THE WILTING COEFFICIENT AND ITS INDIRECT DETERMINATION[1]

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THE WILTING COEFFICIENT

If the roots of a plant are well established in a mass of soil, the plant gradually reduces the water content until permanent wilting occurs. The water remaining in the soil under this condition has been termed non-available by previous writers. We have found, however, that plants can reduce the soil moisture content somewhat below the point corresponding to the permanent wilting of the leaves, so that the water content at the wilting point is not strictly non-available. In fact, this loss of water from the soil to the air goes on through the plant tissues even after the death of the plant, and appears to be limited only by the establishment of a state of equilibrium between the soil and the air. The plant during the drying stage acts simply as a medium for the transference of water, and while the rate of loss is reduced, the final result is the same as if the air and soil were in direct contact. By means of the wax seal method, which effectually prevents all direct loss of water from the soil, we have been able to demonstrate conclusively that there is a continued loss of water from the soil through the plant long after wilting occurs. This is shown by the results given in the accompanying table (table I).

The wheat seedlings were grown in sealed glass pots containing about 200 grams of soil. The second column of the table gives the water content of the soil corresponding to the wilting of the plants. The third column gives the number of days intervening between the wilting and the death of the plants, at which time the moisture content of the soil had been materially reduced, as shown in the fourth column. A still greater loss of water occurred during the subsequent period, at the end of which the moisture content of the

[1] Published by permission of the Secretary of Agriculture.

soil had been reduced to the point indicated in the last column of the table. The mean moisture content of the soil at the death point had been reduced to 85 per cent of the water content at the wilting point, while the mean soil moisture content at the end of the experiment was only 63 per cent of that at the wilting point.

TABLE I

THE WATER CONTENT OF THE SOIL IN SEALED POTS AT THE WILTING POINT AND DEATH POINT FOR KUBANKA WHEAT, AND AT A LATER PERIOD

Pot no.	Wilting point	Time interval in days	Death point	Time interval in days	Final percentage
4..........	7.0	28	5.2	126	3.1
6..........	7.9	25	5.9	126	2.6
7..........	7.0	25	5.5	126	3.5
8..........	6.6	19	6.4	126	4.9
9..........	7.1	27	5.9	134	4.8
10..........	7.8	27	6.9	134	5.9
11..........	6.9	19	5.9	126	4.3
12..........	7.3	27	6.6	134	5.9
13..........	8.0	27	6.9	37	6.1
14..........	7.3	27	6.2	134	4.9
Mean ...	7.3		6.2		4.6

The water remaining in the soil at the time the plant wilts cannot then with propriety be termed "non-available." We have shown that a considerable part of it is available, being absorbed by the roots of the dying or dead plant and evaporated from its aerial tissues, this process becoming slower and slower as the water content is reduced, and reaching its final limit in a condition of equilibrium between the soil and the air.

It appears advisable, therefore, to use a more specific term for the moisture content of the soil corresponding to the wilting point of a plant, and we have employed the term "wilting coefficient" in this sense in the present paper. The wilting coefficient is defined then as the percentage water content of a soil when the plants growing in that soil are first reduced to a wilted condition from which they cannot recover in an approximately saturated atmosphere without the addition of water to the soil.

The method used in determining the wilting coefficient has been described in a previous paper.[2] The plants are grown in small glass pots, evaporation from the soil surface being prevented by means of a wax seal. The conditions are maintained as nearly uniform as possible until the plants wilt permanently. Special care is taken to secure uniformity in the texture and water content of the soil mass before filling the pots. Sudden fluctuations in soil temperature are avoided by keeping the pots in a water bath during the growth of the plants. When these precautions are observed, the physiological measurement of the wilting coefficient is as accurate as the physical methods of measuring the moisture retentiveness of a soil. It is shown in the paper already referred to that the probable error of the mean wilting coefficient for 13 or more determinations is only about 0.005 of the actual determinations in the case of loam and clay soils. For single determinations the probable error is about 0.02 of the mean value. In the case of sands, the corresponding probable error is about twice as great as in the loam and clay soils.

INDIRECT DETERMINATION OF THE WILTING COEFFICIENT

In all plant investigations in which the water supply may become a limiting factor, it is necessary to determine from time to time the amount of moisture in the soil available for plant growth. If we make the specific assumption that growth cannot take place unless the water content of the soil is equal to or exceeds the wilting coefficient, then the percentage of soil moisture available for growth at any time is represented by the actual moisture content minus the wilting coefficient. If the actual water content is less than the wilting coefficient, then the percentage of available water is negative, that is, water to this amount must be added to the soil before any growth can take place.

