A Method for Calculating Error of Soil Moisture Volumes in Gravimetric Sampling

BY
JOHN D. HEWLETT
JAMES E. DOUGLASS

THE MOST commonly used means of measuring soil moisture has been the gravimetric method (Lull and Reinhart 1955). Expressed in percent by weight, these measurements are of limited value in determining quantities of water in the soil, and in many studies it is necesary to convert them to quantitative units, usually inches of water per unit depth of soil. Soil moisture expressed in percent by volume is a more convenient value, one which can easily be converted to inches, acre-feet, or pounds of water per cubic foot of soil. Most hydrologic studies, including those to determine evapotranspiration rates from soil moisture depletion trends, require moisture estimates in volumetric units. Such estimates are difficult to obtain by gravimetric methods.

The Gravimetric Method

The gravimetric method of soil moisture sampling, as used in this paper, refers to the process of determining volumes of soil moisture by separate sampling of bulk density and moisture in percent of ovendry weight of soil. Conversion of mean moisture by weight ($\overline{Pw}$) and mean density ($\overline{D}$) in grams per cubic centimeter to mean moisture in percent by volume ($\overline{Pv}$) for any plot or area is as follows:

$$\overline{Pv} = \overline{D}\,\overline{Pw} \qquad (1)$$

Separate measurement is generally made necessary because of the damage which would be done to the sampling site if the difficult task of extracting undisturbed samples were attempted each time moisture estimates are needed. Moisture samples are therefore extracted by use of King (Viehmeyer) tubes, augers, and other devices at each sampling date, and bulk density is collected only once.

Moisture sampling tubes now in use have sharp cutting bits .75 inch inside diameter, designed to collect about 85 cubic centimeters of soil per foot of depth. Because of compaction, it has been found impossible in most soils to calculate density from tube samples with any degree of accuracy. The most popular density samplers are roughly four times the diameter of the King tube and collect about 250 cubic centimeters of relatively undisturbed soil.

Usually, sampling has been carried out on plots of various sizes, depending on local terrain, but seldom larger than a few hundred feet square. Density and moisture samples are both located independently within the plot, or in some cases density samples collected in adjacent areas are assumed to be satisfactory for estimating mean density. The aim is to express the average amount of soil moisture for the entire plot, often by horizons or strata. Because of the great amount of time and work involved, seldom are more than one or two plots established in a soil-cover complex (population). For this reason, practically no information is available on variation from plot to plot within a type boundary, although some data on variation of moisture and density from point to point within plots have accumulated.

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TABLE 1. Comparison of soil moisture estimates in percent by volume as calculated by various methods from the same data.

Bulk density and moisture estimates	Mean	Correl. with density	Standard deviation	Coef. of variation
Bulk density (250 cc sample)	1.082	—	0.15	.14
Pw_0 (from density sample)	35.16	—.87	6.1	.17
Pw_1 (tube sample 12″ away)	35.40	—.76	6.2	.18
Pw_2 (duplicate tube sample)	35.64	—.76	6.2	.18
$\frac{Pw_1 + Pw_2}{2}$ (mean tube sample)	35.52	—.82	5.5	.15
Pv_1 $(D \times Pw_1)$	38.30	—	—	—
Pv_2 $(D \times Pw_0)$ random pairing	37.85	—	8.7	.23
Pv_3 $(D \times Pw_0)$ paired with neighbor	37.47	—	5.1	.14
Pv_4 $(D \times Pw_1)$	37.75	—	3.9	.10
Pv_5 $(D \times \frac{Pw_1 + Pw_2}{2})$	37.66	—	3.5	.09
Pv_6 $(D \times Pw_0)$ undisturbed sample	37.26	—	2.7	.07

mean D and mean Pw are multiplied, the resulting estimate (Pv_1 in the table) is higher than the mean of all products. The positive bias is the result of negative correlation of D and Pw. In this case, a bias of $+1.04$ Pv is introduced by this short-cut multiplication, which, because samples are not customarily paired, has been the usual method of calculation in soil studies. In addition to the bias, another limitation of this method is the lack of valid information about the variance of the product $\bar{D} \times \bar{Pw}$. Since it is impossible to calculate covariance where samples are collected independently, equation (2) does not apply. In this case, the only way to determine variance is through very costly replication of plots.

