

DETERMINING WATER CONTENT OF DIFFERENT SOILS BY THE NEUTRON METHOD

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The neutron scattering method for measuring soil water content has been used extensively in soil water studies. Its wide acceptance results from the greater precision and rapidity of measurement than is possible with the gravimetric method. Additional major advantages of the neutron method over other methods include measurement in a relatively large volume of soil and over the full range of soil water.

As the neutron method developed, universality of the calibration curve was frequently stated or implied (6, 8). As a consequence, much use of the method has been based on acceptance of one calibration curve for all mineral soils. However, a few published results indicate that the calibration for neutron depth probes may be significantly affected by the soil apart from its water content (2, 3, 5). The basis for the development of the method is the interaction of fast neutrons in the soil with hydrogen of the water molecules. Although this interaction accounts for the preponderance of neutron interactions in moist soil, the relationship of count rate to water content can be affected by non-water hydrogen and certain chemical elements which either scatter or capture slow neutrons to some degree.

A major disadvantage of the depth probe used in the neutron method has been its reported unsuitability for measurements near the surface. Fast neutrons escape into the atmosphere resulting in a reduced sensitivity of the measurement.

Inasmuch as the neutron method is primarily used to determine soil water content *in situ* a field study was undertaken (1) to ascertain

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the relationship between count rate and water content for soils differing in texture and bulk density and (2), to evaluate calibration at shallow depths.

MATERIALS AND METHODS

A Nuclear-Chicago P-19^a depth probe with a 3.97-mc., Ra-Be source was calibrated in five field soils. Counting rates were obtained from a Nuclear-Chicago 2800-A² portable scaler. Three of the selected soils were of the Hanford series and were located within a radius of one kilometer. The textures of these soils were loamy sand, sandy loam, and very fine sandy loam with bulk densities of 1.44, 1.50, and 1.32 g/cc., respectively. The remaining soils were an Arlington sandy loam with a bulk density of 1.63 g/cc. and a Ducor clay with a bulk density of 1.61 g/cc. Seven aluminum access tubes were installed to a depth of 90 cm. on a 6 m. × 6 m. area of nearly level soil at each site. Tubing had an outside diameter of 4.45 cm. and a wall thickness of .147 cm. Soils were wetted to at least 60 cm. below the depth of measurement. Data for calibrations were obtained at intervals under a drying regime for a rainless summer period of six weeks. Each set of readings on a subsequent date required using a different access tube at a soil site. Care was taken to level the soil around access tube and to maintain the same length of tube above the soil surface for each set of readings. Soil water content was determined by the gravimetric method.

The following procedure was employed each time measurements were made. The probe was placed with the effective center of measurement at 15-cm. depth intervals beginning at 7.5 cm., and 1-minute counts were made. Immediately following the operation soil samples were taken

²Trade names and company names are included for the benefit of the reader and do not imply any endorsement of the equipment by the U.S.D.A.

TABLE 1
Percentage of count rate variation associated with
change in soil water content

Soil	Depth		
	>30 cm.	15-30 cm.	0-15 cm.
Hanford loamy sand	97	97	98
Hanford sandy loam	99	99	98
Hanford v. f. sandy loam	97	90	98
Arlington sandy loam	76	96	97
Ducor clay	94	90	99