The percentage of moisture in the soil at the wilting point varies greatly in different types of soil. This appears to have been established first by SACHS,[3] and has been further investigated

[2] BRIGGS, L. J., and SHANTZ, H. L., A wax seal method for determining the lower limit of available soil moisture. BOT. GAZ. 51:210–219. 1911; also The wilting coefficient for different plants and its indirect determination. U.S. Dept. Agric., Bur. Pl. Ind., Bull. 230. 1911.

[3] SACHS, J., Bericht über die physiologische Thätigkeit an der Versuchstation in Tharandt. Landw. Versuchs-Stat. 1:235. 1859.

by GAIN,[4] HEINRICH,[5] and more recently by HEDGCOCK.[6] No quantitative correlation between the soil texture and the non-available moisture was established, and only in the case of a few soil types was the non-available moisture recorded.

In field studies of soil moisture, determinations of the total water content can easily be made. The errors which enter into the determination of the wilting coefficient under field conditions are very great, due to the direct evaporation from the soil, local variation in soil texture, and non-uniform root distribution, combined with the difficulty of determining the exact wilting point when the roots occupy a large soil mass. Furthermore, it is only during periods of extreme drought that conditions are favorable for wilting coefficient determinations in the field. In view of these difficulties, it becomes important to ascertain whether the wilting coefficient can be determined by an indirect method based upon the relationship of the wilting coefficient to the moisture retentiveness of the soil as measured by physical methods.

Accordingly we have compared the wilting coefficient with the moisture equivalent, the hygroscopic coefficient, the moisture holding capacity, and mechanical analysis for a series of soils ranging from sands to clays. In the wilting coefficient determinations Kubanka wheat (Grain Investigations no. 1440) has been used as an indicator. The results of these comparisons are given in the following sections:

RELATION OF THE WILTING COEFFICIENT TO THE MOISTURE EQUIVALENT

The moisture equivalent of the soil is the percentage of water which it can retain in opposition to a centrifugal force 1000 times that of gravity.[7] In making the determinations the soils are

[4] GAIN, E., Action de l'eau du sol sur la végétation. Rev. Gén. Botanique 7:73. 1895.

[5] HEINRICH, R., Zweiter Bericht über die Verhältnisse und Wirksamkeit des Landwirtschaftlichen Versuchs-Station zu Rostock, 1894, p. 29.

[6] HEDGCOCK, G. G., The relation of the water content of the soil to certain plants, principally mesophytes. Bot. Survey Nebraska. VI. Studies in the vegetation of the State II. 1902:5–79.

[7] BRIGGS, L. J. and MCLANE, J. W., The moisture equivalent of soils. U.S. Dept. Agric., Bur. Soils, Bull. 45. 1907; also, Moisture equivalent determinations and their application. Proc. Amer. Soc. Agronomy (1910) 2:138–147. 1911.

placed in perforated cups and moistened with an amount of water in excess of the amount they can hold in opposition to the centrifugal force. After standing 24 hours, the cups are placed in a centrifugal machine, which is operated at a constant speed so chosen as to exert a force 1000 times that of gravity upon the soil moisture. Each soil then rapidly loses water until the capillary forces are increased sufficiently to establish equilibrium with the centrifugal force employed. The moisture content of each soil is now not only in equilibrium with a force 1000 times that of gravity, but is also in capillary equilibrium with every other soil which has been similarly treated, so that if the soils are placed in capillary contact in any combination whatever, no movement of water from one soil to another will occur. The moisture content of each soil under these conditions is the moisture equivalent of that soil. This method, then, provides a means of determining and comparing the retentiveness of different soils for moisture when acted upon by a definite force, which is measured in absolute terms and is reproducible within narrow limits.

In the accompanying table (table II) is given a comparison of the wilting coefficient and the moisture equivalent for a series of soils ranging in texture from a coarse sand to a clay. The names applied to the soils have been determined from the mechanical analyses in accordance with the soil classification table used by the Bureau of Soils.[8] The soils are arranged in the order of increasing moisture equivalents. For the moisture equivalent determinations we are indebted to Mr. J. W. McLane. All moisture determinations are expressed as percentages of the dry weight of the soil used.

The moisture equivalent determinations given in the table represent in each case the mean of two determinations. The number of wilting coefficient determinations made upon each soil is shown in the fourth column, and the mean of these determinations is given in the fifth column. The last column gives the ratio of the moisture equivalent to the wilting coefficient for each soil.