In calculating Pv_2, moisture and density values were paired using a table of random numbers and the standard deviation of the products derived. The actual products have a standard deviation of 8.7 percent (Table 1); calculated from separate variance by equation (2), the standard deviation is about the same. As expected, the correlation coefficient r is not significantly different from zero, so that the third term of equation (2) drops out.

Pv_3 is calculated by pairing moisture from each undisturbed sample with density of the neighboring cluster (40 feet away). Because r has some significance at this distance, the standard deviation (5.1), whether by equation (2) or directly from the products, is less than for Pv_2.

However, if moisture samples are collected with a King tube within a foot of the density sample, the correlation coefficient averages $-.76$ and Pv_4 is considerably less variable (standard deviation 3.9 percent). Variance estimated on this basis compares favorably with that estimated from the undisturbed samples (Pv_6).

One further comparison demonstrates the effect of increasing the number of moisture samples to two in each cluster, both collected within 12 inches of the undisturbed sample. Pv_5 is calculated by multiplying each density value by the mean of two adjacent King tube samples. The correlation is somewhat higher than when a single Pw sample is used. The standard deviation is slightly reduced, from 3.9 to 3.5 percent by volume.

It might be possible to solve precisely for the optimum combination of D and Pw samples per cluster if the correlation were known in advance. Since, however, correlation must be determined on the collected data, this is of limited value. Perhaps the best rule of thumb is to base the proportion of density to moisture samples (within clusters) on the ratio of their respective coefficients of variation, estimated from prior knowledge of local soil conditions. From Table 1, the ratio would be .14/.18, or roughly one to one. One way to interpret this ratio is that just as much additional information would be secured by one more moisture as by one more density sample. In this case another moisture sample may be advisable, since the additional labor is small by comparison with that required to secure another density value. But it is also implied that a third moisture sample would supply very little information without additional density sampling.

Following the scheme outlined above, the total number of clusters, N, needed to sample an area of fairly uniform soil and cover conditions can be readily estimated from equation (2):

$$N = \frac{\bar{D}^2 S^2_{Pw} + \bar{P}^2_w S^2_D}{S^2_{\bar{P}v}} + \frac{2\,\bar{D}\,\bar{P}_w\, r\, S_D\, S_{Pw}}{S^2_{\bar{P}v}} \qquad (3)$$

Some prior knowledge of mean D and Pw, their respective variances and correlation, is needed to estimate in advance the clusters required to measure moisture in a soil strata to a given standard error. Generally the experimenter should have sufficient prior knowledge to gain a valuable lead on the size and nature of his sampling problem.

Application to Field Data

To demonstrate the use of this technique, comparison is made between soil moisture data at the Coweeta Hydrologic Laboratory and the Union Research Center of the Southeastern Forest Experiment Station. At Coweeta, soil texture is generally a fine sandy loam, and surface conditions have been relatively undisturbed in recent decades. Soils at Union Research Center contrast both texturally and in land-use history. Characteristic of the wide Piedmont belt of the Southeast, the soils at Union have truncated profiles. Under continuous cropping and subsequent abandonment, portions of the A and sometimes the B horizon have eroded away, leaving a 4- to 6-inch layer of sand at the surface.