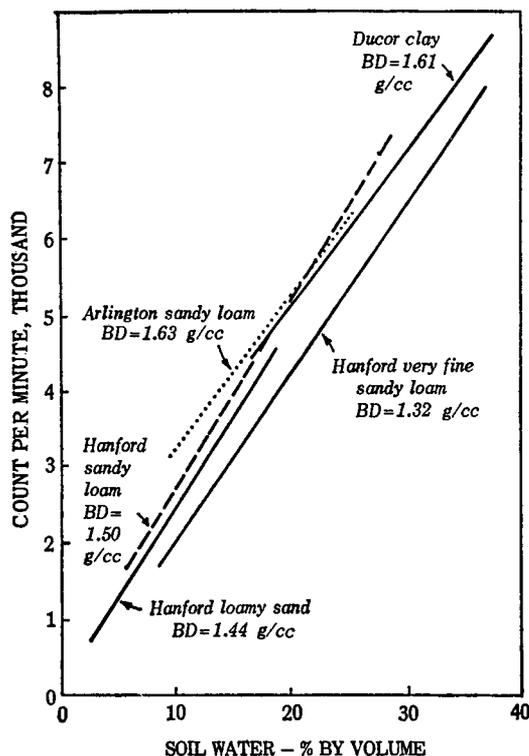


Fig. 1. Neutron calibration curves for different soils at depths greater than 30 centimeters.

in 15-cm. depth increments, weighed and dried to constant weight at 105°C. Six samples per increment were taken in a circular pattern within 15 cm. of the tube and the water data were averaged. Soil bulk density in 15-cm. increments to a depth of 45 cm. was determined with a volume sampler for each soil at each sampling date. Bulk density measurements for increments between 45 and 75 cm. were obtained once for each soil. Standard deviations for all bulk density determinations below the 30-cm. depth

were 0.03, 0.03, 0.02, 0.06, and 0.05 g/cc. for the Hanford very fine sandy loam, Hanford sandy loam, Hanford loamy sand, Arlington sandy loam, and the Ducor clay, respectively. Six 1-minute standard shield counts were made immediately before and after counts were made for the soil. These shield counts were made 61 times over the 5-week study period. The standard deviation of the averages of the sets of 6 counts was 78 counts per minute. Because of this low variability in instrument performance, actual counts in the soil were not related to shield counts for calibration but were directly plotted against soil water content. Regression equations were calculated for the 0-15, 15-30, and >30-cm. soil depths.

RESULTS

Count rate was closely associated with volumetric water content for each soil and depth (table 1). A good linear fit between count rate and water content was obtained for the shallower depths as well as for the combined deeper increments. With one exception change in soil water content accounted for 90 per cent or more of the change in count rate. A very high correlation between count rate and water content throughout was obtained for the two coarsest textured Hanford soils. The finer textured Hanford very fine sandy loam and Ducor clay showed slightly lower correlations at the 15- to 30-cm. depth.

Soil effects

The relationship between count rate and soil water content at depths below 30-cm. varied among the soils studied (fig. 1 and table 2). For example a much lower count rate was obtained with the neutron method for a given water content in the Hanford very fine sandy loam than in the other soils. This difference was significant at the 5 per cent level of probability. Assuming a rate of 5000 CPM and the maximum difference among calibrations for the soils used in this study, the error would be 4.4 per cent water by volume or approximately 0.8 surface cm. for a 15-cm. depth increment. This error would be markedly increased as data, for several depth increments are summed to determine the water content of a rooting or storage zone.

The calibration curves shown in fig. 1 and defined in table 2 cover the ranges of soil water

TABLE 2

Count rate (CPM) as determined from calculated regression on volumetric water content, P_v , for three soil depths

Soil	Depth		
	>30 cm.	15-30 cm.	0-15 cm.
Hanford loamy sand	144 + 237P _v	410 + 183P _v	21 + 129P _v
Hanford sandy loam	322 + 244P _v	143 + 246P _v	15 + 130P _v
Hanford v. f. sandy loam	-104 + 220P _v	724 + 203P _v	-260 + 161P _v
Arlington sandy loam	1244 + 200P _v	-427 + 259P _v	253 + 116P _v
Ducor clay	1188 + 198P _v	380 + 219P _v	-2043 + 211P _v

content encountered in the field. Therefore, the count rate at zero water content was not determined. If the curves obtained are extrapolated some will not show a zero count rate for zero moisture content. Laboratory calibration curves obtained at low soil water contents by Marais and Smit (3) suggest that such relationships can be expected. Results of field studies by Holmes (1) indicate negative intercepts if curves relating count rate and equivalent water content are extrapolated.

