EXPLOITS AND ENDEAVOURS IN SOIL WATER MANAGEMENT AND CONSERVATION USING NUCLEAR TECHNIQUES[*]

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Abstract

Soil water management and conservation efforts have been immensely aided by the advent of nuclear techniques since the 1950s, most notably by the introduction of the neutron moisture meter (NMM). At the end of World War II, the understanding of nuclear physics had increased tremendously, and there was a concerted effort to turn this knowledge to productive and peaceful uses. In 1949, a method for "the measurement of the moisture content of soil by the slowing of neutrons" was described and subsequent research and development resulted in commercial availability of the NMM by the late 1950s. Research on water management and conservation began replacing gravimetric sampling with the NMM almost immediately, and crop water use data for a wide range of annual and perennial crops in a wide range of soils and climates became available in the 1960s. Although weighing lysimeters remained an important tool for crop water use determination, the wide range of soil and climate effects could not have been investigated without the NMM due to the expense of lysimeters. Advantages of the method included, and still include, a relatively large sampling volume, so that fewer samples are required, and precision better than 0.01 m^3 m^{-3} when correctly calibrated, which exceeds that of gravimetric sampling for equal numbers of samples. The NMM was used for irrigation scheduling in research in the 1950s. But, in the early 1970s, improvements in portability, reliability, and user interface allowed the NMM to become an important tool for irrigation scheduling in production farming. Many of the uses of the NMM require measurement of the change over time of soil water stored within and below a crop or plant stand root zone. Accurate measurement of changes in water content depends on the accuracy of the calibration equation slope. Calibrations are specific to soils and soil horizons, so site-specific calibration is required. Because errors in calibration slope are likely without correct calibration methods, research on calibration methods is discussed and guidelines for accurate calibration are given.

1. INTRODUCTION

At the end of World War II, the understanding of nuclear physics had increased tremendously, in particular the interactions of neutrons with atoms, which knowledge was essential to the development of the atomic bomb and fission reactors. There was a concerted effort to turn this knowledge to productive and peaceful uses. In 1949, George Pieper described a method for "the measurement of the moisture content of soil by the slowing of neutrons" [1]. In 1950, the US Civil Aeronautics Administration published Technical Report 127, describing a method for measuring soil moisture based on neutron thermalization [2]. Independently, Wilford Gardner and Don Kirkham developed essentially the same method, which was published in Soil Science [3]. The method is based on two facts. First, of the elements common in soils, hydrogen is by far the most effective in converting fast neutrons to thermal neutrons through collisions. Second, of the hydrogen-bearing soil constituents, water is usually the most plentiful and the only one that changes rapidly to an important extent.

The method uses a radioactive source of fast neutrons (mean energy of 5 MeV) and a detector of slow neutrons (~0.025eV or 300 K). High-energy neutrons emitted from the source (~10^{27}/s) are either slowed through repeated collisions with the nuclei of atoms in the soil (scattering), or are absorbed by those nuclei. A small fraction will be deflected back to the detector. Of these, an even smaller fraction (~10^3/s) will have been slowed to thermal (room temperature) energy levels and will be detected. The most common atoms in soil (aluminium, silicon and oxygen) scatter neutrons with little energy loss

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[**]http://www.cprl.ars.usda.gov/programs/.

because they have much greater mass than a neutron. However, if the neutron collides with a hydrogen nucleus its energy is reduced on average to about half, because the mass of the hydrogen nucleus is the same as that of the neutron. On average, nineteen collisions with hydrogen are required to thermalize a neutron. Carbon, nitrogen, and oxygen are relatively less efficient as neutron thermalizers (about 120, 140 and 150 collisions, respectively). The concentration of thermal neutrons changes mainly with the hydrogen content of the surrounding material. On the time scales of normal interest in water management, changes in H and O content occur mainly due to changes in soil water content. Thus, the concentration of thermal neutrons can be directly related to soil volumetric water content.

The US Corps of Engineers contracted with Nuclear-Chicago Corporation[1] in 1955 to design and manufacture a portable field system; and by 1960 several hundred neutron moisture meters (NMMs) were in use [4]. They were produced by other companies and institutions around the world, and began to be used in agricultural and hydrological research. Early NMMs were two-piece units consisting of a scalar readout and associated counting circuitry in one enclosure, connected by a cable to a cylindrical probe that was locked in a radiation shield when not in use, and that was lowered into a cylindrical, cased hole in the soil for readings. The probe contained a radioactive source of fast neutrons and a detector tube for detecting thermalized neutrons. This system is a profiling NMM and has been used to measure soil profile water contents to many meters depth. Alternatively, the scalar and cable were connected to a flat-bottomed unit that contained both the source and detector tubes, and which was placed on the soil surface. In either case, precision of early units was lower than we see today. For instance, Hauser [5] analysed multiple soil profile readings and found that moisture measurements in 183-cm deep profiles would have to differ by more than 1.6 cm before being considered significantly different. He attributed about half the error to the imprecise timers available. Work through the 1950s and early 1960s focused on equipment designs to improve depth resolution, linearity of the calibration, and portability; and on laboratory and field tests to measure the volume of influence and its center in relation to the probe geometry.

For profiling NMMs, the measurement volume is approximately a sphere with radius of about 0.15 m in a wet clay soil and increasing to 0.5 m as water content declines to 0.02 m^3 m^{-3} [6]. For a soil of specified volumetric water content (θ_v, m^3 m^{-3}), about 95% of the measured slow neutrons are from a sphere of radius R (cm) [7]:

$$R = 100/(1.4 + 10\theta_v) \tag{1}$$

However, since 1965 the design, detector efficiency, and source strength of profiling NMMs has changed such that measurement volumes may be smaller and depth intervals between readings as small as 0.15 m are useful [8].

For non-intrusive measurements, the surface NMM is placed on the soil surface. The source and detector are located just above the base of the meter and are commonly separated by several cm. The volume measured is roughly hemispherical and extends into the soil for a distance that decreases as the soil water content and density increase, and which varies from ~0.15 m in wet soil to ~0.3 m in dry soil [6]. The precision is less than can be attained with a profiling meter; and it suffers even more when soil moisture changes greatly with depth near the surface [9], a common occurrence. Good precision has been reported under fairly stringent conditions including: 1) flattening the surface to fit the gauge bottom with no air gaps, 2) marking the measurement site so that the gauge can be repeatedly placed in identical position, and 3) using a cadmium neutron absorber shield around the meter (except for the bottom) to reduce effects of surrounding vegetation [10]. However, even in the latter study the strong depth dependency of calibration coefficients and the inability to accurately estimate the depth of reading led to great uncertainty as to the accuracy of measurements. For example, calibrations developed for the surface to 2-cm and surface to 8-cm depth ranges could not be used to accurately determine the water content in the 2- to 8-cm depth range.

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[1]Mention of trade names or other proprietary information is made for the convenience of the reader and does not imply endorsement, recommendation or exclusion by the USDA-Agricultural Research Service.

Extensive work measuring crop water use with the neutron probe began in the early 1960s in Israel [11,12] and in the late 1950s in the United States [13–15]. In Israel, water requirements were measured for eight field crops, five orchard crops, and four other species over a 20-year span from 1954 to 1974, with the NMM being used after 1963 [11,12]. In Israel, this work clearly demonstrated that the yield vs. water use relationship was not independent of climate. In the Southwestern United States, crop water requirements were measured for seventeen field crops using the NMM in the 1960s and 1970s [13, 14]. Work begun in California in the late 1950s found that the variability between sites in water use determinations by the soil water balance method was less when the NMM was used than when gravimetric methods were used [15].

Studies of irrigation efficiency necessarily include estimation of crop water use and determination of soil water distribution in the field. The NMM became an important tool for such investigations despite the difficulty of accounting for deep percolation losses or upward movement of water from shallow water tables [16]. One method of accounting for such vertical water fluxes is to use tensiometers placed at several depths in order to find two depths at which the soil water potential is so nearly equal that the driving force for water flux between those depths is negligible. The plane between these two depths is called the zero flux plane. The crop water use can then be calculated from the soil water balance for the zone from the surface to the zero flux plane [17].

Weighing lysimeters have been used for many years for precise (e.g., 0.05 mm) measurement of evaporation (E) and evapotranspiration (ET) from bare and cropped soils [18]. However, lysimeter installations suffer from some serious drawbacks including disturbance of the soil profile, interruption of deep percolation and horizontal flow components and uneven management of lysimeter compared to field soil [19]. Other drawbacks include heat flux distortions caused by highly conductive steel walls [20,21] and high cost, e.g., US\$ 65,000 [22] and US\$ 80,000 [23].

Alternatives to lysimetry for the measurement of E and ET (both mm) include mass balance techniques that involve measuring the components of the water balance equation for a soil profile of given depth:

$$\Delta S = P - (E \text{ or } ET) - D - R \tag{2}$$

where

ΔS is the change in soil profile water storage,
P   is precipitation (including irrigation),
R   is runoff, and
D   is deep percolation, i.e., water moving across the bottom boundary of the soil profile (all in mm).

Solving for E or ET gives

$$E \text{ or } ET = -\Delta S + P - D - R \tag{3}$$

Measurement intervals commonly range between hours and weeks and are usually no smaller than the required period of ET measurement. Measurement of each variable in the right-hand side of Eq. 3 presents its own unique problems, and it should be stated that lysimetry has three sources of measurement error as well [lysimeter mass (ΔS), precipitation (P), and runoff (R)]. However, the water balance technique is applicable in many situations for which lysimetry is inappropriate or impossible and is, in addition, much less expensive.

Soil profile water content measurement techniques range from destructive sampling using augers or coring tubes to non-destructive techniques such as gamma-ray attenuation, neutron thermalization and capacitance measurements in access tubes. Techniques also include various sensors including resistance blocks, heat flux based sensors, and time domain reflectometry (TDR) probes that are buried at specific depths. Destructive techniques are commonly avoided because they cannot repeatedly measure the same locations and the time involved in handling the samples. Of the non-destructive techniques, neutron thermalization (NS) was proposed by Van Bavel and Stirk in 1967 [24]

for ET studies and has often been used since [25,26]. Due to the small changes in water content associated with single day ET and the limited precision of NS, especially near the surface, the water balance method has usually been restricted to measurement of ET over periods of several days [27]. Wright [26] compared ET measured by a weighing lysimeter to that measured by soil water balance using NS and concluded that large errors in the water balance method occurred if the depth of the profile measured by NS did not exceed the depth of wetting due to irrigation. The errors were then due to excessive water flux through the bottom of the profile. Bertuzzi et al. [28] simulated sampling strategies that combined the NMM for measurements at 0.2 m and deeper with accurate thin layer sampling in the top 0.2 m of soil. They concluded that daily water use could be accurate to ±0.5 mm with this method if the zero flux plane did not move below the bottom of the NMM access tubes or if accurate estimation of the flux rate could be obtained. They suggested that capacitance probes might be used for the accurate thin layer measurements. Evett et al. [29] investigated the joint use of TDR and NS for estimating ET and compared it to weighing lysimeter measurements with good results.