It will be seen from an inspection of the table that the soils used in the comparison show a wide range in moisture retentiveness,

[8] Soil Survey Field Book, 1906.

the moisture equivalent increasing from 1.6 per cent in sand to over 30 per cent in the clay loam; while the wilting coefficient ranges from 0.9 per cent in sand to 16.5 per cent in the clay loam. The mean ratio of the moisture equivalent to the wilting coefficient for all the soils examined is 1.84. The probable error of this mean is ±0.013; that is to say, considering the series to be representative of soils as a whole, the chances are even that if a similar series of determinations were made the mean of the ratios would fall between 1.827 and 1.853.

TABLE II

THE RELATION OF THE WILTING COEFFICIENT TO THE MOISTURE EQUIVALENT IN SOILS RANGING FROM SAND TO CLAY

No.	Soil type	Moisture equivalent	Wilting coefficient		Ratio of moisture equivalent to wilting coefficient
			No. dets.	Average	
7	Coarse sand	1.6	11	0.9	1.78
2	Fine sand	4.7	16	2.6	1.81
8	Fine sand	5.5	3	3.3	1.67
9	Fine sand	6.7	2	3.6	1.86
3	Sandy loam	9.7	9	4.8	2.02
10	Sandy loam	11.9	3	6.3	1.89
4	Fine sandy loam	18.1	13	9.7	1.87
12	Loam	18.9	3	10.3	1.83
A	Sandy loam	19.6	1	9.9	1.98
B	Fine sandy loam	19.9	1	10.8	1.84
C	Fine sandy loam	22.1	1	11.6	1.90
5	Loam	25.0	12	13.9	1.80
D	Loam	27.0	1	15.2	1.78
13	Clay loam	27.4	2	14.6	1.88
14	Clay loam	29.3	4	16.2	1.81
E	Clay loam	30.0	1	16.5	1.82
6	Clay loam	30.2	16	16.3	1.85

Mean...1.84
Probable error of mean.........±0.013

It will be noted that the greatest departures in the ratios are found among the sandier soils. This is due to the fact that a slight experimental error in determining either the moisture equivalent or the wilting coefficient affects the ratio markedly owing to the small percentages of moisture with which we are dealing in these soils.

The significant feature of the results here presented is the fact that through the wide range of moisture retentiveness exhibited by the soils employed, the ratio of the moisture equivalent to the wilting coefficient appears to be constant within the limits of experimental error. In other words, two determinations of the moisture retentiveness of these soils, one physical and the other physiological, show a linear relationship which is independent of the texture of the soil. The relationship is expressed by the following formula:

$$\frac{\text{Moisture equivalent}}{1.84 \pm 0.013} = \text{wilting coefficient.}$$

In order to compare the available moisture content of one soil with that of another, we must know or be able to estimate accurately the wilting coefficient of each soil. The minimum limit of moisture available for growth is the datum line from which all comparisons should be made. This datum can be established directly by wilting coefficient measurements, or it can now be calculated by means of the ratio just established. The latter method for field work is far simpler and more expedient. The soil sample taken in the field for soil moisture determination, although ample for duplicate measurements of the moisture equivalent, is usually not large enough for a single wilting coefficient determination. Moreover, the period of time required for wilting coefficient determinations, combined with the uncertainty which accompanies all physiological work when duplication is impossible, makes this determination less expedient and the results in such cases less reliable than those derived from the moisture equivalent by the use of the ratio here established.

The relationship established between the wilting coefficient and the moisture equivalent led us to believe that a similar relationship might be found for some of the other physical measurements of soil moisture retentivity. We have accordingly made similar comparisons of the wilting coefficient with the hygroscopic coefficient, the moisture holding capacity, and the soil texture, as expressed by mechanical analysis. The last mentioned determination does not measure moisture retentivity, but it does measure certain properties of the soil which determine the moisture retentivity to a large extent. We will now consider the results of these comparisons.

THE RELATION OF THE WILTING COEFFICIENT TO THE HYGROSCOPIC COEFFICIENT

When a dry soil is placed in a saturated atmosphere, it will absorb water vapor until a condition of approximate equilibrium is attained. The moisture content of a soil under such conditions is known as the hygroscopic coefficient of that soil.

The determination of the hygroscopic coefficient, unless carried out with special precautions, is not very exact. It is influenced by variation in temperature and by any departure from a condition of complete saturation of the surrounding air.[9] The time element is also an important factor, since the soil absorbs water very slowly, particularly near the point of equilibrium. In fact, equilibrium would not be theoretically obtained until the interstitial spaces of the soil were practically filled with water. The method thus has certain inherent disadvantages which are not encountered in moisture equivalent determinations.

