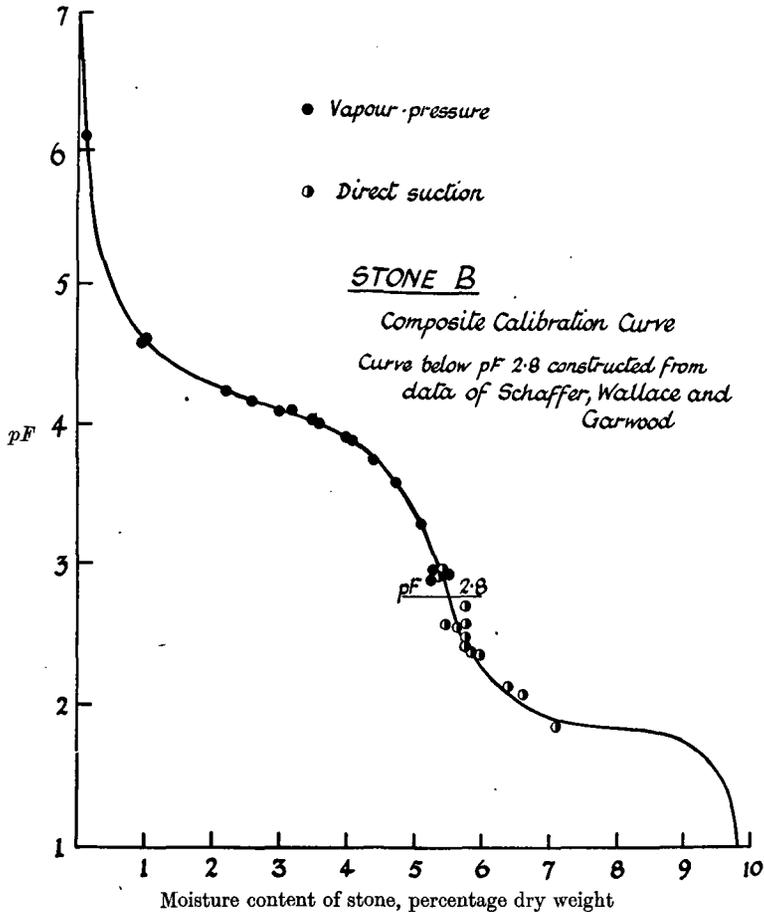

Fig. 3

reducing to a minimum the disturbance caused by the release of water from the stones into the soil. It is obviously easier to regulate this preliminary drying in a range of low sensitivity.

Measurements of suction in soil were made on a sample taken nearly two years earlier from an unmanured area adjoining the Rothamsted Park Grass Plots. The soil, taken between 3 and 18 in., had been mixed and sieved while still moist through a 3 mm. sieve into a large earthenware bin. During the filling of the bin the soil had been well packed down. It had then been thoroughly watered and allowed to drain through a hole in the side of the bin just above the base. Except for occasional light watering, the soil

had not been disturbed during the intervening time and had been covered with sacking to check evaporation.

Six flat areas were prepared at the surface of the soil in the bin and six stone plates, which had been vacuum-saturated and partially dried by exposure to the air, were pressed firmly into them. Two plates were of stone A, three of stone B and one of stone C. Each stone was covered with an inverted Petri dish, left in place for 24 hr. and then weighed. From these weights, and the calibration curves, plate A2 gave 3·30 for the logarithm of the suction, A5 gave 2·87, B3 gave 3·17, B4 gave 3·20 and B5 gave 3·00. The weight of the C stone was outside the range for which it had been calibrated.

Table 1

Area	pF indicated by stone blocks					Mean	Moisture content
	A2	A5	B3	B4	B5		
1	3·30 3·22	3·35	3·30	3·25	3·20	3·27	15·2
2	3·27	3·25	3·30	3·20 3·35	3·07	3·24	16·8
3	3·10	2·82	3·17	3·20	2·95	3·05	18·3
4	3·15	2·87 2·95	2·90	3·20	2·95	3·00	18·0
5	(2·97)	3·00	3·17 3·35	3·40	3·10	3·20	15·5
6	3·27	2·95	3·05	3·20	3·00 3·02	3·08	16·7
7	—	3·05	3·05	—	(2·80) 3·15	3·07	16·9
8	—	3·00	2·95 3·00	—	2·85	2·95	17·7
9	—	2·85	2·80	—	2·80	2·82	19·7
10	—	2·80 2·90	2·85	—	2·85	2·85	18·8
11	—	3·05	3·00	—	3·00	3·02	17·3

In order to find out how much the suction in the six areas really differed, the plates were moved round so that each one occupied each area for 24 hr. and finally returned to its original area. A sample of the soil was then taken from each area for moisture determination. The results are set out in the upper part of Table 1. In spite of some erratic variations, it is evident that, given the same soil suction to be measured, plates A2 and B4 tended to give results about 0·1 higher, while plates A5 and B5 tended to give results about 0·1 lower than plate B3. There were also differences between soil suctions as shown by the mean values obtained for each area. It chanced that the plate first put on area 2, which had the highest suction, was A2 (a high-reading plate), while that first placed on area 4, with the lowest suction, was A5 (a low-reading plate).