Early NMMs were not suitable for routine irrigation scheduling due to their bulk, weight, and difficult operation and data recording, and non-robust design [30]. Improvements in design addressed many of these concerns; and in the 1970s irrigation scheduling using the NMM became common [31]. Before the NMM, gravimetric sampling was the most common soil water measurement method for irrigation scheduling. The NMM proved to require less labour both because fewer samples were required and because the wait for soil to dry was eliminated, although it cost more to acquire the equipment [32]. Overall, of soil water monitoring methods available in the 1970s and 1980s, it had the "best combination of features for irrigation scheduling" [32]. Invention of a scheduling method that worked by tracking the rate of soil water depletion rather than depending on absolute water contents allowed the number of samples needed to be reduced to one or two tubes per uniformly irrigated field [31,32]. Comparison of the soil water tracking method with computerized scheduling based on estimates of crop water use showed that scheduling was more accurate with the tracking method, particularly over longer periods when computerized methods failed to account well for the status of soil water [31].

A recent search for research that used the NMM turned up over 1,100 papers published since 1970 that mentioned the NMM in the abstract. Certainly, many more research papers have been published that described the NMM as a routine and reliable method for soil water content measurement.

The NMM has influenced many important areas of investigation including:

— crop water use determination,
— irrigation efficiency determination,
— irrigation scheduling,
— tillage effects on crop water use,
— root water uptake patterns/soil effects,
— partitioning of rainfall and irrigation to runoff and infiltration,
— temporal and spatial variability of soil water content,
— measurement of soil hydraulic conductivity,
— wetting front movement studies,
— species and cultivar adaptation to water deficit stress,

to name relatively few.

It would be difficult to overestimate the importance of the neutron thermalization method in soil science and hydrological research and development over the past 50 years. It was the first useful, non-destructive method of repeatedly sampling the moisture content of soil profiles throughout and below the root zone. It led to the widespread measurement of crop water use values that are essential to irrigation management and the planning of large-scale irrigation developments. In 1998, a panel of scientists, expert in soil water measurement using time domain reflectometry (TDR), capacitance, and neutron thermalization methods, convened by the International Atomic Energy Agency, recommended that the neutron thermalization method not be replaced in the agency's research and training programs [33]. Three reasons were given: i) the method measures a relatively large volume of soil compared

with TDR and capacitance instruments and so integrates across small-scale variability of soil properties and reduces the number of measurements needed, as well as reduces the sensitivity of the method to soil disturbance caused by installation, ii) the method is reliable and easy to use compared with others, and iii) the technology is mature, bringing to bear a large knowledge base of proven solutions to particular problems of use. To this I would add that the large volume of measurement makes field calibration much easier than it is for TDR and capacitance probes.

Of less practical importance, but still a valuable research tool, the gamma-ray attenuation method has been widely used for studies of soil bulk density and water content [34]. Before the introduction of TDR, the gamma-ray method was the best and practically the only way to obtain water content data for thin layers of soil. Many column studies have been done using the method, but field applications are relatively infrequent, except in soils engineering where the moisture/density gauge is commonly used to assess compaction of fill materials. Other important uses of nuclear techniques include the use of radioactive fallout products from nuclear bomb testing as tracers for groundwater recharge studies, which is another example of the continuing effort of people of good will around the world to beat swords into ploughshares.

2. CALIBRATION AND USE

Since the 1950s, NMMs have improved in portability, programmability, weight and size. The advent of more-efficient detectors and the availability of Americium-241 produced in fission reactors resulted in the use of safer radioactive sources. The theory of operation of NS gauges and field calibration methods are described in several publications including Refs. [35] and [36]. The precision of measurements possible with NS has always been high and satisfactory for many soil water investigations with standard error <0.01 m^3 m^{-3} [6,35].

However, careful calibration and use remain essential to accurate soil water measurement with the NMM. This is particularly true because an important application of the NMM is to measure crop water use, where the primary aim is not to measure water content of soil, but the change in water content over a time period. Gardner [35] analysed variance in θ_v due to the variance of neutron counts (ignoring errors in the slope and intercept of the calibration equation), and on that basis stated that the NMM measures change in water content less precisely than it does water content. He then stated that, for change in water content measurements, because "variations in parameters a and b (N.B. the regression coefficients) usually are not involved as in water content measurements … the overall accuracy is better." While it is true that the variances of the intercept and slope drop out of the calculation of the variance of a water content change measured at a single point in the field, this generally does not ensure the accuracy of change in water content values. In general, error estimation for changes in water content must include the error associated with the slope of the regression equation [37]. Only under two conditions is the accuracy of the change in water content assured. Errors in the calculated change in water content vanish only:

— for the trivial case of no change in the water content (even if the water content from the NMM is incorrect), and
— if the calibration error is in the intercept and not in the slope.

Neither condition is very likely. Many dry-land and irrigated crops will end the season with less stored soil water than at the beginning. Moreover, calibration errors are at least as likely to involve the slope as the intercept. In fact, in principle the intercept is a more conservative measure, reflecting only the mean of measured water contents.

Two common failures in NMM calibration are the failure to obtain a spread of water contents large enough to cover the expected range of water contents during field operations and large enough to accurately determine the slope of the calibration equation, and the combining of data from soil horizons with different neutron scattering and absorption properties into a single regression analysis. In the latter case, reported errors in slope have ranged up to +24% [37] and −59% [38]. Hignett and Evett [38] examined the error possible if data from the loam and clay horizons of a duplex soil in Australia were combined in a single calibration (Fig. 1, Table I). The combined regression will give

water contents that are close to actual values in the clay horizon, but will be far from correct in the loam horizon (errors greater than 0.05 m^3 m^{-3}). As the soil wets and dries, the reported change in profile water content will be in error due to the slope error in the combined calibration regression when applied to the loam. To be sure, if data as clearly different as those shown in Fig. 1 are available, then most practitioners would perform separate regression analyses on the data for the clay and loam horizons. However, the data shown are the result of repeated careful volumetric sampling at several different locations and water contents in each horizon. For less-careful and -complete sampling, it is easy to envision that scatter in the data or a reduced range of water contents encountered would preclude the observer from seeing that the data come from distinctly different populations. The reduced sensitivity of the method in clay illustrated in Fig. 1 is due to non-water hydrogen contained in the clay. The amount of non-water hydrogen reported as water content equivalent (We, g/g) can be considerable as shown in Ref. [36]:

$$We = 0.124\ (\pm 0.012)C + 0.015 \tag{4}$$

where

C is fraction of clay content of the soil in g/g.

Non-water H was measured as the water released from initially oven-dry soil heated to 600°C in an oxygen atmosphere for eighteen Australian clays.

TABLE I. REGRESSION EQUATIONS OF WATER CONTENT (θ_V, m^3 m^{-3}) vs. COUNT RATIO (C_R) FOR FIG. 1 (DATA FOR AN AUSTRALIAN DUPLEX SOIL [38])

Texture	Depth (m)	Regression equation	RMSE[a]	r^{2} [b]	N[c]
Loam	0.3	$\theta_v = -0.037 + 1.150C_R$	0.005	0.99	6
Clay	0.6	$\theta_v = 0.060 + 0.513C_R$	0.010	0.96	6
Combined	0.3–0.6	$\theta_v = 0.084 + 0.472C_R$	0.027	0.85	12

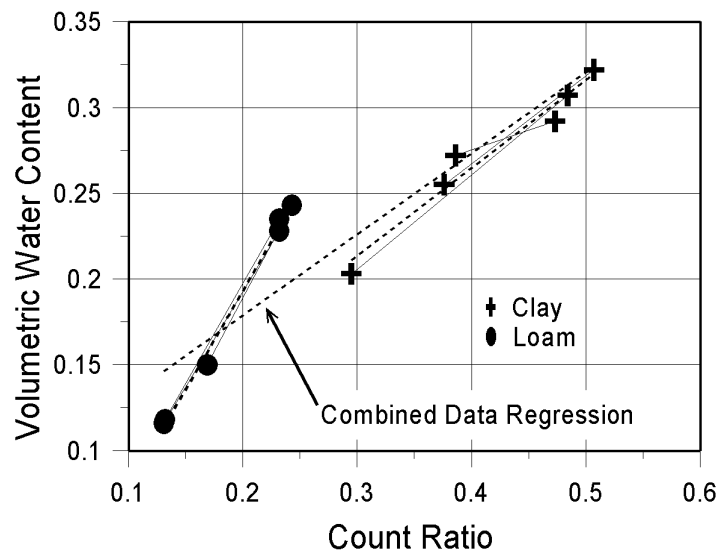[a]Root mean squared error. [b]Coefficient of determination. [c]Number of samples.

FIG. 1. Field calibration in a soil with variable texture using three pairs of access tubes in each texture. Regressions (broken lines) show clear differences in slope for loam and clay soils. The common regression shows a similar slope to the clay (offset by ~0.02), but is biased for the loam. Profile water content change calculated using the common calibration will be considerably in error.