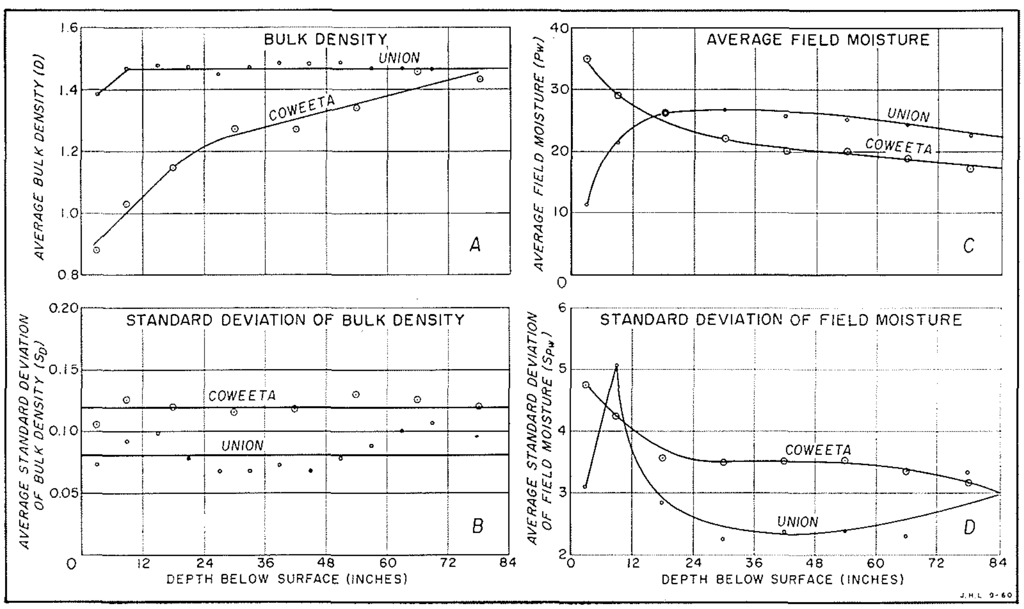

FIGURE 2. *A comparison of moisture and density variables which affect the precision of moisture estimates on plots at Coweeta and Union.*

The remainder of the profile is largely clay or clay loam.

The curves in Figure 2, compounded from thousands of observations in the two areas, illustrate differences between Coweeta and Union soils in moisture and density characteristics. Soils at Union are much heavier, but vary less than at Coweeta. However, there is a striking increase in bulk density with depth at Coweeta. The term "average field moisture" may be defined as the mean moisture (*Pw*) within specific strata around which seasonal or annual field moisture contents tend to vary. This follows from the fact that rainfall at the two centers is usually sufficiently well distributed to keep soil moisture fluctuating around a general level in each strata. Coweeta and Union (Figure 2c) illustrate trends in moisture content with depth below the surface.

Unfortunately, information about the correlation of *D* and *Pw* under various field conditions is scarce at both centers. Since the degree of correlation is crucial, the collected data must be relied on to furnish its estimate. But by using the average values from Figure 2 and assuming a range of correlation values, the size and difficulty of the sampling job necessary to meet study objectives can be estimated. Assuming, for the sake of illustration, correlation coefficients r equal $-.40$ and $-.80$, the number of clusters, each containing one *D* and one *Pw* sample, can be determined from equation (3). Table 2 contains these estimates for Coweeta and Union, giving *N* for a desired precision of one standard error equal 1 percent by volume (.12 inch per foot soil depth). Required numbers vary between strata; for example, the 6- to 12-inch layer at Union has proved to be particularly difficult to sample because of the textural discontinuity at the base of the plowed soil. Such layers might call for special treatment.

More important, however, Table 2 illustrates the influence of high correlation (assumed in this case) in reducing the size of the job in both types of soil. The data also illustrate the tendency for correlation to compensate for the seemingly erratic influence of separate variances in reducing sample numbers, particularly at Coweeta where density is light and variable. In the 6- to 12-inch layer at Union, however, an increase in correlation results in only slight reductions in *N*, possibly reflecting the mixture of two types of soil in this layer.

Discussion

Where normal variation in density does not involve drastic changes in texture, absolute volumes of soil moisture do not vary as much from point to point at Coweeta and Union as measurements on a percent-by-weight basis have indicated in the past. The standard deviation among 60 undisturbed

TABLE 2. The number of sample clusters (N) required at Coweeta and Union to hold expected standard error of moisture estimates to one percent by volume. (Data are listed for two assumed levels of correlation.)