The hygroscopic moisture determinations given in this paper were carried out in a double-walled ice chest kept in a subterranean room, where the temperature was approximately 20 C°.[10] The bottom of the chest was covered with water and the zinc walls were lined with blotting paper which was kept saturated.

A comparison of the hygroscopic coefficient and the wilting coefficient for a number of soils is given in the accompanying table (table III). The soils used are the same as those employed in the preceding experiments, being arranged in order of increasing moisture equivalents.

The hygroscopic determinations given in the table are the mean of duplicate measurements. The determinations range from 0.5 per cent in sand to 13.2 per cent in clay loam. The corresponding wilting coefficients have been discussed in connection with the preceding table.

The ratio of the hygroscopic coefficient to the wilting coefficient is given for each soil in the last column of the table. The mean of this ratio is 0.68, with a probable error of ±0.012. We have,

[9] HILGARD, E. W., Soils. 1906. p. 196.

[10] Determinations by J. W. MCLANE.

then, in this ratio a second method of determining the wilting coefficient, when the hygroscopic coefficient is known, as follows:

$$\frac{\text{Hygroscopic coefficient}}{0.68 \pm 0.012} = \text{wilting coefficient.}$$

HEINRICH[11] determined the non-available moisture in six types of soil, using the wilting points of corn and oats as indicators. He

TABLE III

THE RELATION OF THE WILTING COEFFICIENT TO THE HYGROSCOPIC COEFFICIENT IN SOILS RANGING FROM SAND TO CLAY

No.	Soil type	Hygroscopic coefficient	Wilting coefficient		Ratio of hygro. coefficient to wilting coefficient
			No. dets.	Average	
7	Coarse sand	0.5	11	0.9	0.556
2	Fine sand	1.5	16	2.6	0.577
8	Fine sand	2.3	3	3.3	0.698
9	Fine sand	2.3	2	3.6	0.639
3	Sandy loam	3.5	9	4.8	0.729
10	Sandy loam	4.4	3	6.3	0.699
4	Fine sandy loam	6.5	13	9.7	0.670
12	Loam	7.8	3	10.3	0.757
A	Sandy loam	6.3	1	9.9	0.636
B	Fine sandy loam	6.6	1	10.8	0.611
C	Fine sandy loam	7.5	1	11.6	0.646
5	Loam	9.8	12	13.9	0.705
D	Loam	9.6	1	15.2	0.631
13	Clay loam	11.8	2	14.6	0.808
14	Clay loam	13.2	4	16.2	0.815
E	Clay loam	11.2	1	16.5	0.679
6	Clay loam	11.4	16	16.3	0.700

Mean... 0.680
Probable error of mean......... ±0.012

also measured the hygroscopic coefficient of each soil used in his experiments. We have computed from his measurements the mean ratio of the hygroscopic coefficient to the wilting coefficient, together with the probable error of the mean, obtaining the value 0.696±0.03, as compared with the ratio 0.68±0.01 obtained from our experiments. While HEINRICH'S determinations show more variation than our own, the ratio obtained from his results agrees within the limits of his probable error with the ratio obtained in

[11] HEINRICH, R., *l.c.* 28–32.

our experiments. A single determination by ALWAY,[12] in which barley plants were used, gave a ratio of 0.65.

In the absence of a more definite relationship between non-available moisture and the hygroscopic coefficient, ALWAY[13] has advocated deducting the hygroscopic coefficient from the field soil moisture determinations as a basis for comparing the available moisture in soils. Our measurements, however, show that the wilting coefficient is about 1.47 times the hygroscopic coefficient, so that very misleading results may be obtained from this approximation, particularly when the moisture supply is limited. For example, consider two soils containing respectively 14.7 per cent and 20 per cent of water and each having a hygroscopic coefficient of 10 per cent. Under these conditions all the water in the first soil is practically non-available for growth, while the second contains over 5 per cent of available moisture. Simply deducting the hygroscopic coefficient would lead to the erroneous conclusion that both soils contained considerable available moisture.

It is important in this connection to distinguish clearly between the hygroscopic coefficient, as used above, and the hygroscopic water content, which is simply the water content of "air-dry" soil. The latter term has recently been used by DUGGAR,[14] who, in discussing HEINRICH's results as given by CAMERON and GALLAGHER,[15] says: "It will be noticed that so soon as the amount of water in ordinary soil becomes about three times the hygroscopic water content, it begins to assume physiological importance." The water content of air-dried soil may vary according to atmospheric conditions from practically zero in the case of some sun-dried desert soils to the hygroscopic coefficient

[12] ALWAY, F. J., Soil studies in dry land regions. Bur. Plant Industry, Bull. 130. 17–42. 1908.