Slopes of regression lines relating count and per cent water by volume below 30 cm. were similar for the different soils. Regression coefficients ranged between 198 and 244 and were not significantly different at the 5 per cent level (table 2). A common slope for the regressions indicates that one calibration curve would have been satisfactory for estimating net changes in water content, which occur over an interval of time in the field. At the 15- to 30-cm. depth there was no statistically significant difference among soils either in slope or intercept of the regression lines.

A common calibration curve also would have been satisfactory for measuring soil water content in the 0- to 15-cm. layer of the three coarser textured soils (fig. 2 and table 2). Statistical analysis showed the Hanford loamy sand, Hanford sandy loam, and Arlington sandy loam to be of the same population with respect to water content as determined from their calibration curves. However, the slopes of the two finer textured soils, Hanford very fine sandy loam and Ducor clay, were each of a different population and separate calibration curves are necessary for these two soils.

Depth effects

As would be expected from the escape of fast neutrons into the atmosphere, the change in

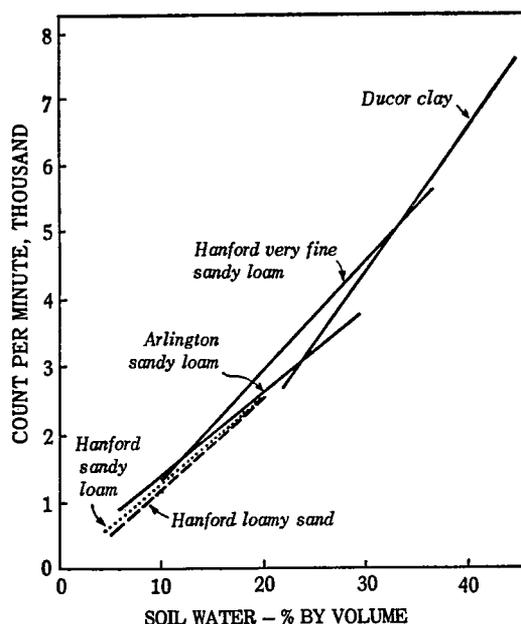


FIG. 2. Neutron calibration curves for different soils at the 0-15 cm. depth.

count rate with change in moisture content was much less in the 0- to 15-cm. depth than for greater depths. Calibration curves obtained at greater depths are obviously not satisfactory for determining soil water in the surface 15 cm. The average regression coefficient for the loamy sand and the sandy loams at the 0- to 15-cm. depth was 55 per cent of that calculated for below the 30-cm. depth. With finer texture and greater moisture-holding capacity this difference decreased, and for Ducor clay regression coefficients at all depths were similar.

Regression coefficients for the 15- to 30-cm. layer in each soil was similar to those for greater depths. The regression coefficient for the Hanford loamy sand, the coarsest textured soil was

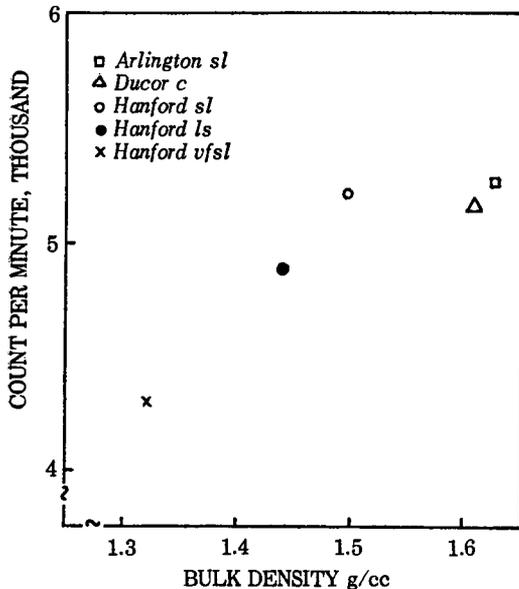


FIG. 3. Change in count rate with bulk density of the soil at 20 per cent water by volume.

statistically different from the coefficients for other soils although the magnitude of difference was relatively small. Therefore, net changes in water content in the 15- to 30-cm. depth could have been measured satisfactorily using the calibration curves for below 30 cm. Intercepts of the regression lines for the 15- to 30-cm. layer, however, were markedly different from greater depths for the three intermediate textured soils. The error in the amount of water measured would therefore be large if only a single calibration curve was used for depths greater than 15 cm. in each of these soils.