Depth in inches	Coweeta		Union	
	$r = -.40$	$r = -.80$	$r = -.40$	$r = -.80$
0 - 6	22	7	16	13
6 - 12	18	6	47	37
12 - 24	17	7	15	8
24 - 36	17	8	11	5
36 - 48	18	9	11	5
48 - 60	19	10	11	5
60 - 72	19	11	12	6
72 - 84	18	10	15	8

samples of moisture volume referred to in Table 1 (Pv_6) was only 2.7 percent in quite variable forest soil. This constitutes a coefficient of variation of only .07, compared with .14 for density and .17 for *Pw* when measured separately.

Restricting gravimetric sampling to plots to reduce variation is therefore of little value unless many replications of the plot are possible, or the plot itself is the entire population to be sampled. In the former case, the optimum plot will most likely become the "cluster." In the latter case, paired samples within the plot will eliminate bias and help increase precision.

Consideration of the data in Table 1 and Figure 2 suggests that plot area limitation is not so critical as it may appear. Coefficients of variation in the 0-6 inch stratum, as determined from many 33 × 33-foot plots at Coweeta (plotted values in Figure 2) are .12 for density and .14 for moisture. Comparable coefficients on the 10-acre stand were .14 and .18, respectively. The increase in variance on the larger area is mostly compensated, in terms of moisture in percent by volume, by a corresponding higher correlation of *D* and *Pw* as their respective ranges increase. With a sampling design which takes advantage of correlation, the size of the sampling block may be less critical than is usually expected. Careful delineation of sampling areas to eliminate obvious differences in soil-vegetation cover types will usually be sufficient. Some additional precision may be obtained, as in any sampling problem, by arbitrary stratification into smaller blocks, each to be sampled by random methods. In this way the term "plot" becomes equivalent to "cluster" as defined above, and the collected data become more amenable to standard statistical treatment.

In general, moisture values which have an error greater than 1 percent by volume will be of little value in most comparative studies of soil moisture, whether comparison is from place to place, or from time to time. Using the tools referred to earlier, precision in the order of 1 percent will be hard to obtain where bulk density has a coefficient of variation .05 or greater. A 1-percent change in moisture in a 12-inch soil stratum is roughly the evapotranspiration to be expected on an average day. If it requires 10 to 20 sample clusters (Table 2) to provide this limited level of precision, the use of gravimetric sampling in studies of evapotranspiration at Coweeta and Union has doubtful possibilities.

Fortunately, newer methods are available. One now in fairly general use involves a radioactive source which emits "fast" neutrons. As these are slowed down by collision with hydrogen atoms (chiefly present as water in soils), their contact with a detector tube makes possible the measurement of the density of the moisture field surrounding the source. Thus, by neutron-scattering methods (Van Bavel 1958), soil moisture in percent by volume can be estimated independently of bulk density variations. Furthermore, by permanent installation of access tubes in field soils, changes in soil moisture with time can be observed directly in percent by volume, rather than as differences between two independent samples of moisture. When these instruments are perfected, their superiority in principle over the gravimetric methods may result in virtual replacement of the latter in many field studies.

Summary

The precision of estimates of soil moisture on a volume basis by gravimetric sampling methods is examined in theory, particularly as applied at the Coweeta Hydrologic Laboratory in the mountains of North Carolina and the Union Research Center in the Piedmont of South Carolina. The method most commonly used in research in hydrology, forestry, and agriculture is one involving separate measurement of bulk density and moisture in percent by weight, from which percent by volume contents are computed. It is shown that correlation between these two variables greatly affects the precision of estimate. A method of

calculating sampling error (instrumental error not separated) is presented, and its implications with regard to sampling design examined. Results indicate the importance of pairing density and moisture samples as closely together as possible, which leads to the conclusion that sample "clusters" are superior to plots, as the latter have been used. A field test is described in which the effects of different methods of calculating moisture in volumes are illustrated and compared.

Application of these techniques to average values of moisture, density, and their variances at the two research centers demonstrates the value of statistical methods in determining the size of the sampling job. It is pointed out, however, that even at best the limitations of the gravimetric method in these soils will for the most part preclude its use for hydrologic purposes.

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