[13] ALWAY, F. J., Studies of soil moisture in the "Great Plains" region. Jour. Agric. Sci. **2**:334. 1908.

[14] DUGGAR, B. M., Plant physiology. 1911, pp. 56, 57.

[15] CAMERON, F. K., and GALLAGHER, F. E., Bureau of Soils, U.S. Dept. Agric., Bull. 50, pp. 57, 58. An error occurs in CAMERON and GALLAGHER's paper in connection with HEINRICH's results. They give his determinations on air-dried soils, but state that these determinations were made after exposing the soils to a saturated atmosphere for a week.

when exposed in a saturated atmosphere. There is consequently nothing definite or reproducible about such determinations, unless the conditions under which the measurements were made are also known, and any ratio derived from such measurements is likely to give misleading results when applied to other determinations.

THE RELATION OF THE WILTING COEFFICIENT TO THE SATURATION COEFFICIENT AND THE "MOISTURE HOLDING CAPACITY" OF SOILS

The saturation water content or the saturation coefficient is the percentage of water held in the soil when all interstitial space is filled with water. The "moisture holding capacity" is the percentage of water a soil can retain in opposition to the force of gravity when free drainage is provided. This is dependent upon the height of the soil column employed, diminishing as the height of the column is increased.[16] When the soil column is made very short, for example 1 cm. in height, the two determinations are practically identical. Both are greatly influenced by the packing and the granulation of the soil, so that determinations are subject to wide variation in the hands of different observers.

In the accompanying table (table IV) the wilting coefficients of a series[17] of soils are compared with the moisture holding capacity. Following HILGARD,[18] the latter determinations were made with a soil column 1 cm. in height, with free drainage.

The moisture holding capacity of the soils used in the comparison ranged from 23 to 71 per cent. In this case the ratio between the moisture holding capacity and the wilting coefficient is not constant. However, an approximately constant relationship is obtained if the moisture holding capacity is first reduced by 21. The ratio of the moisture holding capacity less 21 to the wilting coefficient is shown in the last column of the table. The mean ratio for the 15 soils

[16] HILGARD, E. W., and LOUGHRIDGE, R. H., Rept. Calif. Sta. 1892–94.
BRIGGS, L. J., Mechanics of soil moisture. U.S. Dept. Agric., Div. of Soils, Bull. 10. 1897.

[17] In this work it was not possible to secure samples of all the soils used in the preceding experiments.

[18] HILGARD, E. W., Soils. 1906, p. 209.

examined is 2.90 ± 0.06. The relationship between the wilting coefficient and the moisture holding capacity is then:

$$\frac{\text{Moisture holding capacity} - 21}{2.9 \pm 0.06} = \text{wilting coefficient.}$$

TABLE IV

RELATIONS OF THE WILTING COEFFICIENT TO THE MOISTURE HOLDING CAPACITY

No.	Soil type	Moisture holding capacity percentage	Wilting coefficient percentage	Ratio of moisture holding capacity −21 to wilting coefficient
7...........	Coarse sand	23.2	0.9	2.44
2...........	Fine sand	29.9	2.6	3.40
8...........	Fine sand	28.5	3.3	2.27
9...........	Fine sand	31.4	3.6	2.84
F...........	Sandy loam	44.9	8.3	2.88
G...........	Sandy loam	50.1	9.5	3.06
H...........	Loam	55.9	11.0	3.17
I...........	Loam	58.6	11.6	3.24
J...........	Loam	59.8	11.7	3.30
86...........	Clay loam	54.2	13.8	2.40
K...........	Clay loam	58.2	14.7	2.52
L...........	Clay loam	63.2	14.9	2.83
M...........	Clay loam	71.3	15.0	3.35
N...........	Clay loam	67.2	15.7	2.94
O...........	Clay loam	69.5	16.7	2.90

Mean..........2.90

Probable error of mean ratio .... ±0.06

RELATION OF WILTING COEFFICIENT TO SOIL TEXTURE AS EXPRESSED BY MECHANICAL ANALYSIS

Soil texture has been more extensively used than any other physical property for the quantitative description of soils, and unfortunately it has been one of the most difficult to interpret from the standpoint of moisture retentiveness. Texture is quantitatively expressed by means of the mechanical analysis, which shows the composition of the soil when the particles are separated into groups according to size. The accuracy with which the texture of the soil can be expressed by this means is dependent upon the number of groups into which the particles are separated. But the difficulty of securing a complete separation of the finer particles into the desired groups places a practical limit upon the number of groups, which is usually limited to seven.[19]

[19] BRIGGS, L. J., MARTIN, O. F., and PEARCE, J. R., The centrifugal method of mechanical soil analysis. U.S. Dept. Agric., Bur. Soils, Bull. 24. 1904. p. 33.