Because soils often are wetter at greater depth, a common mistake is to derive the desired range in water contents from samples taken at different depths. If this is done, differences in calibration coefficients due to water content differences are often confounded with differences due to soil materials because soil materials commonly change with depth. The degree of spread in the water contents has a direct effect on the calibration equation r^2 value and thus the proportion of the variability in water content that is explained, through the calibration equation, by variations in count ratio. This is illustrated in Fig. 2. In Fig. 2a, the original data for a wet and dry site calibration are shown along with the calibration equation, which had r^2 of 0.967 and SSE of 0.014 m^3 m^{-3}. In Figs. 2b and 2c the wet end data points have been moved closer to the dry end points. The relative positions of the points have not been changed and they have all been moved an equal distance along a line whose slope is equal to the regression slope for the unaltered data. Thus, the degree of noise in the data due to noise in counts or in volumetric water contents has not been altered. This fact is reflected in the standard error of estimate, which remained the same at 0.014 m^3 m^{-3} for regressions on the altered data sets. But, the intercept became increasingly more negative and the slope more positive as the range of water contents decreased. For Fig. 2b, the differences in slope and intercept were not large, but, for Fig. 2c, the slope increased by 0.039. This represents an error of about 0.04 m^3 m^{-3} over a range of 1 in count ratio, which is equivalent to a water content range of about 0.26 m^3 m^{-3} for the original data, or about a 16% error rate. The apparent invariant width of the 95% confidence intervals is misleading. Although the confidence intervals around the data points do not change, the confidence intervals outside the range of the data points (not plotted) increase dramatically. Thus, another advantage of a wide range of water contents is greater confidence in subsequent measurements over the range of water contents likely to be encountered in the field.
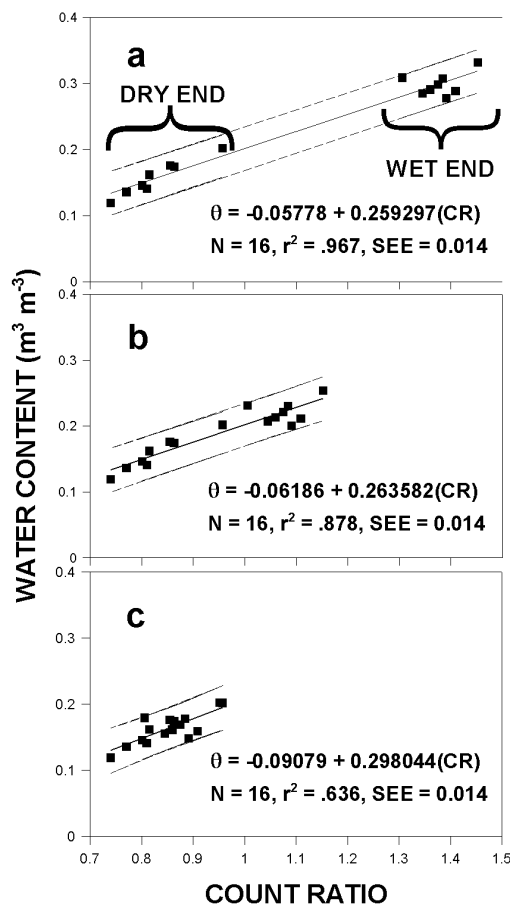

FIG. 2. An unaltered set of data from a wet site-dry site neutron probe calibration (a), and calibrations for the same data but with the wet end points moved closer (b) and still closer (c) to the dry end by sliding them along the regression slope. In each plot, the middle line is the regression line and the upper and lower lines are the 95% confidence intervals.

The following discussion will concentrate on recommendations for use and calibration. Some of it is drawn from a chapter on the neutron thermalization method [38].

2.1 Statistics of neutron emission

Neutron emission is a random process that occurs according to a Poisson probability distribution. An important property of the Poisson distribution is that, for a series of counts over equal time periods, the standard deviation is equal to the square root of the mean value. The sample mean, m, is computed as

$$m = \frac{1}{N} \sum_{i=1}^{N} x_i \tag{5}$$

where

x_i is the value of a single count,
N   is the number of counts.

The sample standard deviation, s, is computed as

$$s = \left[\frac{1}{N-1} \sum_{i=1}^{N} (x_i - m)^2 \right]^{1/2} \tag{6}$$

For a properly operating gauge with the probe in a constant environment, the ratio of $s/(m)^{1/2}$, called the Chi ratio, should be close to unity. This ratio is related to the χ statistic by

$$\frac{s}{m^{1/2}} = \left(\frac{\chi^2}{N-1} \right)^{1/2} \tag{7}$$

Values of χ^2 for a given probability level are given in statistical tables for different values of $(N-1)$. We may write the right-hand side of Eq. (7) for the upper and lower limits of χ^2 and thus obtain upper and lower values of the Chi ratio for the chosen probability level and number of samples. For example, for a 95% probability level and thirty-two samples, we find the values of χ^2 as 17.5 for $P = 0.975$ and 48.1 for $P = 0.025$; and from Eq. (7) the Chi ratio should be between 0.75 and 1.25 about ninety-five times in every hundred. Note that some gauges divide the count by a fixed number in order to reduce the displayed count to a reasonably small value. If the above calculations are applied to such reduced counts, the Chi ratios computed will be incorrect. To compute Chi ratios, the user should first multiply the recorded counts by the factor that the gauge used to reduce them.

These facts allow the user to check gauge operation by computing the Chi ratio. In fact, all modern gauges include an internal function for doing so, either through a special "STAT" function, or as a normal part of taking a standard count (see below). The range of the Chi ratio for a particular gauge will depend on the number of samples that that particular gauge uses in computing the standard count and Chi ratio values. An occasional Chi ratio outside of the 95% range is no large cause for concern, but should be checked by making another test. However, a series of Chi ratio values that average above or below unity signals a problem in the gauge electronics or internal geometry, and indicates inaccurate readings. For this reason, a quality assurance program for NMM measurements should include daily measurement and recording of the standard count and Chi ratio.

2.2 The standard count

While modern instruments are quite reliable, it is good operating practice to measure the count rate in a standard medium at regular intervals (i.e. daily) to check the machine for faults. Even if the Chi ratio remains near unity, a sudden change in the standard count signals a problem with the gauge that should be corrected before more field readings are taken. Problems that can occur include failure of electronic components, cable and connector failures, and detachment of the detector tube inside the probe (change in geometry of measurement). For profile meters, an ideal standard is a 200-L container (or, at least 0.55 m diameter and 0.8 m height) filled with distilled water and equipped with a central access tube of the same material and size as is used in the field [39]. The centre of measurement of the

probe should be located in the centre of the volume of water; and the access tube should extend to the bottom of the container to avoid the influence of nearness of the end of the tube.

Many users prefer the convenience of using the small plastic shield in the meter body as a standard. In this case the count can be affected by nearby bodies. However, it is acceptable provided the shield is mounted at least 0.8 m above the soil surface during the count (Fig. 4 in [40], Fig. 1 in [41]), and at least 3 m from surrounding objects. The operator should stand at least 3 m away to avoid influencing the count. In a 10-year study, probe shield counts were found to be reliable and highly precise [42,43]. The depth control stand described above is useful for this purpose. Neutron probe calibrations that used the depth control stand for standard counts resulted in values of standard error <0.01 m^3 m^{-3} [44]. Even though recommended by some manufacturers, the practice of placing the meter on its case for the count is to be avoided because the case is not of sufficient height to avoid the influence of materials below the case. Although placement of the meter on the tailgate of a vehicle may raise it to the necessary height above the soil, the nearness of neutron absorbers and moderators in the body and fuel tank of the vehicle makes it poor practice.

2.3. The count ratio

Calibration equations for surface gauges and profile meters are typically linear functions of a count ratio (C_R). The value of C_R is the ratio of the count, x, made in the measured material to a standard count, x_s.

$$C_R = x/x_s \tag{8}$$

It is good practice to express the calibration in terms of the count ratio. Using a calibration based on count ratio rather than in terms of direct counts, allows the same calibration equation to remain valid even as the source strength decays. The half-life of ^{137}Cs is 30.6 years and that of ^{241}Am is 458 years. To maintain 0.1% accuracy for density measurements (^{137}Cs), the standard count must be re-determined every 2 weeks. To do the same for moisture measurements (^{241}Am), the standard count must be re-determined every 8 months. By use of the standard count and count ratio, an accurate calibration may be used for many years. To reduce random error, it is recommended that the standard count used in Eq. (8) be a running average of the previous ten standard counts. This is particularly important for calibrations or for repeated measures used to determine crop water use over small time intervals.

2.4. Access tube materials

Aluminium is recommended for access tubes because it has minimal effect on neutrons. However, it is relatively expensive, not particularly strong and can quickly corrode in saline or alkaline conditions. Mild steel tubing is inexpensive, strong, and will last for at least 3 years in all but very acid soils. It has the disadvantage that it absorbs neutrons and decreases sensitivity of the instrument by about 2% but with no apparent effect on accuracy, hence may have the apparent effect of slightly increasing calibration error. Stainless steel can be used, but is expensive and also decreases sensitivity. Plastics including polyethylene have been used successfully and have the advantages that they are slightly flexible (useful in stony soils) and inexpensive. However, the density and wall thickness of plastic tubes vary, particularly between batches, which introduces a small additional random error. Calibration must be done using material of the same batch as the main installation. The root mean squared error of regression increased by 0.003 m^3 m^{-3} when PVC rather than Al tubing was used by Allen et al. [45]. Neutron count values were ~50% larger for Al vs. PVC tubing in two studies, due to neutron capture by the chlorine atoms in the PVC [41,45]. Neutron counts obtained using steel tubing are lower than those obtained when using Al, but are closer to counts with Al than to counts with PVC [46]. Thus, the NMM is slightly more sensitive to water content changes when using Al or steel tubing than when using PVC tubing. Coefficients of determination (r^2) values decreased consistently but nearly negligibly by 0.006 to 0.013 when steel rather than Al tubing was used for field calibrations of four types of NMM [47]. Accurate and precise calibration and water-content measurement are much more dependent on other factors explained below than on the material used for access tubing.

2.5. Access tube dimensions

The access tube should be as small as possible to maximize sensitivity, but have sufficient tolerance to allow the probe to move freely, even if there are small distortions in the tube. Tubes of 44 to 56 mm outside diameter and walls of 1.6 mm thickness are used commonly. Both larger diameter and greater wall thickness may result in decreased meter counts [41]. Larger diameter tubes are used with larger diameter probes. The larger diameter tends to increase the radius of the volume of influence and decrease the vertical resolution of the instrument [8]. Access tubes should be about 0.3 m longer than the greatest depth to be measured. This allows 0.15 m extra at the bottom to prevent the deepest reading from being influenced by the soil at the end of the tube [48], and 0.1 to 0.15 m of tube to extend above the surface to make the tube visible in the field and to prevent accession of surface water. The desirable maximum depth will depend on the particular study. But in studies to determine crop water use, it should be well below the maximum depth of rooting and below any expected zero flux plane for soil moisture [26]. Protrusion from the soil should be minimized to prevent rainfall collection and heat conduction from the soil surface.

2.6. Removable extensions

For long-term installations where tillage is needed, the tube is constructed so that the top section (usually 0.3 m) is held in place by a slightly oversized sleeve. The top section of tube is removed before tillage and the tube is plugged. Methods of locating tubes after tillage include measurements from fixed reference points, the use of a metal detector, and the use of coloured wire attached to the tube before burial. There may be problems with calibration where the extension attaches (extra wall thickness), with soil disturbance adjacent to the tube, and with water leaks if the soil becomes saturated. However, tube extensions are routinely used successfully.