Bulk density effects

Calibration curves for soils at depths greater than 30 cm. show a higher count rate for soils with higher bulk density at a given water content (fig. 1). The apparent effect of bulk density is to change the amount of water indicated without markedly changing the slope of the calibration curve. Statistical analysis of the regression equations was previously discussed. Inasmuch as the calibration curves for a sandy loam and a clay were similar but markedly different from the calibration curve for a very fine sandy loam, it appears that texture *per se* had no effect below the 30-cm. depth.

The relationship between count rate and

bulk density for these different soils suggests that the effect of bulk density on count rate is dependent on other soil characteristics (fig. 3). The count rates for the Arlington and Ducor soils which have much higher bulk densities were equivalent to that for the Hanford sandy loam. Among the closely related soils of the Hanford series bulk density apparently is the chief factor affecting soil water measurement by the neutron method (fig. 3). A change of 0.1 g/cc. in bulk density was equivalent to a count change of 500 per minute at 20 per cent water by volume. Non-water hydrogen and certain other soil elements with a relatively high cross section for scatter of slow neutrons would increase the counting rate. Marais and Smit (4) showed that hydrogen present in organic matter increases the count rate for a given water content. Some soil elements, notably boron, have a high cross section for capture of slow neutrons thereby decreasing the counting rate. By adding boron to soil Holmes and Jenkinson (2) changed the calibration curves for the neutron meter. The observed effect of the different groups of effective soil constituents depends on their relative contents. On a volume basis these contents are bulk density dependent. Increasing the bulk density of material high in non-water hydrogen was shown by Marais and Smit to markedly increase the counting rate at the same water content.

Bulk density of soil may change with depth in the profile. The effect of such a change is illustrated in fig. 4. The regression line for the 15- to 30-cm. depth where bulk density was higher shows a higher count rate. The difference while not great is statistically significant. It suggests that a single calibration curve may not be adequate for moisture measurements even in a soil at depths where escape of neutrons is not a factor.

DISCUSSION

Indiscriminate use of a single calibration curve developed for a single soil at one bulk density may lead to substantial error in soil water measurements with the neutron method. Accurate determination of soil water content requires a knowledge of the soil bulk density, including changes in this property with depth of measurement. Changing the bulk density of a soil 0.2 g/cc. would markedly affect the neutron meter calibration curve. Adjusting the calibra-

tion curve for different bulk densities appears feasible and such adjusted curves may be sufficiently accurate for other soils of the same series as shown by these results. However, if widely different soils are involved in soil water measurements with the neutron method, a calibration curve would be required for each soil. In this respect, our results agree with those recently reported by Holmes (1). His data also show a marked effect of the soil on count rate change with water content. For many field experiments, especially those where repeated measurements are made, the neutron method is the most satisfactory for determining soil water even though an on-site calibration is necessary.

Our results, like those of Marais and Smit (4), show that the calibration curve has more universality for determining changes in soil moisture content than in determining the amount of water *per se*. The paucity of published calibration data on different soils precludes drawing any far-reaching conclusions from this observation, however.

A high linear correlation between count rate and soil water content can be obtained for surface layers above 15 cm., provided the geometry of the surface and bulk density remains constant. A uniformly level soil surface was maintained for measurements in this study. A similar condition is required when using a surface probe (7). Usually a significant loss in sensitivity of measurement occurs with the neutron source at the 7.5-cm. depth. Soil texture largely determines the magnitude of this effect. Whereas for coarse-textured soil the method was found to be one-half as sensitive at the 0- to 15-cm. depth increment as at increments below 30 cm., there was little difference for clay at the field water contents observed.

The necessity for developing a separate calibration curve for the 15- to 30-cm. depth will usually depend on physical characteristics of the soil. The surface effect on count rate extends deeper in coarse-textured soil with its lower water content. Another limitation to including this depth with greater depths for calibration may be the changed bulk density resulting from previous tillage effects.