The use of mechanical analysis as a basis for determining the moisture retentiveness of a soil is further complicated by the fact that soils having a high clay content will show great differences in the amount of colloidal material, which greatly affects the moisture retentiveness. Furthermore, the particles constituting a given group may lie much nearer one limit of the group than the other, so that a given group does not always have the same properties. We are then led to conclude that the particles constituting a given group in the mechanical analysis do not always have the same moisture retentiveness per unit mass, or that their specific retentivity when measured alone is modified to some extent by admixture with particles from other groups.

BRIGGS and McLANE,[20] using the method of least squares, have established a relationship between the mechanical composition and the moisture equivalent, based upon data covering 104 soil types. The resulting probable error of the coefficients in the relationship established is ± 1.7 per cent.[21] In attempting the correlation of the mechanical composition with the non-available moisture, we have used the same *relative* values for the sand, silt, and clay coefficients that were obtained by BRIGGS and McLANE in their moisture equivalent correlation. The actual values of the coefficients were adjusted to give the best calculated values for the wilting coefficient, but the same proportion among the coefficients was maintained. The formula used was as follows:

$$0.01 \text{ sands} + 0.12 \text{ silt} + 0.57 \text{ clay} = \text{wilting coefficient.}$$

In this formula the "sands" refer to the percentage of particles ranging from 2 to 0.05 mm. in diameter, the "silt" to particles from 0.05 to 0.005 mm. in diameter, and the "clay" to particles smaller than 0.005 mm. in diameter. In the accompanying table[22] (table V) is given the mechanical composition of each of the soil types, the computed value of the wilting coefficient as determined by the above formula, the observed value of the wilting coefficient,

[20] BRIGGS, L. J., and McLANE, J. W., *l.c.*, 18.

[21] This value should not be confused with the probable error of a single determination, as given by BRIGGS and McLANE.

[22] We are indebted to the Bureau of Soils for the mechanical analysis. No mechanical analyses were available for samples nos. 6 and 14.

and the residuals or the difference between the observed and the computed values.

TABLE V

COMPARISON OF THE OBSERVED WILTING COEFFICIENT WITH THAT FOUND BY COMPUTATION FROM THE MECHANICAL ANALYSIS

No.	Soil type	Coarse sand mm. 2—0.25 percentage	Fine sand mm. 0.25—0.05 percentage	Silt mm. 0.05—0.005 percentage	Clay mm. 0.005—0 percentage	Wilting coefficient: Computed percentage	Wilting coefficient: Observed percentage	Residuals	Ratio of obsvd. to comp.
7....	Coarse sand	60.4	37.1	0.8	1.6	1.8	0.9	+0.9	0.50
2....	Fine sand	28.2	64.4	4.7	3.9	3.1	2.6	+0.5	0.84
8....	Fine sand	35.4	55.1	4.8	4.5	3.6	3.3	+0.3	0.92
9....	Fine sand	29.9	56.7	5.0	8.2	3.8	3.6	+0.2	0.95
3....	Sandy loam	33.1	50.0	8.6	7.5	4.9	4.8	+0.1	0.98
4....	Fine sandy loam	2.8	59.8	30.2	6.9	10.3	9.7	+0.7	0.94
12....	Loam	3.4	55.5	21.8	19.1	9.5	10.3	−0.8	1.08
A.....	Sandy loam	32.4	28.8	26.7	11.8	9.9	9.9	0.0	1.00
B.....	Fine sandy loam	15.8	42.4	28.7	12.9	10.7	10.8	−0.1	1.01
C.....	Fine sandy loam	19.2	35.6	30.6	14.7	11.4	11.6	−0.2	1.02
5....	Loam	2.0	48.8	37.7	12.3	13.5	13.9	−0.4	1.03
D....	Loam	3.6	35.2	41.4	14.4	14.6	15.2	−0.6	1.04
14....	Clay loam	5.1	27.0	35.2	32.5	14.5	16.2	−1.7	1.12
E.....	Clay loam	3.2	43.7	45.1	17.1	16.0	16.5	−0.5	1.03
6....	Clay loam	4.4	20.5	52.6	22.0	16.6	16.3	+0.3	0.98