2.7. Control of probe depth placement and shield height

It is common practice to place the NMM on top of the access tube before releasing the probe from the shield and lowering it for readings in the soil. This practice is not recommended for two reasons. First, when the NMM is placed on top of the access tube, the shield in the meter body may influence near-surface counts to a degree that depends strongly on the height of the meter above the soil [48]. Second, in field use, the actual height of access tubes above the soil is likely to change with tillage, rainfall induced compaction, erosion or deposition, or other factors, resulting in an equivalent change in the depth of probe placement. For readings at depths of less than 0.2 to 0.3 m, the depth of the probe will influence the reading and the calibration due to loss of neutrons to the atmosphere [9,49,50]. Hauser [50] found that the calibration equation intercept became more positive as depth decreased but that the slope remained constant. However, Evett [44] found that the slope became smaller and the intercept larger as depth decreased.

These problems are addressed by using a depth-control stand. This device comprises a length of access tube fixed to a 0.2-m length of slightly larger tubing that is, in turn, supported by a foot resting directly on the soil (Fig. 3). The larger diameter of the lower length of tubing allows it to be slipped over the top of an access tube so that the foot rests on the soil surface. This maintains the reading depth at an exact distance relative to the soil surface. Cable stops are arranged to achieve the desired depth placement of the probe. Instructions for fabricating and using a depth-control stand are available[2]. The stand described is tall enough to be suitable for taking standard counts with the NMM mounted on the stand and the probe locked in the gauge shield (see below).

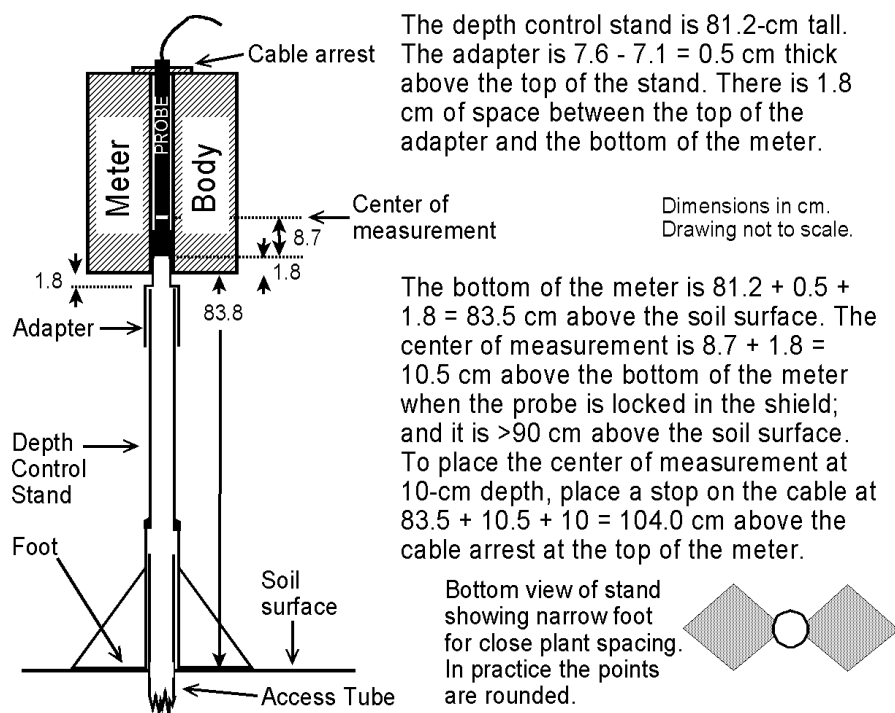[2]Evett, S.R., Construction of a Depth Control Stand for Use with the Neutron Probe, USDA-ARS-CPRL, Bushland, TX, http://www.cprl.ars.usda.gov/programs/ (posted July 2000).

The depth control stand is 81.2-cm tall. The adapter is 7.6 - 7.1 = 0.5 cm thick above the top of the stand. There is 1.8 cm of space between the top of the adapter and the bottom of the meter.

Dimensions in cm.
Drawing not to scale.

The bottom of the meter is 81.2 + 0.5 + 1.8 = 83.5 cm above the soil surface. The center of measurement is 8.7 + 1.8 = 10.5 cm above the bottom of the meter when the probe is locked in the shield; and it is >90 cm above the soil surface. To place the center of measurement at 10-cm depth, place a stop on the cable at 83.5 + 10.5 + 10 = 104.0 cm above the cable arrest at the top of the meter.

Bottom view of stand showing narrow foot for close plant spacing. In practice the points are rounded.

FIG. 3. Example dimensions relevant to placing cable stops on cables to achieve accurate depth placement of the probe centre of measurement when using a depth-control stand.

2.8. Access tube installation

Neutron moisture meters are relatively immune to installation problems because the soil volume affected by access tube placement is small compared to the volume of measurement. The tube needs to be tight fitting with no cavities around the tube, both because the calibration depends on the cavity size [41], and to prevent free surface water from leaking down the tube. A rubber stopper or inverted tin can should be used to prevent rain and animals from entering the tube. It is also a good idea to clearly mark the tube with a number to aid identification. Several methods of installation are commonly used.

2.8.1. Push and sample

The tube is inserted a short distance into the soil and pushed down in shallow lifts while augering from inside the tube. Augering is limited to a few centimeters in advance of the tube. For this method, the tube should be beveled on the inside so that all soil is pushed toward the center as the tube is pushed down. This method provides the best results, minimizing compaction of soil near the tube and voids between the tube wall and soil, but is very difficult and time consuming if done manually.

2.8.2. Sample and ream

A hydraulically driven push tube or hand auger is used to dig a slightly undersized hole. Then the access tube is pushed into the hole and an auger used to clean out the excess soil by extracting it from inside the tube. Hand augering is preferable to machine angering or push tube sampling to minimize soil disturbance around the tube. It is difficult to keep the tube from wandering from the axis of the hole during insertion, which leads to voids between the outside tube wall and the hole. To keep the access tube centred in the undersized hole, put a bevel on the outer edge of the access tube. In this case, the hole diameter should be only very slightly smaller than the tubing outside diameter. If a push tube is used to install access tubes it may cause compaction around the tube, particularly if the bit on the push tube is bevelled on the outside, and if installation is into a moist, compressible soil.

2.8.3. Slurry

A slightly oversized hole (2 mm) is dug using an auger or push tube. The access tube is sealed at the bottom, and a slurry of local soil with 10% cement as a binder is poured down the hole and the access tube quickly inserted so that the slurry rises to fill the gap around it. The slurry should be as dense as possible to minimize shrinkage on drying. If local soil is unsuitable, a mixture of 10% cement, 40% kaolin clay, and 50% water (by weight) can be used. The clay in this mixture will affect the calibration, necessitating a field calibration procedure, particularly if the local soil is low in clay content. This method is recommended except where extreme accuracy is required. Note that the shrink/swell clay bentonite should not be used. It will shrink on drying, leading to the possibility of free water travelling down shrinkage cracks immediately adjacent to the access tube.

Note that with most tube installation methods, the soil sample extracted from the hole may be used for calibration checks. If there is a risk of water entering the tube from below, the tube should have a rubber plug, a hydraulic cement seal (poured down a tube inserted inside the access tube), or other watertight material. Traffic by vehicles during installation should be controlled to ensure that access tubes are not installed in wheel tracks. Compaction by foot traffic in the immediate vicinity of an access tube should be avoided. This may require the use of a protective platform, such as a pallet during installation.

2.9. Vertical reading interval, maximum reading depth, and number of tubes

Design of a NMM installation is a compromise between the number of tubes needed for a sufficiently precise measure of soil water and the cost of installing and reading the network of access tubes. Modern instruments can take a reading of adequate precision in 30 seconds. Readings are often taken at 0.2-m intervals. Therefore ten readings, or 5 min are needed to scan a single tube to 2 m depth. If tubes are located close together then a reading rate of ten tubes per hour is a reasonable goal for a single instrument and operator. The number of tubes that can be read in a day will decrease as travel time to the site and between tubes increases.

From Eq. (1), the depth range of each measurement can be assumed to be at least 0.15 m above and below the reading point. In reported field studies, the depth interval between readings has been as small as 0.15 or even 0.10 m [27,51]. Depth intervals should not be larger than 0.15 m in soils with large and rapid changes in water content with depth [8, 52–54]. Intervals as small as 2.5 and 7.5 cm did not improve the accuracy of soil moisture measured in a profile with a large and rapid change in water content [54]. Although water contents near such interfaces are incorrect, the errors tend to compensate on either side of the interface if small intervals (≤15 cm) are used; and calculations of change in water content over time remain accurate [54]. Intervals of larger than 15 cm can cause larger errors [54]. A depth interval of 0.10 m was reported to improve precision of profile water content [27], but the improvement was likely due to the increased counting time resulting from the additional readings rather than any new information about the profile [55]. Depth intervals of greater than 0.3 m are sometimes used where water content changes slowly with depth. However, this is done at the risk of losing some information as the effective range of the NMM may be only 0.15 m from the probe in wet soil. The desirable maximum depth of reading will depend on the particular aims of a study. But in many studies it should be well below the maximum depth of rooting and below any expected zero flux plane for soil moisture [26].

The number of samples required to measure water content to a given precision depends on the sample size and on the spatial variability of water content both horizontally and vertically. Variability tends to increase as sample size decreases, particularly for samples smaller than the representative elemental volume. Water content varies as a function of soil properties, topography, climate, tillage, and the type and growth stage of any plants. Decisions about the number of access tubes needed to achieve an acceptable precision require additional information about the soil and plant environment to be studied. If previous experimental work has been done, then one may use information about site variability from that work. References dealing with variance and spatial variability of NMM measurements include

Haverkamp et al. [56], Sinclair and Williams [57], Vandervaere et al. [51,58], and Vauclin et al. [59]. The NMM measures, at minimum, a volume of ~0.014 m^3. Comparing this with the much smaller sampling volumes of most time domain reflectometry (TDR) and capacitance probes gives an idea of how many measurements would be needed with these technologies to give a field or plot mean profile water content with precision comparable to that from neutron thermalization. Approximately twenty-four soil samples (50 mm diameter and 0.3 m long) would be needed to sample the same soil volume as one NMM measurement. This fact explains why calibration methods that fail to provide multiple soil samples for every neutron probe reading tend to be imprecise. Variance in soil properties can also affect the precision of the calibration of the NMM (see below).

2.10. Calibration

Contrary to Gardner [35], manufacturers' calibration equations are seldom useful for routine soil moisture determination [60–62]. Calibration of NMMs involves correlating measured count ratio values with independently determined volumetric water contents, θ_v (m^3 m^{-3}). For modern gauges and the normal range of values of soil water content, the calibration is linear and of the form

$$\theta_v = b_0 + b_1 C_R \tag{9}$$

where

b_0 and b_1 are the calibration coefficients as determined by linear regression, and
C_R is the count ratio defined above.