There is a general tendency for the mean suction to vary inversely with the soil-moisture content, as one would expect, but there are irregularities. These may well be due to uneven packing of the soil in the bin. It is obvious, from general principles, that packing is a factor in the relationship between suction and moisture content. An illustration of its effect is furnished by a comparison between the moisture content of the soil in the bin at a suction of 1000 cm., namely, 18 %, and that obtained for another sample of Park Grass soil by Schofield (1935), namely, about 25 %. In Schofield's experiments the soil was sprinkled air-dry on a silt-coated filter paper and then soaked with water. Finally, a suction of 1000 cm. was applied through the filter. Treated in this way the soil was undoubtedly more loosely packed than in the bin. The soil in the bin had not

been air-dried, and the slaking action of water on dry soil had not disturbed the packing as in Schofield's experiments.

Suction measurements made on the Park Grass soil in situ gave values for the logarithm ranging between 2·5 and 2·8 for moisture contents between 17·3 and 22·6 %. This indicates that the state of the soil in the bin was similar to that in the field.

Comparison with filter apparatus

While the measurements with the stone plates were in progress, a filter apparatus, kindly lent by Dr W. S. Rogers, was set up. The filter consisted of a dense porous earthenware plate, circular in section and held by a heavy cylindrical brass cup with an inner flange and rubber washer on to which the plate was pressed by a screw collar. The cup had two outlets, and when in operation was connected to a mercury manometer by a continuous column of boiled water, all air being excluded from the apparatus. The plate had been made to specification and withstood a full atmosphere's suction on test.

The filter was pressed into contact with an area of the bin soil near area 3. After 24 hr. a suction of nearly 400 cm. was recorded, and the reading subsequently increased about 25 cm. each day for the ensuing week. As it turned out, the suction to be measured was over 1000 cm., the upper limit of the instrument. The bin was, therefore, watered and left for several weeks and another series of measurements were made using A5, B3 and B5. The results for the stone plates are recorded in the lower part of Table 1. The filter was placed near to area 9 and the manometer gave substantially the same readings as before, although the suction was distinctly lower and was just within the theoretical range of the instrument.

Similar comparisons made in the field indicated that when the soil suction was less than about 400 cm. the filter apparatus could be relied on to give substantially the correct value in 24 hr. For these lower suctions the stones gave reasonably correct values, but could not compare in accuracy with the filter apparatus. When the filter apparatus read about 400 cm. the suction might be close to this figure or might be much greater. In these circumstances the stones provided the only means for a true evaluation of the suction.

In attempts to build a filter apparatus that would give correct readings to higher suctions, various filter materials were tried, including wash-leather coated with silt, cellulose ultra-filter membranes and porous earthenware filters. None of these succeeded. The claim of Mathieu (1933) to have measured suctions close to 1000 cm. was tested by plotting his results as log-suction against moisture content. Comparing the shape of this curve with the true log-suction/moisture curves of the soils that have been examined in the laboratory, we conclude that his instrument failed to record correctly suctions over about 200 cm. Why these instruments fail to reach the theoretical limit we do not know, but we suspect that the principal cause is the fall in moisture conductivity of the soil with rise in suction. Even where, as in Mathieu's apparatus, means are provided for setting the suction in the apparatus to a value near that to be expected in the soil, it appears to be impossible to prevent the release of water into the soil when the suction is high. Owing to the low moisture conductivity and hysteresis this water materially reduces the suction in a thin layer of soil against the filter.

Suggested refinement in calibrated absorber technique

The disturbance caused by the release of water from the stone plates has already been mentioned. Strictly speaking, the process of measuring suction with a calibrated absorber should be to find, by extrapolation from a number of measurements in which different small quantities of water are released into the soil, the moisture content of the absorber when it just would not give up any water. Lack of time prevented our making a detailed study of this refinement of the technique. To take full advantage of it, the individual absorbers would have to be separately calibrated.