The ratio of the observed to the computed value of the wilting coefficient is also given in the last column of the table in order to provide a basis of comparison as regards accuracy with the other physical measurements. The mean ratio[23] is 1.00, with a probable error of ±0.025. This large probable error is due mainly to soil no. 1, which has a departure no greater than some of the other soils, but which on account of its very small wilting coefficient gives a ratio which is widely divergent from the rest of the series. The formula for computing the wilting coefficient, when affected with its probable error, then becomes:

$$\frac{0.01 \text{ sands} + 0.12 \text{ silt} + 0.57 \text{ clay}}{1 \pm 0.025} = \text{wilting coefficient.}$$

[23] In determining the values of the sand, silt, and clay coefficients so as to give a mean ratio equal to unity, soil no. 1 was disregarded, since a better general agreement was obtained in this way. This is virtually what would have happened if the method of least squares had been applied to the experimental data. In all calculations of probable error, however, this soil has been included with the rest.

COMPARISON OF THE ACCURACY OF THE INDIRECT METHODS FOR DETERMINING THE WILTING COEFFICIENT

Since the numerical value of the ratio used in calculating the wilting coefficient by indirect methods varies considerably according to the method employed, it is necessary for purposes of comparison to express the probable error in each case as a percentage of the ratio which it affects. This comparison is given in the accompanying table (table VI).

TABLE VI

SHOWING THE COMPARATIVE ACCURACY OF THE RATIOS USED IN THE INDIRECT METHODS FOR DETERMINING THE WILTING COEFFICIENT

Method	Ratio	Probable error of mean ratio	
		Absolute value	Percentage of ratio
Moisture equivalent.......	1.84	±0.013	±0.7
Hygroscopic coefficient.....	0.68	±0.012	±1.8
Moisture holding capacity ..	2.90	±0.06	±2.1
Mechanical analysis	1.00	±0.025	±2.5

The probable error of the mean ratio shows the degree of uncertainty that is attached to the value given for the ratio. That is to say, if the moisture equivalent series were repeated, the chances are even that the mean ratio would fall between 1.827 and 1.853. In other words, in a soil having an observed moisture equivalent of 18.4 per cent, the chances are even that in so far as the accuracy of the ratio is concerned the wilting coefficient lies between 9.93 and 10.07 per cent. This corresponds to an uncertainty of ±0.7 per cent in the value of the wilting coefficient calculated by means of the ratio 1.84, as shown in the last column of the table.

The last column of the table shows the probable error of the mean ratio expressed as a percentage of the ratio itself. This affords at once a means of comparing the accuracy of the different ratios. It will be seen that the probable error arising from the uncertainty of the ratio in calculating the wilting coefficient by the moisture equivalent method is about 0.7 per cent; by the hygroscopic coefficient method 1.8 per cent, or over twice as great; by the moisture-holding capacity method 2.1 per cent, or three times as great; and by the mechanical analysis method 2.5 per cent, or nearly four times as great.

It should be recognized clearly that the formulae which have been deduced will not necessarily give the correct calculated value of the wilting coefficient within the limits of the probable error of the ratio. The uncertainty regarding the value of the observed quantity (moisture equivalent, hygroscopic coefficient, etc.) enters into the calculation of the wilting coefficient for any particular soil, in addition to the uncertainty of the ratio. According to the formulae, a linear relation exists between the observed quantity and the wilting coefficient in each case, and the observed departures are attributed to accidental experimental errors. If this is true, then the probable error of the calculated wilting coefficient for a given soil can be made to approach the probable error of the ratio as a limit simply by increasing the accuracy and number of the determinations of the observed quantity.

The probable error of a single determination of the wilting coefficients in our experiments is given below for each method, expressed in per cent of the wilting coefficient.

Moisture equivalent method, ± 2.9 per cent
Hygroscopic coefficient method, ± 7.1 per cent
Moisture holding capacity method, ± 8.3 per cent
Mechanical analysis method, ± 10.0 per cent

These errors are not to be applied to any other determinations, since they represent simply the degree of accuracy attained in our particular experiments. If the number of physical measurements made upon each soil had been increased, the error would have been reduced.