Because of the wide variety of agricultural soils, it is necessary to calibrate for specific soils even though NMMs come with factory calibrations. If possible, it is best to calibrate in the field so soil horizon-specific calibration coefficients may be determined. Otherwise, fairly large errors may result because calibration coefficients vary widely for horizons rich in clay, organic matter, $CaCO_3$, $CaSO_4$, or close to the surface. Several calibration methods are commonly used. Each has qualities that recommend it for a particular use.

2.10.1. Method 1: laboratory method for a uniform soil

If a soil is uniform to considerable depth, a laboratory calibration may be appropriate. Excavate approximately 2 m^3 of soil from the field and transport it to the laboratory. Air dry and crush it to pass a 5-mm sieve. Mix it thoroughly and pack into a steel container of at least 1.22-m both in diameter and height (to obtain an equivalent infinite volume [9]), open at top and bottom and divided so that it can be split vertically into two halves to simplify removal of the soil. An access tube of the same composition and size as used in the field is mounted in the centre of the container.

Add air-dry soil to the container in quantities of 40 kg, spread evenly, and lightly pack. Obtain NMM counts at four depths (the container centre point, at 0.1 m above and below it, and at 0.1 m depth) for five times the normal counting period. At the same depths, take at least five volumetric samples for gravimetric water content and density. Split the container into its two halves and remove the remaining soil, crushing any cohering lumps. If the soil has >2% organic matter or clay then it should be repacked using a greater packing pressure (a smaller rammer) to achieve a higher density and the count rate again taken to measure the effect of density and non-water H. The soil is then removed, crushed and distilled water is sprayed onto it to achieve about a 5% increase in water content, and the soil thoroughly mixed and left to stand overnight under a cover. After mixing again, the container is repacked, and the NMM readings repeated for the higher water content (at high and low density if necessary), followed again by volumetric soil sampling. This process is repeated until the soil is too wet to work. For each reading depth, the volumetric water content of the packing is estimated from the average density and the gravimetric water content of the soil and plotted against the count ratio of the NMM. For each packing, the data for the centre depth and 10-cm above and below it may be combined. Data for the 10-cm depth are used for a separate near-surface calibration. A linear regression is then fitted to the data points using the variable (count ratio or water content) with the least error as the dependent variable. This is because regression theory requires that the independent

variable be known precisely; and both NMM count and water content have error [63]. If water content is known more precisely, and is used as the independent variable, then the equation can be inverted before use. If the high- and low-density points are fitted separately, then the effect of density and volumetric non-water H (which changes with density) can be measured also.

Laboratory calibration can result in regression equations with low values of standard error of regression. But, it is difficult to pack soil to field bulk density at all water contents, the method is time consuming, and it may be difficult or impossible to account for soil-horizon-specific variations in NMM response that require separate calibrations. Also, it is never clear that laboratory calibrations reflect field conditions.

2.10.2. Method 2: field calibration for uniform soil or soil horizons

This is the most common calibration method. A calibration should include as wide a range of soil water contents as possible. It is best to establish both wet and dry sites in a field for calibration, either at the same time or sequentially (Fig. 4). A dry site may be established by growing a crop that normally dries the profile, and/or by waiting for a time of year when the soil is normally dry. A wet site may be established by berming an area and ponding water on it until the wetting front has descended below the lowest horizon to be calibrated. If the soil is a heavy clay it may take many days to wet up. Typically, three access tubes will be installed at each of the dry and wet sites with at least a 1-m spacing between tubes. Prior to using the NMM, check the depth stops on the cable to ensure accurate depth positioning (Fig. 3). Take at least three standard counts, and check counts and Chi ratios for stability. Take 60-second or longer counts at all the depths required for calibration. For the wet site, wait an appropriate time after ponded water is removed in order to allow rapid internal drainage to take place before taking counts. This ensures that soil water content does not change appreciably between the time counts are taken and the time that soil samples are obtained. For the same reason, it is important to obtain the gauge readings and soil samples for the wet site on the same day.
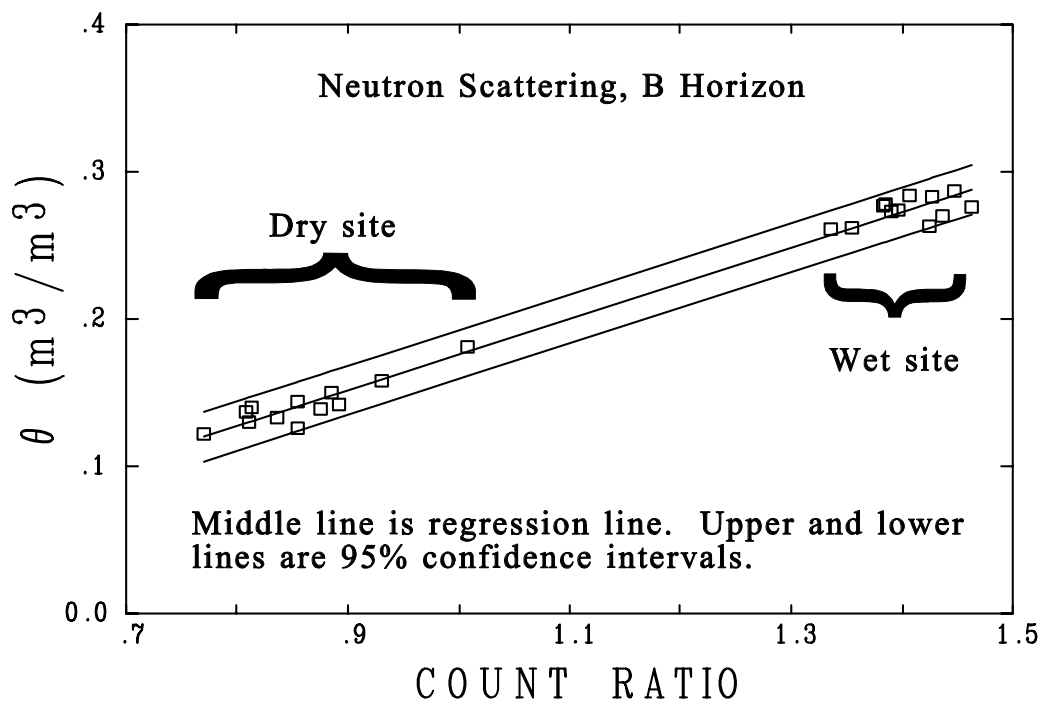

FIG. 4. *Typical differences in water content between wet and dry profiles and calibration line from a wet-site/dry-site calibration.*

Take at least four volumetric soil samples at each depth around each tube. Sample around the wet site tubes immediately after counts are taken. A volumetric soil sampler such as the Madera probe [44] (Fig. 5) or thin-walled metal cylinders should be used (Fig. 6) [64]. Use of thin-walled samplers to obtain undisturbed samples usually requires a clearance ratio $(D_i - D_e)/D_e$ of 0.01 or larger (Fig. 5) [64]. Open-ended samplers such as these are recommended because they allow the user to observe the sample condition after the sampler is inserted in the soil, and thus allow checking for soil compression or shattering during insertion. Closed-end samplers, with or without removable metal sample cylinders, are to be avoided because of potential compression. For tube samplers of 50-mm diameter, a wall thickness of no larger than 1.2 mm is desirable [64]. This gives a ratio of cutting-edge surface to sample surface of 0.05 (surface areas normal to the axis of insertion). To lessen compaction, the sample surface area should be at least 90% of the area of the hole created by the sampler. A minimum of four samples should be taken from within 0.1 m of the tube at the reading position (that is, sample from the volume of soil measured by the probe). Take care when removing the soil near the tube so as not to disturb the remaining soil before the remaining samples are taken (avoid compaction or soil loosening). If using the Madera probe or a similar tube probe, samples may be taken horizontally from the side of a pit dug on one side of the access tube. Alternatively, the soil may be removed to a depth about 0.1 m above the reading depth and the samples taken vertically (Fig. 6). To calibrate at depths greater than 0.5 m it is best to dig a trench not closer than 0.5 m from the tube, then work from the trench to excavate to the sample depth. While taking soil samples, note depth of any soil horizons that might lead to different calibrations. Before regression analysis, calculate the mean and standard deviation of soil water content and bulk density for each depth at each access tube. Examine these data and recompute the means after removing obvious outliers. For example, in Table II each of the N values is the mean of four samples taken at a particular depth at a particular access tube (six samples for the 10-cm depth). This method is designed to provide a mean soil water content for the volume of soil that is read by the NMM. It can routinely produce root mean squared error values (RMSE) for linear regression of <0.01 m^3 m^{-3} (Table II) [44].
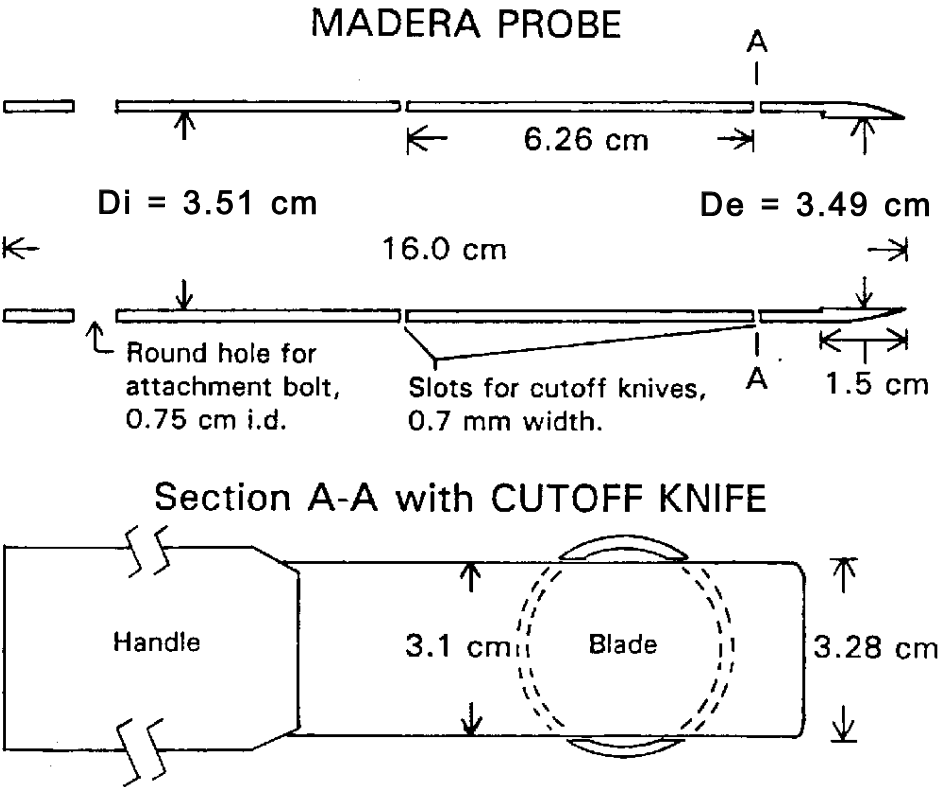

FIG. 5. The Madera probe may be obtained from Precision Machine Company, Inc., 2933 North 36th Street, Lincoln, NE 68504-2498 USA, tel 402-467-5528, fax 402-467-5530.