CONCLUSIONS REGARDING THE SCOPE OF THE METHOD

The experiments we have carried out with the calibrated stone plates have been admittedly rather limited in scope. Nevertheless, they suffice to show that the method is feasible. Even at its present stage of development it gives results of fair accuracy over the range of suctions that cannot be determined by other methods. The ingenious device of Bouyoucos & Mick (1940), in which the moisture of a soil is gauged by the electric resistance of a block of plaster of Paris buried in it, is, of course, a porous absorber. Hitherto the device has been used empirically, but it is possible that a sufficiently close relationship will be found between resistance and the suction in the block for it to be used as a calibrated absorber with the great advantage that it can stay in position in the soil while a continuous record is made.

Measurement of vapour pressure of soil samples

The sealed-tin technique, described in the calibration of the stone plates, was also applied to determine directly the V.P.D. of soil samples. This was done because satisfactory measurements of the freezing-point depression could not be made with several soils (see next section).

About 30 g. of soil was spread over the bottom of the tobacco tin, and the procedure was then otherwise exactly as already described. It was found, however, that the distillation in 24 hr. per unit difference of V.P.D. was not constant, as with the stone plates, but varied with the V.P.D. of the soil samples. For samples with a V.P.D. less than 0·1 % the distillation was about 150 mg., a figure in satisfactory agreement with that calculated from the equation for the diffusion of water vapour through still air. For samples with a V.P.D. about 1 % the distillation was little more than half, and was therefore about the same as that obtained with the stone plates up to 1·5 % V.P.D. Evidently the resistance offered by the air to vapour diffusion is not the only obstacle to distillation. The constancy of the additional resistance in the case of the stone is, no doubt, connected with its peculiar pore-size distribution, causing it to lose very little water between 0·05 and 1·5 V.P.D. in the case of stone A and 0·03 and 1·0 V.P.D. in the case of stone B. Over these ranges of V.P.D. the resistance to water movement through the stones does not change much. In soils the condition is quite different. There is a considerable change in water content and there must be a large change in the resistance to water movement. This presumably causes the change in the rate of distillation.

If the rate of distillation had been independent of the V.P.D. for soils as for the stones, a single measurement would suffice to give a fairly accurate value of any unknown V.P.D.

up to 1·2%, the value corresponding to the wilting coefficient. As this rate is not constant it is necessary to make at least two experiments to obtain a dependable value. If, however, the aim is to find the moisture content at pF 4·2 (i.e. make an indirect determination of the wilting coefficient), a single measurement with a solution of pF 4·2 on two or three samples near to the correct moisture content would enable the desired moisture content to be found by plotting the amount of water distilled in 24 hr. against the moisture content of the soil. This method can be applied to any soil, but it would be troublesome to use except in a constant temperature room, as rigid control of the temperature is essential for success. Saturated barium nitrate solution at 20° C. has a pF close to 4·2.

Difficulties in determining freezing-point depression

In applying the freezing-point technique of Schofield & Botelho da Costa difficulties have been encountered with certain soils. There is a tendency, particularly in wet heavy soils, for water to condense on the wall of the boiling tube containing the soil sample during the preliminary cooling. In consequence of this, the soil in contact with the tube becomes wetter and so has a lower freezing-point depression than the main mass. The resulting uneven distribution of moisture is undesirable in itself, as it causes uncertainty about the moisture content to which the observed freezing-point depression corresponds. It is probably also the cause of the premature freezing which frequently occurs with heavy soils and with soils rich in organic matter. With any soil sample the success of a freezing-point determination depends on finding a condition of packing in which it can be supercooled and then suddenly made to freeze by a twist of the thermometer. Light- and medium-textured soils are tolerant in this matter and are easily handled after a little practice. With clays and mucks it is much more difficult to find the right conditions. In the case of a harbour mud from Cochin measurements could only be made over a very limited range of moisture contents for which the freezing-point depressions were between 0·2 and 0·5° C. A soil from Methwold Fen would not freeze properly at any moisture content.

Comparison of direct suction, vapour pressure and freezing-point on the same soil samples

The accuracy of the sealed-tin method for vapour pressure is such that a V.P.D. of 0·1% can be measured to within about ±0·01. This means that a pF in the neighbourhood of 3 can be obtained to ±0·05. As already noted, the V.P.D. of plates of stone B, which had been vacuum saturated and then brought to pF 3 by direct application of 1000 cm. suction through a filter, was in very satisfactory agreement with the value to be expected from the thermodynamic formulae given in equation (2), p. 418. A similar comparison was made with soil and, in order to include the freezing-point depression, the soil used was a sample taken between 9 and 13 in. deep from Stackyard Field at the Woburn Experimental Station. This soil contains a considerable proportion of coarse sand, and it was the most satisfactory of those tested for freezing-point depression. The sample was washed free of salts, air-dried, and thoroughly mixed.