FORMULAE SHOWING RELATIONSHIPS BETWEEN PHYSIOLOGICAL AND PHYSICAL MEASUREMENTS OF MOISTURE RETENTIVITY

For convenience in reference, the formulae for determining the wilting coefficient of a given soil by indirect methods are here presented in collected form, together with the probable error.

$$\text{Wilting coefficient} = \frac{\text{moisture equivalent}}{1.84(1 \pm 0.007)}$$

$$\text{Wilting coefficient} = \frac{\text{hygroscopic coefficient}}{0.68(1 \pm 0.018)}$$

$$\text{Wilting coefficient} = \frac{\text{moisture holding capacity} - 21}{2.90(1 \pm 0.021)}$$

$$\text{Wilting coefficient} = \frac{0.01 \text{ sands} + 0.12 \text{ silt} + 0.57 \text{ clay}}{1 \pm 0.025}$$

SUBSIDIARY FORMULAE

We have also included the subsidiary formulae which follow as the result of the interrelationships established. The probable error has been omitted, since its determination from the formulae would always include the experimental errors of the wilting coefficient determination, due to the fact that the physical measurements are not directly compared.

For the determination of moisture equivalent[24]

Moisture equivalent = wilting coefficient × 1.84
Moisture equivalent = hygroscopic coefficient × 2.71
Moisture equivalent = (moisture holding capacity − 21) × 0.635
Moisture equivalent = 0.02 sand + 0.22 silt + 1.05 clay

For the determination of the hygroscopic coefficient

Hygroscopic coefficient = wilting coefficient × 0.68
Hygroscopic coefficient = moisture equivalent × 0.37
Hygroscopic coefficient = (moisture holding capacity − 21) × 0.234
Hygroscopic coefficient = 0.007 sand + 0.082 silt + 0.39 clay

For the determination of the moisture holding capacity

Moisture holding capacity = (wilting coefficient × 2.9) + 21
Moisture holding capacity = (moisture equivalent × 1.57) + 21
Moisture holding capacity = (hygroscopic coefficient × 4.26) + 21
Moisture holding capacity = (0.03 sand + 0.35 silt + 1.65 clay) + 21

These formulae establish for the first time a relationship between the various physical and physiological measurements of moisture retentivity, and while the coefficients may be modified as a result of further investigation, it is believed that the equations will prove of practical value in the study of the relationship of the plant to soil moisture, both in the field and laboratory.

For the determinations of the maximum available moisture

The maximum moisture available for growth in any soil is represented by the difference between the moisture holding capacity and the wilting coefficient. It is possible, therefore, to express the *maximum* amount of available moisture that a soil is capable of holding in terms of the relationships given above. It should be recalled that the moisture-holding capacity determinations, upon

[24] These equations refer to moisture equivalent determinations made with a centrifugal force equal to 1000 grams and should not be confused with the equation given by BRIGGS and McLANE (*l.c.*) in which a force of 3000 grams was employed.

which the relationships are based, were made with a soil column 1 cm. in height. The amount therefore is far in excess of that found in drained soils under field conditions. The relationships are expressed in the following formulae:

Maximum available moisture = (wilting coefficient $\times 1.9$) $+21$
Maximum available moisture = moisture equivalent $+21$
Maximum available moisture = (hygroscopic coefficient $\times 2.8$) $+21$
Maximum available moisture = (0.02 sand + 0.23 silt + 1.08 clay) $+21$
Maximum available moisture = (moisture holding capacity $\times 0.65$) $+7$

The formulae show that difference in the maximum amount of available moisture that two soils are capable of holding is equal to the difference in their moisture equivalents; to 1.9 times the difference of their wilting coefficients; and to 2.8 times the difference of their hygroscopic coefficients.

Summary

An investigation was made to determine whether the wilting coefficient of a soil can be computed from physical measurements of its moisture retentivity. A comparison of the wilting coefficient is made with the moisture equivalent, the hygroscopic coefficient, the moisture-holding capacity, and the mechanical analysis, for a series of soils ranging from sand to clay. From this comparison, a series of linear relationships is established, as expressed in the following equations, which form a means of computing the wilting coefficient when direct determinations are not feasible.

$$\text{Wilting coefficient} = \frac{\text{moisture equivalent}}{1.84\,(1 \pm 0.007)}$$

$$\text{Wilting coefficient} = \frac{\text{hygroscopic coefficient}}{0.68(1 \pm 0.018)}$$

$$\text{Wilting coefficient} = \frac{\text{moisture holding capacity} - 21}{2.90(1 \pm 0.021)}$$

$$\text{Wilting coefficient} = \frac{0.01\text{ sand} + 0.12\text{ silt} + 0.57\text{ clay}}{1 + 0.025}$$

The second term of the quantity within the brackets shows the probable error of the relationship in each case, and constitutes a measure of the relative accuracy of the different methods.

U.S. Department of Agriculture
Bureau of Plant Industry
Washington, D.C.