A variant of this method was used by Allen et al. [45] and Dickey et al. [65] in which samples were taken with a 1.22-m-long tube probe pushed into the ground with a hydraulic ram. Wet and dry sites were used. The sample was extruded from the tube onto a tray and sectioned into lengths corresponding to the depth intervals measured with the NMM. The process was repeated to create a hole at least 1.5-m deep. The volume of each sample was calculated as the area of the cutting edge of the tube probe multiplied by the length of that section. Access tubes were installed in the holes created by sampling and NMM measurements taken at the centres of the depth ranges sampled. The method achieved the best results of the three methods they compared in three soils (which did not include method 2 described here), but also gave consistently higher C_R values, a result of compression of soil around the tube probe that was particularly evident in a clay loam soil. The RMSE of regression ranged from 0.006 to 0.013 m^3 m^{-3}. This variant is not recommended in soils that compress easily as soil in the sampler may be compressed or dilated during sampling. The USDA-SCS (now NRCS) method is similar except that the Madera probe fitted to an extension tube is used to take a 60-cm^3 sample at each reading depth with hand augering to deepen the hole between samples [62,66]. In the study of Allen et al. [45] the RMSE of regression ranged from 0.011 to 0.014 m^3 m^{-3} for the SCS method; but C_R values were not raised by soil compression. Both of these methods are designed for calibration during access tube installation so that the access tube may be used for subsequent moisture readings [45]. But, both have dual disadvantages:

— the soil sampled is removed from the hole before NMM counts are measured, and
— there is only one sample per depth associated with each NMM count.

The accuracy of this variant can be improved considerably by taking cores at three or more places around the access tube and close enough to be within the measurement volume [26].

TABLE II. CALIBRATION OF WATER CONTENT
(θ_V, m^3 m^{-3}) vs. COUNT RATIO (C_R) FOR THE
AMARILLO FINE SANDY LOAM WITH METHOD 2,
USING A DEPTH-CONTROL STAND (FROM [67])

Depth (cm)	Regression equation	RMSE[a]	r^{2} [b]	N[c]
10	$\theta_v = 0.014 + 0.2172 C_R$	0.004	0.997	6
30–190	$\theta_v = -0.063 + 0.2371 C_R$	0.007	0.988	44
30–90	$\theta_v = -0.066 + 0.2421 C_R$	0.008	0.988	24
110–190	$\theta_v = -0.057 + 0.2299 C_R$	0.006	0.992	20

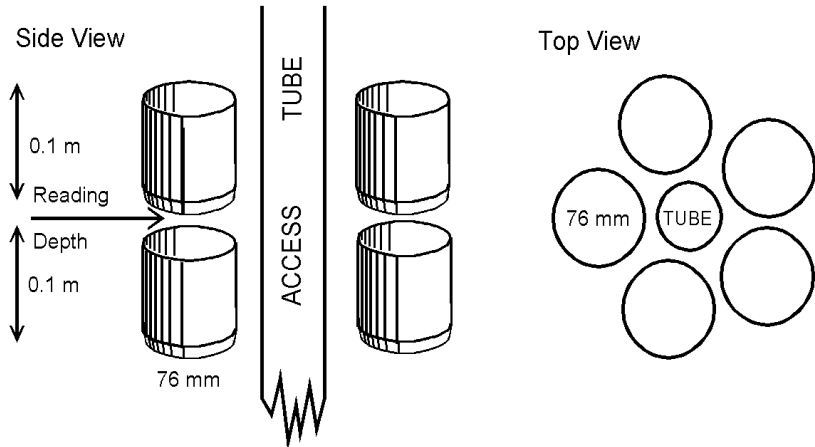[a]Root mean squared error. [b]Coefficient of determination. [c]Number of samples.

FIG. 6. Placement of volumetric sampling cylinders for optimum sampling of the NMM measurement zone.

2.10.3. Calibration for near-surface readings

The loss of a substantial fraction of neutrons from the surface during near-surface readings (<0.3-m depth for fine-textured soils, <0.38-m depth for sands [54]) necessitates a separate calibration for any depths in this zone. Special techniques for surface-layer calibration are described by Sartz and Curtis [60], Grant [49], Parkes and Siam [37], and Hauser [50]. However, the ordinary field calibration procedure (method 2) is quite adequate provided a depth-control stand is used (see calibration for 10-cm depth in Table II).

2.11. Transferring calibration coefficients between meters/checking meter calibration

Calibration of NMMs is time consuming whether done in the laboratory or the field. It is desirable to be able to transfer the calibration between a calibrated meter and a new or repaired one, and to be able to check a calibration. There are both field and laboratory methods for transfer.

For the field method, one identifies or creates soil profiles having large differences in water content, similar to the wet and dry sites created for a field calibration (see above). The calibrated meter is used to determine water contents at various depths in one or more access tubes both in the dry and the wet profiles. If separate calibrations exist for different soil horizons, it is prudent to have at least three access tubes in each site. Counts in these tubes with the meter to be calibrated or checked are used to compute count ratios for that meter corresponding to each depth, and the transfer calibration is established by linear regression vs. water contents from the calibrated meter [47]. Care must be used to establish the centre of measurement at equivalent depths for both meters. Unlike transfer using laboratory standards, the field method works well for transfer of calibration between meters of different manufacture or internal design (S.R. Evett, unpublished data).

In the laboratory, calibration transfer can be done by preparing drums of media with sufficient volume such that counts would not increase if further volume were added (quasi-infinite volume) and with media characteristics that produce widely different count numbers. Once a calibration is transferred to such a set of drums, the calibration may be transferred to NMMs of the same design, with some precautions [68]. Meters from different manufacturers have different source-detector configurations and respond to these media differently so that, in general, calibrations cannot be transferred between them. Even for a single manufacturer and model number, if the NMMs were manufactured many years apart, the internal characteristics may be sufficiently different that calibrations cannot be transferred in this manner (S.R. Evett, unpublished data). In any case, once a calibration is transferred, the NMMs involved should be used to obtain soil water content values in wet and dry sites in the field and those values checked for correspondence across meters. Of course, the transferred calibration will be valid only for the soil in which the initial calibration was done.

Media used have included water, aluminium sulphate ($Al_2(SO_4)_3 \times 18H_2O$), urea ($NH_2CONH_2$) [39,69], ammonium alum ($Al_2(SO_4)_3(NH_4)_2SO_4 \times 24H_2O$) [70], and high-density polyethylene plastic cylinders of various radii [68]. Nakayama and Reginato [47] found that water contents were more accurate by up to 0.03 m^3 m^{-3} when using a field transfer method than when using plastic cylinders. Depending on its size and constitution, each medium will represent a particular equivalent water content. At least two such media are required, one with a small equivalent water content and one with a large equivalent water content. For long-term stability, the media should be prepared so that their properties do not change with time. For example, in the 10-year study of Stone et al. [43], urea was hygroscopic and took up water even though sealed in polyethylene sheeting and doubly sealed in a steel drum, while aluminium sulphate protected in the same way was quite stable. McGuinness et al. [70] were able to create media with equivalent water contents ranging from 0.033 to 0.434 m^3 m^{-3} by mixing ammonium alum with silica sand, and found the resulting mixtures to be very stable "even when exposed to air." If a medium does not represent a quasi-infinite volume (e.g., the plastic cylinders of Reginato and Nakayama [68]), then care must be taken to remove the meter shield and any other objects from the vicinity of the medium during counts.

To transfer a calibration to the media, a calibrated meter(s) is centred in each medium and a count is made for a sufficiently long time to minimize count variance. Standard counts are also obtained (see

above); and the equivalent water content for each medium is calculated from the calibration equation. Subsequently, the same meter, or a very similar meter, may be used to obtain counts in the media and standard counts, and a calibration may then be calculated using the equivalent water contents as the independent variable.

3. SOME CALIBRATION STUDIES

Stone et al. [71] conducted the ASCE (American Society of Civil Engineers) Neutron Probe Calibration Study on three agricultural soils, Millville silt loam, Nibley silty clay loam, and Kidman sandy loam. Sub-studies were done on methods of bulk density measurement, effects of the geometry of source and detector tube (source at bottom of detector, or source centred around detector), and effects of access tube material (aluminium, steel or polyvinyl chloride plastic). No attempt was made to produce calibrations for different soil horizons, probably because sample numbers were inadequate (they ranged from six to eighteen for the entire profile). Three access tubes were installed in a wet site and three in a dry site for each soil, with 10 cm of tube protruding above ground level. Sampling depths were at 15 cm below ground surface and in 15-cm increments below that to 150 m. Shield counts, used to calculate count ratios, were taken with the gauges resting on the top of an access tube at 1.5 m above the soil surface. Calibration equations were calculated by linear regression analysis of measured volumetric water content vs. count ratios.

A probe with the source centred around the detector tube (model 3223, Troxler Electronics Inc., Research Triangle Park, NC) showed greater sensitivity to water content than the probe with the source at the bottom of the detector (model 503DR, Campbell Pacific Nuclear (CPN) International, Martinez, CA) [48]. The two probes were equally sensitive to proximity to the surface. The centred detector-source probe showed slightly better resolution of vertical changes in moisture content and of a cavity placed in the soil adjacent to the access tube. Both probes were sensitive to placement above the bottom of the augered access hole. Changes were 1.64 standard deviation (SD) for the Troxler and 1.19 SD for the CPN, from readings with the probes about 10 mm above the bottom of the hole, when the hole was augered another 15 cm deeper and readings were taken at the same depth. This suggests that calibration efforts should ensure that the augered hole extends well beyond the lowest depth of reading. Despite the greater sensitivity of the Troxler probe, there was no significant difference in the precision of calibration curves developed for the two brands of gauges [72]. Standard errors of estimate ranged from 0.0068 to 0.0193 m^3 m^{-3} for CPN gauges and from 0.0056 to 0.0197 m^3 m^{-3} for Troxler gauges [45].

Access tube materials affected the calibration equation slope a great deal, but affected the intercept only slightly. Both brands of gauge were more sensitive to water content when used with aluminium tubing and least sensitive when used with PVC tubing. Sensitivity with steel tubing was in between that for Al and PVC tubing [72]. Calibration equation standard errors of estimate ranged from 0.0056 to 0.0147 m^3 m^{-3} for Al access tubes and from 0.0111 to 0.0193 m^3 m^{-3} for PVC access tubes, indicating a slight reduction in precision of calibration when using PVC tubes.