Inasmuch as bulk density may vary significantly within a soil profile, calibration of the neutron method at more than a single bulk density for a given soil may be necessary for ac-

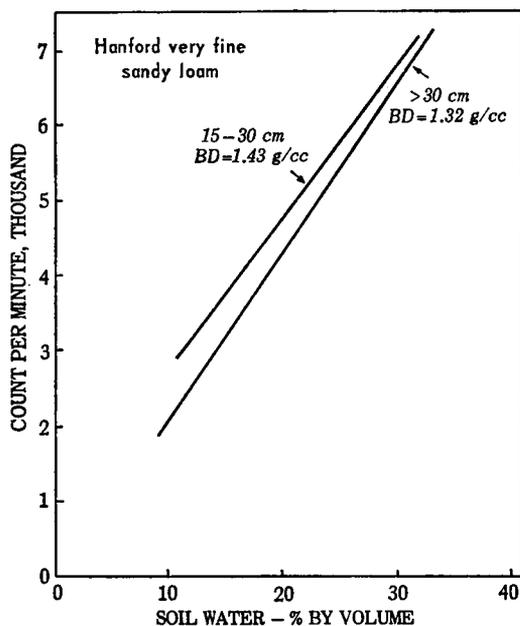


FIG. 4. Effect of bulk density on counting rate at a soil sampling site.

curate water content measurements. Most satisfactory use of the neutron method in agronomic experiments will depend on the selection of soil areas which are as uniform as possible.

SUMMARY

The relationship between count rate obtained with the neutron method and soil water content below the 30-cm. depth differed for several soils. The maximum difference observed was equivalent to 4.4 per cent water by volume or approximately 0.8 surface cm. for a 15-cm. depth increment. Curve slopes were similar for the soils investigated. Higher count rates were associated with a higher bulk density of the soil. Soils for which the counting rate difference was the greatest, differed 0.3 g./cc. in bulk density. Counting rates for soils of the same series were closely related to bulk density in contrast to the lack of a relationship among series. The most accurate soil water determinations, by the neutron method, require calibration for the soil in question including the consideration of bulk density changes in the profile.

A high linear correlation between count rate and soil water content was obtained for the 0- to 15-cm. layer. Repeated field determinations of soil water content in the undisturbed 0- to 15-

cm. layer can be satisfactorily obtained by calibrating for the particular soil and carefully controlling depth of measurement.

REFERENCES

- (1) Holmes, J. W. 1966 Influence of bulk density of the soil on neutron moisture meter calibration. *Soil Sci.* 102: 355-360.
- (2) Holmes, J. W. and Jenkinson, A. F. 1959 Techniques for using the neutron moisture meter. *J. Agr. Eng. Res.* 4, 100-109.
- (3) Marais, P. G. and W. B. de V. Smit. 1960 Laboratory calibration of the neutron moisture meter. *S. African J. of Agr. Sci.* 3: 581-599.
- (4) Marais, P. G. and W. B. de V. Smit. 1962 Effect of bulk density and of hydrogen in forms other than free water on the calibration curve of the neutron moisture meter. *S. African J. of Agr. Sci.* 5: 225-238.
- (5) Mortier, P. and DeBoodt, M. 1956 Determination of soil moisture by neutron scattering. *Netherlands J. Agr. Sci.* 4, 111-113.
- (6) Stolzy, L. H. and G. A. Cahoon. 1957 A field-calibrated portable neutron rate meter for measuring soil moisture in citrus orchards. *Soil Sci. Soc. of Am. Proc.* 21: 571-575.
- (7) Van Bavel, C. H. M. 1961 Neutron measurement of surface soil moisture. *J. Geophys. Res.* 66: 4193-4198.
- (8) Van Bavel, C. H. M., Nixon, P. R., and Hauser, V. L. 1963 Soil moisture measurement with the neutron method. *Ag. Res. Serv.* 41-70, 39 pp.