About 200 g. was then wetted with distilled water under vacuum and left for 24 hr. 30 g. samples were then spread on each of the bottoms of the filters used in calibrating the stones. The soil was placed in direct contact with the earthenware filters, thoroughly

soaked with distilled water, and left for 24 hr. with the full suction of a water-pump applied to the filters. The soil was then sampled for moisture content. The remainder was immediately put into tins for the vapour-pressure measurement and, after further sampling for moisture content, was transferred to boiling tubes for freezing-point determinations.

The results of these experiments are shown graphically in Fig. 4. The moisture content and suction of the soil as it left the filters is represented by the letter D in a circle at
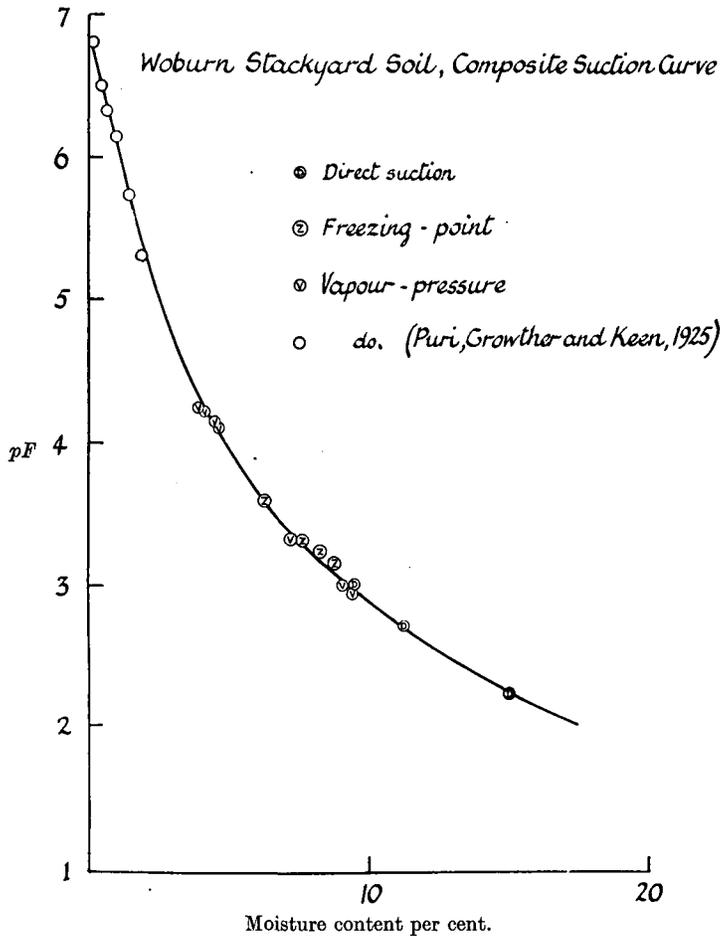

Fig. 4

pF 3. The two letters V in circles close beside it are the pF values calculated from vapour pressure and the corresponding moisture content. The three letters Z in circles a little to- the left show the pF values calculated from the freezing-point depressions and the corresponding moisture contents after allowing for the ice formed. The points further to the left show the results of vapour-pressure and freezing-point measurements in drier samples. The points to the right were obtained by applying lower suctions to the filter apparatus.

The results, as a whole, are very concordant, and the curve can be continued through the points calculated from the vapour-pressure measurements of Puri, Crowther & Keen (1925)

on a very similar sample of soil. A curve through the points for the freezing-point determinations would lie a little above one through the vapour pressure points. This may be because the ice formed in the freezing was a little underestimated. Of the two determinations, the vapour pressure is certainly the more reliable. The small discrepancy between the vapour pressure points and the suction point at pF 3 slightly exceeds the probable error of the vapour pressure measurements. Unfortunately the constant temperature room had to be vacated to permit of structural alterations before these measurements could be repeated and the cause of the slight discrepancy discovered.

SUMMARY

1. A filter apparatus cannot be relied upon to give a correct reading of the suction of soil water when this exceeds about 400 cm. of water.

2. Owing to the contribution of dissolved matter to the freezing-point depression the suction in a soil of normal low salt content can only be obtained from the freezing-point depression with reasonable accuracy when it exceeds about 4000 cm. of water (freezing-point depression greater than 0·3° C.).

3. Suctions in the range 400 to 4000 cm. have been measured with the aid of calibrated absorbers consisting of thin plates of Portland stone.

4. The plates were calibrated up to 1000 cm. by the application of suction through a filter, and above 1000 cm. by measuring the vapour-pressure depression by a new technique.

5. When applied direct to soil, the new vapour-pressure technique is more reliable than the freezing-point method, and can be applied to materials which do not exhibit a well-defined freezing-point.

6. A suitable soil was washed free from salts and brought to 1000 cm. suction on a filter. Measurements of the vapour-pressure depression and the freezing-point depression checked well with the thermodynamic formulae.

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