Three soil sampling methods for neutron probe calibration that do not destroy the site were compared by Allen et al. [45] and Dickey et al. [65]. Two were down-hole methods for which samplers were pushed into the soil at the bottom of an augered hole to take fixed volumetric samples. Of these, the SCS Madera sampler, with a 60-cm^3 sample volume, resulted in better calibrations (lower standard error of estimate) than the Utah State University sampler that had a smaller volume of 15 cm^3. The third method, involving a Giddings coring tube, produced the smallest calibration error estimates. With this method the coring tube was inserted by a hydraulic coring machine (Giddings Machine Co., Fort Collins, CO) and the soil core was pushed out of the tube onto a tray where it was cut into sections of known length, which were placed in soil cans. Volume of each sample was calculated from the inside diameter of the coring tube cutting edge and the sample length. Use of the Giddings coring tube did result in compaction of the soil around the hole in which the access tube was subsequently installed, and this caused the calibration slope to change. Thus, although the calibration error estimate was smaller with this method of sampling, the calibration probably did not provide an accurate representation of the field soil water content. An added disadvantage of the Giddings coring method is

that it requires an expensive tractor or trailer mounted hydraulic coring machine, which may be difficult to operate in the field. Two types of driven, ring samplers were also tested [65]. These required destruction of the site because holes had to be dug to take samples at every depth. These samplers were closed at the ends causing some samples to be compacted. Calibration equation error estimates were higher with data from the ring samplers.

Evett and Steiner [67] calibrated three Troxler and three CPN gauges in an Amarillo fine sandy loam with a sandy clay loam B horizon between 30- and 110-cm depth and a calcic horizon (Btk) below 110 cm. They used schedule 10, galvanized steel electromechanical tubing for access tubes, which were installed by pushing them into hand-augered holes of the same diameter as the outside diameter of the tube. A dry soil site was found in a fallow field and a wet site was created adjacent to it by berming an area and ponding water on it until the soil was wetted to 2-m depth. Three access tubes were installed in each site. The wetted soil was allowed to drain to field capacity (43 h) before sampling began, and sampling at the wet site was conducted in one 11-h period to minimize changes in soil water content due to drainage.

Shield counts were taken before and after counts in the access tubes, and each standard count used for calculating count ratios was the average of at least six shield counts. The CPN gauges reported a χ ratio for each standard count. The χ ratio is a statistic that is valuable for screening shield counts. It is the ratio of the standard deviation of counts to the square root of the mean count. Because the count of thermalized neutrons behaves as a Poisson distribution, the χ ratio should equal unity. Shield counts for which the χ ratio was <0.9 or >1.1 were eliminated from consideration. In order to avoid any influence of soil moisture on the count, shield counts were taken with the gauge resting on a depth control stand 82 cm above the soil surface. Counts in the access tubes were also taken with the gauge resting on the stand. Neutron probe readings (1-min counts) were made at 10-cm depth and in 20-cm increments below that to 190 cm.

Four soil samples were taken at each depth with a Madera sampler. For the 10-cm depth the sampler was pushed vertically into the soil until the sampling volume was centred at 10 cm, the sampler was twisted to shear the soil at the bottom and then pulled out. For depths below 10 cm, the soil was excavated on one side of the access tube and samples were taken by pushing or driving the sampler horizontally into the soil on either side of the access tube. Two samples were taken on opposite sides of the access tube just above and just below each reading depth in order, to integrate the soil volume measured by the neutron probes. During sampling, if a sample was obviously compressed or shattered it was discarded and another taken adjacent. During data reduction, the four samples were commonly averaged to give one water content per sampling depth for each access tube. However, the existence of four samples per depth for each access tube allowed samples identified as outliers during regression analysis to be discarded, particularly if values of water content and bulk density for those samples were widely divergent from the mean of the other samples.

A good range of water contents was achieved between the wet and dry sites (Fig. 7). Results of these techniques were very good. Root mean squared errors were less than 0.012 m^3 m^{-3} for all calibration equations, and often were of the order of 0.005 m^3 m^{-3}. There was no difference in the precision of calibration equations obtained for the two brands of moisture gauge. Enough samples were obtained to allow individual calibration equations to be calculated for the 10-cm depth, the 30- to 90-cm depth range, and the 110- to 190-cm depth range. There were important differences in the slopes and intercepts of these equations. Earlier, similar results were obtained using these calibration techniques on a Pullman clay loam and a Ulysses silt loam [44]. In the earlier study, only two access tubes were installed at each site. The Pullman soil is a Paleustoll in the US taxonomy and has a strong Bt clay horizon (illuvial clay), and a calcic horizon with up to 45% by mass of $CaCO_3$. Distinctly different calibration equations were found for these two horizons as well as for the 10-cm depth. In 1993, field calibrations using these methods were done on the Ulysses silt loam and the Amarillo fine sandy loam.
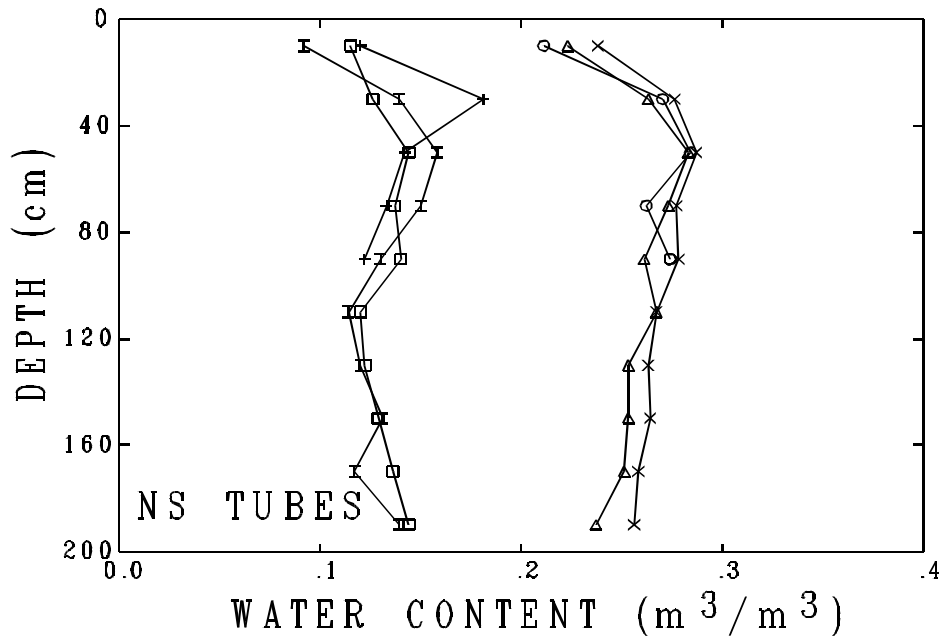
FIG. 7. Water content profiles at neutron scattering (NS) access tubes: dry site tubes: (□), (I), and (+); and wet site tubes: (X), (Δ), and (O).

Standard errors of estimate were less than 0.01 m^3 m^{-3} for all horizons, and there were important differences between calibration slopes for different horizons of the Amarillo soil. For the Ulysses soil, which lacks strong illuvial clay and calcic horizons, there was no important difference between calibration equations for any depth range below the 10-cm depth.

4. TEMPERATURE EFFECT ON STANDARD COUNTS

Figure 8 shows data measured over several months in 1985 using a Campbell Pacific Nuclear 503DR gauge during a field exercise at Marana, Arizona. Each day, a standard count in the shield was taken and the mean count, χ ratio, and time were recorded. The gauge was in the field during the entire time and was equilibrated to air temperature as much as possible. A weather station in the field recorded air temperature every 15 min. The nearest 15-min average air temperature and standard counts for which χ ratios were above 0.9 and below 1.1 were used to build the data set that is shown in the graph.

Linear regression (Fig. 8) showed that the ambient temperature explained 79% of the variation in standard count. The correlation was negative, with lower standard counts for higher temperatures. For a temperature change of 30°C, one could expect a change in standard count of 177. The calibration equation for this probe had a slope of 3.59×10^{-5}. Multiplying the slope by the change in standard count gives a change in measured water content of 0.006 m^3 m^{-3}. This is close enough to a 1% change in water content to cause some concern. Jones and Hauser [73] measured a similar negative correlation between temperature and count rate, which corresponded to a 0.011 m^3 m^{-3} error over a 50°C temperature range for the meter they used. They determined that the temperature effect was not due to the probe or the pre-amplifier circuitry in the probe, but must have been due to the counting or high voltage circuitry in the scalar unit. Hauser, using a more modern probe design, found a similar effect when all parts of the NMM were at equal temperatures [50]. But, he found a positive 6% increase in count when the probe alone was warmed from zero to 52°C.
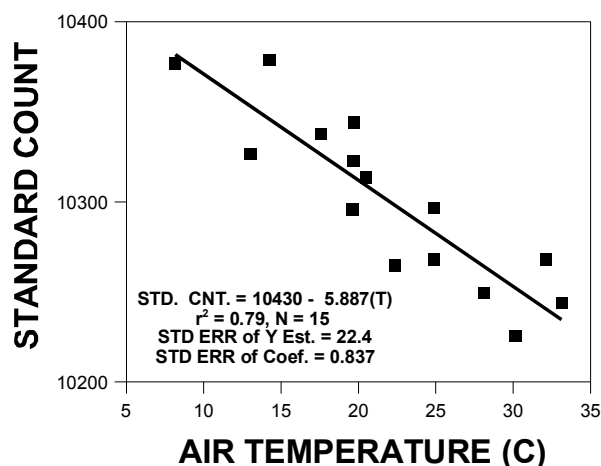
FIG. 8. Standard counts from a neutron moisture meter (model 503DR, Campbell Pacific Nuclear International, Martinez, CA) and corresponding ambient air temperatures at Marana, AZ, USA, 1985.

There are some reasons to expect that the primary source of temperature dependency is the detector tube, which contains boron trifluoride gas. Gas pressure is quite responsive to temperature changes and the detection process may be influenced by gas pressure. The counting circuitry may also be involved, particularly the high voltage and detector circuits, which are somewhat analog in nature. The rest of the circuitry in the probe would be insensitive to temperature because it is basically digital. Certainly the electronics in the gauge readout assembly, where the microcontroller is housed, are entirely digital so the problem almost certainly resides in the probe, either in the detector tube, in the pulse detection and shaping circuit, or in the high voltage circuit.

In the semiarid environment at Bushland, Texas, we may see a 17°C air temperature swing during the working day. There is some potential for the probe to be subjected to even wider temperature swings because it is used in the access tube, as well as in the shield for standard counts. We have little idea what temperature the probe is at while it is in the access tube, but we can be sure that it is changing. While travelling from one access tube to the other, the probe is locked in the shield and may equilibrate with ambient temperature. Once the probe is lowered to the bottom of the access tube it enters a much cooler or warmer environment depending on air temperature. The probe enters another temperature regime each time it is moved to a new depth stop for a reading. Because we do not have a measure of probe or detector tube temperature we cannot correct for temperature swings. We can measure the effect from standard counts in the field or using an environmental housing set to different temperatures for each standard count. But, that information is useless to us unless we can measure the probe temperature during each reading in the access tube and during each routine standard count in the field. Clearly, there is still room for improvement in modern NMM design.

5. COMPARISONS BETWEEN NEUTRON AND OTHER METHODS

A soil water content capacitance probe (CP) gauge (Troxler Electronic Laboratories, Inc., model SENTRY 200AP) was patterned after that of Dean et al. [74] and included some improvements while retaining the desired characteristics. Heathman [75] reported an r^2 of 0.62 for a field calibration of this gauge. Evett and Steiner [67] conducted a rigorous field calibration of four of the Troxler gauges in comparison with six neutron scattering (NS) gauges, using wet and dry sites as described above. Calibrations for the CP gauges exhibited low r^2 values, ranging from 0.04 to 0.71, and root mean squared error values of 0.036 to 0.058 $m^3 \, m^{-3}$. Example plots illustrate the much greater scatter of CP gauge data in comparison with NS gauge data (Figs. 9 and 10).

Some possible sources of variability in the CP gauge readings can be discounted. For instance, Dean et al. [74] showed that, for their design, total thermal (0 to 30°C) and temporal (over 3 h) stability errors amounted to <0.005 $m^3 \, m^{-3}$ error in water content. They also showed that air gaps between the tube and soil would introduce large errors, thus the exacting tube installation procedure. They did not

measure the probe's sensitivity to bulk density variations. But, in a companion paper, Bell et al. [76] noted that bulk density appeared to affect the slope of calibration equations and concluded that more work was required in this area.

The CP gauge is responsive mostly to a soil layer as thin as 8 cm [76] or 12 cm [77] vertically, and within 11 cm of the probe centreline [77]. Thus, small-scale variations in soil properties are more likely to influence the probe's readings than would be the case for the NS gauge. The electric field induced in the soil by the CP is influenced by boundaries between soil volumes having different permittivities [74]. Thus, bulk density or θ_v variations on a small scale could set up boundaries that would influence the size and shape of the sampled volume. Boot and Watson [78] noted that sample heterogeneities can cause anomalous readings from capacitance probes applied to building materials, especially when the wavelength approaches the scale of heterogeneity. Wobschall [79] pointed out that heterogeneous soils can also cause poor results.

Another possible explanation for the poor results with the CP gauges is that the measurement volume is considerably smaller than reported by Bell et al. [76] and Troxler Electronic Laboratories [77]. If this were so then the soil sampling method used by Evett and Steiner [67] would be inappropriate. However, the 15.24-cm measurement interval provided by the stops on the CP gauge probe handle would be too large if the sampling volume were smaller than that stated by Troxler Electronic Laboratories [77]. If the sampling volume is indeed much smaller than reported, then the use of the CP gauge must be reevaluated because many more samples at much smaller vertical sampling intervals must be taken to provide accurate integration of the soil water content profile. In fact, if this hypothesis is true it may be difficult to accurately portray the soil water content profile in many soils because the representative elemental volume may be larger than the gauge's sampling volume. Field calibration of this gauge would also be problematic in this case because an exacting relationship between probe position in the tube and position of soil sampling is implied.

Tomer and Anderson [80] obtained better results with the Troxler CP gauge in a comparison with an NS gauge in a deep aeolian sand (Zimmerman fine sand). Samples for calibration were obtained by taking 5-cm diameter vertical cores. Access tubes were then installed in the coring holes. Because the sand was not cohesive, bulk density values were not used from these samples, but bulk densities from a previous study were used to calculate volumetric water contents. The NS gauges calibration resulted in an r^2 value of 0.966 (N = 31). The CP gauge calibration gave an r^2 value of 0.888 (N = 73), and was similar to the manufacturer's calibration equation, a fact that is not surprising given that the manufacturer calibrates in sand. Soil water lost in a 1.5-m profile over 2 weeks averaged 1.2 cm less as measured by the CP gauge compared with the NS gauge, and the CP gauge routinely gave higher water content measurements. The CP gauge had much higher spatial resolution, a fact that rendered it susceptible to problems with access tube installation.
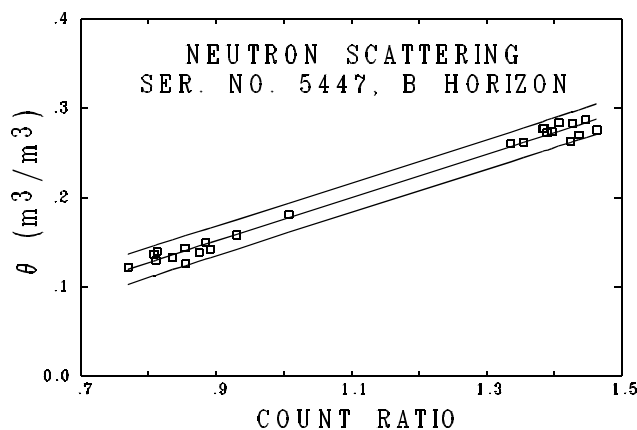

FIG. 9. Typical volumetric water content (θ) vs. count ratio relationship in the B horizon (tubes 1–6). Middle line is the regression line, upper and lower lines are 95% confidence limits on the predictions.
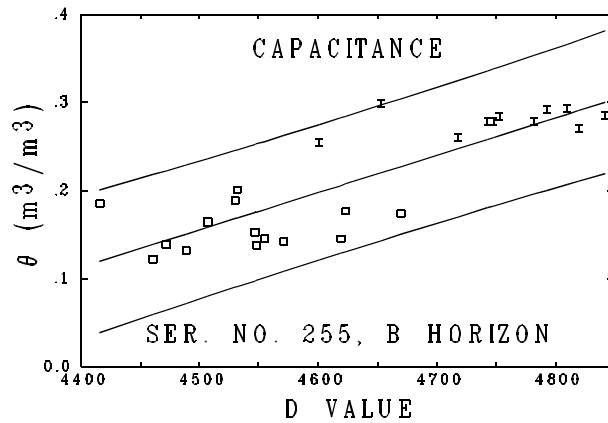
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FIG. 10. Typical relationship between volumetric water content (θ) and the absolute value of the measured frequency shift (D) from capacitance gauges (tubes 7–13), showing dry site data (□) and wet site data (I). Middle line is the regression line, upper and lower lines are 95% confidence limits on predictions.
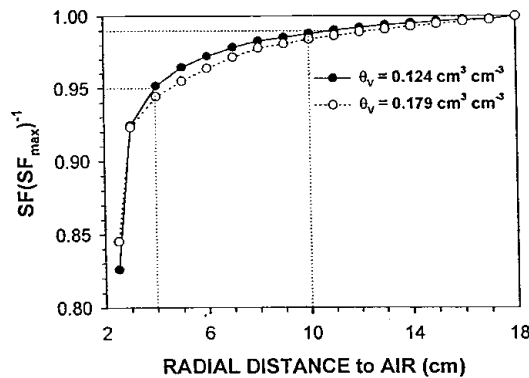

FIG. 11. Relative radial sensitivity of EnviroScan sensors as a function of radial thickness of soil around the access tube (from [82]).

Mohamed et al. [81] compared the Humicap (Nardeux, Loches, France) capacitance probe to a neutron probe (Solo 25, Nardeux, Loches, France). The capacitance probes were buried in augered holes with direct contact between the electrodes and the soil. The capacitance probes were "highly sensitive to change in soil structure and texture," but provided better accuracy than the neutron probe, which was calibrated by a theoretical method. It is likely that the better results obtained for capacitance probes in this study were due to the lack of an air gap between the electrodes and the soil.

Paltineanu and Starr [82] calibrated a capacitance probe (EnvironSCAN, Sentek Pty Ltd., South Australia) in the laboratory using a silt loam soil with good results ($r^2 = 0.992$, N = 15, $θ_v$ range = 0.07 – 0.37 m^3 m^{-3}, RMSE = 0.009 m^3 m^{-3}). Boxes were packed very uniformly (CV for bulk density = 0.5 to 2.9%, CV for $θ_v$ = 0.0054 to 0.065%) with soil at four different water contents for the calibration. The extreme uniformity of packing brings into question how appropriate the calibration would be for a field soil, which is likely to be much less uniform in bulk density and water content on a small scale. Tests of radial sensitivity showed that 99% of the sensitivity was within a 10-cm radius outside of the access tube, and 92% of the sensitivity was within a 3-cm radius of soil outside the access tube (Fig. 11). This reveals that the probe will be quite sensitive to small scale variations of soil properties close to the access tube. Later, the same authors [83] installed these probes in the field for long-term measurements of profile water content. Though they reported success, they did not test to determine if the laboratory calibration proved accurate in the field. The tests they did conduct were comparisons with crop water use estimated using an atmometer, and cannot be considered rigorous. Oddly, they did not report any water contents, only soil water storage and change in storage data. Paltineanu and Starr

[82] considered it inappropriate to compare the capacitance method with neutron thermalization due to differences in measurement method and sphere of influence. However, such differences might well be the point of a comparison, as was shown by Evett and Steiner [67].

At this writing (2000), many capacitance type soil moisture probes or gauges are being introduced in the marketplace. Some of these respond quite well to the dynamics of soil water content, including that due to plant water uptake. Demonstrations have shown that the dynamic behaviour of plant water uptake can provide important information needed for irrigation scheduling. But, there is a lack of scientific literature supporting claims of accuracy of soil water content measurement with these devices, demonstrating that laboratory calibrations may be used successfully in the field, or demonstrating successful field calibrations. Capacitance probes that employ sensors in a plastic access tube are the closest analogue of the neutron probe deployed in an access tube. However, studies to date show that capacitance probes have a very narrow radial range of sensitivity outside of the access tube and thus suffer from disadvantages that include

— sensitivity to soil disturbance during tube installation, and
— sensitivity to small scale variations in soil bulk density (including macroporosity), water content, and texture, which are common to many soils.

Other studies have shown that capacitance probes are still sensitive to soil salinity, temperature, and texture, though perhaps less so than in the past. Though it may be useful for some irrigation scheduling needs, the capacitance probe still cannot be considered a replacement for the neutron probe for soil water content measurements for which accuracy is important.

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