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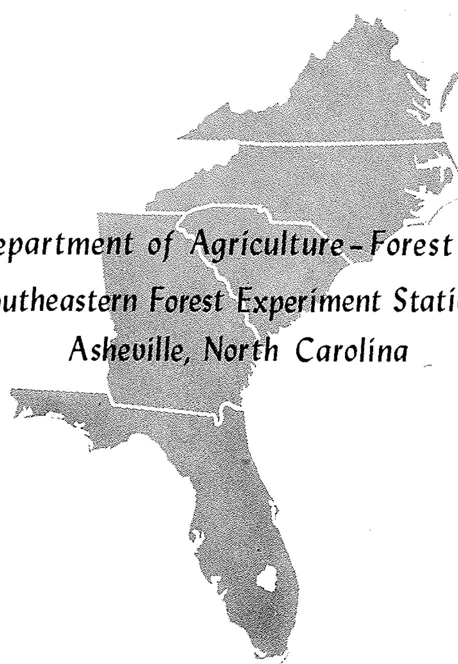

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The neutron method, a rapid, precise way of measuring soil moisture *in situ*, has become widely used in soil research in recent years. Theoretical aspects of the method are well known, but data concerning the error of field moisture measurements and experimental designs which control error are meager. In studies concerning moisture storage, drainage, and evapotranspiration, data are often averaged for an area of land. An important step in planning this sort of study is selection of an experimental design which controls error so that it does not exceed the allowable limit. To do this, one must know something about sources of moisture variation and their magnitude.

Some experience with the error of field measurements (total error arising from all sources) and instrumental sources of error has accumulated. Jarrett (3) discussed theoretical aspects of the error of radiocounting and others (4, 5) have used his work as a basis for estimating the random counting error of individual measurements. This error is usually insignificant if several measurements are made within a soil stratum and particularly when compared with error arising from the variation in moisture from point to point in the soil. The only reported comparison of field measurement errors of the neutron and other methods was by Stone *et al.* (7). They found that for the soil studied one neutron sample gave information equal to seven gravimetric samples. Such information is valuable but does not give the experimenter the information needed for designing a study using the neutron method.

Information pertaining to sources of variation, methods of reducing variance, and designs which capitalize on advantages of the method can be best determined by prestudy sampling of the moisture population. This paper presents results of such a sampling study. Quantitatively the results apply only to the soil studied, but some observed relationships are applicable in principle to other soils and areas and may aid those contemplating use of nuclear equipment.

METHODS

A 19-year-old loblolly pine plantation growing on a nearly level old field in the South Carolina Piedmont was selected for the study. The soil series is Cataula and is characterized by a sandy Ap layer underlain by a clay B horizon. The area appeared to be homogeneous with respect to slope, aspect, topographic position, depth and texture of the Ap layer, soil series, and timber stand characteristics.

Within the plantation, two blocks approximately $\frac{1}{4}$ acre in size were established. Each block was stratified into two plots, and within each plot two randomly located sampling positions were established. At each position two access tubes (subsamples) were installed 36 inches apart and to a depth of 8 feet. The soil from each 1-foot depth was saved for laboratory analyses of texture, wilting point, and moisture equivalent. Moisture content was measured weekly at 1-foot depth intervals (fig. 1) and expressed as inches per foot of soil.

Analysis of variance techniques were used to determine significant differences in the sources of variation. More importantly, the design was used to compute the individual components of variance (6). Components of total variance (identical with sources of variation in the analysis of variance table) were as follows: between blocks; between plots within blocks; between positions within plots; and between determinations at the same position. The value obtained for each component was separate from and unaffected by variation due to all other components. Thus, the greatest contributor(s) to total variance were easily identifiable.

Figure 1. --Moisture content was determined with the Nuclear-Chicago Corporation P-19 Moisture Probe and Model 2800 Scaler. Spacing and relative size of the stand is shown in background.

RESULTS AND DISCUSSION

Total Moisture Content

The moisture content at the same depth varied greatly between sampling points on any one day. For example, the variation in moisture content of the surface foot of soil on one particular day ranged from 2.89 to 5.99 inches. The range of moisture contents encountered at lower depths was also large.

Estimated values of the various variance components are presented in table 1. Each value is the average of 6 independent estimates obtained during a 1-month moisture-depletion period.

In the surface foot, positions within plots were significantly different in moisture content, and this was the chief component of variation. Positions were also significantly different in the 4 to 5 and 0 to 4-foot depths.

The plots-within-blocks component contributed little to variance of moisture in the surface 6 feet of soil. However, in the 6 to 7 and 7 to 8-foot depths, plots within blocks was a major component of variation and the plots held significantly different volumes of moisture.

Below one foot, the block component was the largest contributor to moisture variance, and blocks were significantly different in the 3 to 4, 4 to 5, 5 to 6, 0 to 4, and 0 to 8-foot depths.

The contribution of dual determinations at the same position (2 samples 36 inches apart) varied with depth, normally being small for individual depths and large when summed for several depths. The standard error varied from 0.05 inch for the 6 to 7 and 7 to 8-foot depths to about 0.30 inch for the 0 to 8-foot profile.

Variation of this order could conceivably mask relatively important treatment differences. One naturally speculates about the cause of such large variation between blocks, plots, and positions on an apparently homogeneous site. Vegetation differences were examined but failed to account for the variation. Clay content at each sampling point was next examined because it is generally recognized that texture is correlated with moisture content on a weight or volume basis (1, 2).

Figure 2 illustrates the relationship between total moisture and clay content of all depths and sampling points at one point in time. For each 10 percent increase in clay content, moisture volume increases by about one inch per foot of soil. The correlation is surprisingly strong (r = .88) when differences in moisture tension and soil density from place to place within the soil are considered.

Table 1.--Components of variance in total inches of water by soil depths[1/]

Component of variation	Soil depth in feet									
	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	0-4	0-8
	Components of variance in total inches of water									
Between blocks	0.2210	0.1282	0.2330	0.9500*	1.3796*	1.7301*	1.2223	0.4628	5.8665*	47.4554*
Between plots within blocks	-	-	-	.0346	-	.0692	.1990**	.1898**	-	1.0832
Between positions within plots	1.0103**	.0680	.0465	.0934	.3320**	.0250	-	-	1.1585*	.8680
Between determinations at the same position	.2784	.0576	.0640	.0736	.0976	.1104	.0304	.0480	.7888	1.4560

1/ Dash indicates that the best estimate of the component is 0.
* Significantly different from 0 at the .05 level as determined from analysis of variance table.
** Significantly different from 0 at the .01 level as determined from analysis of variance table.

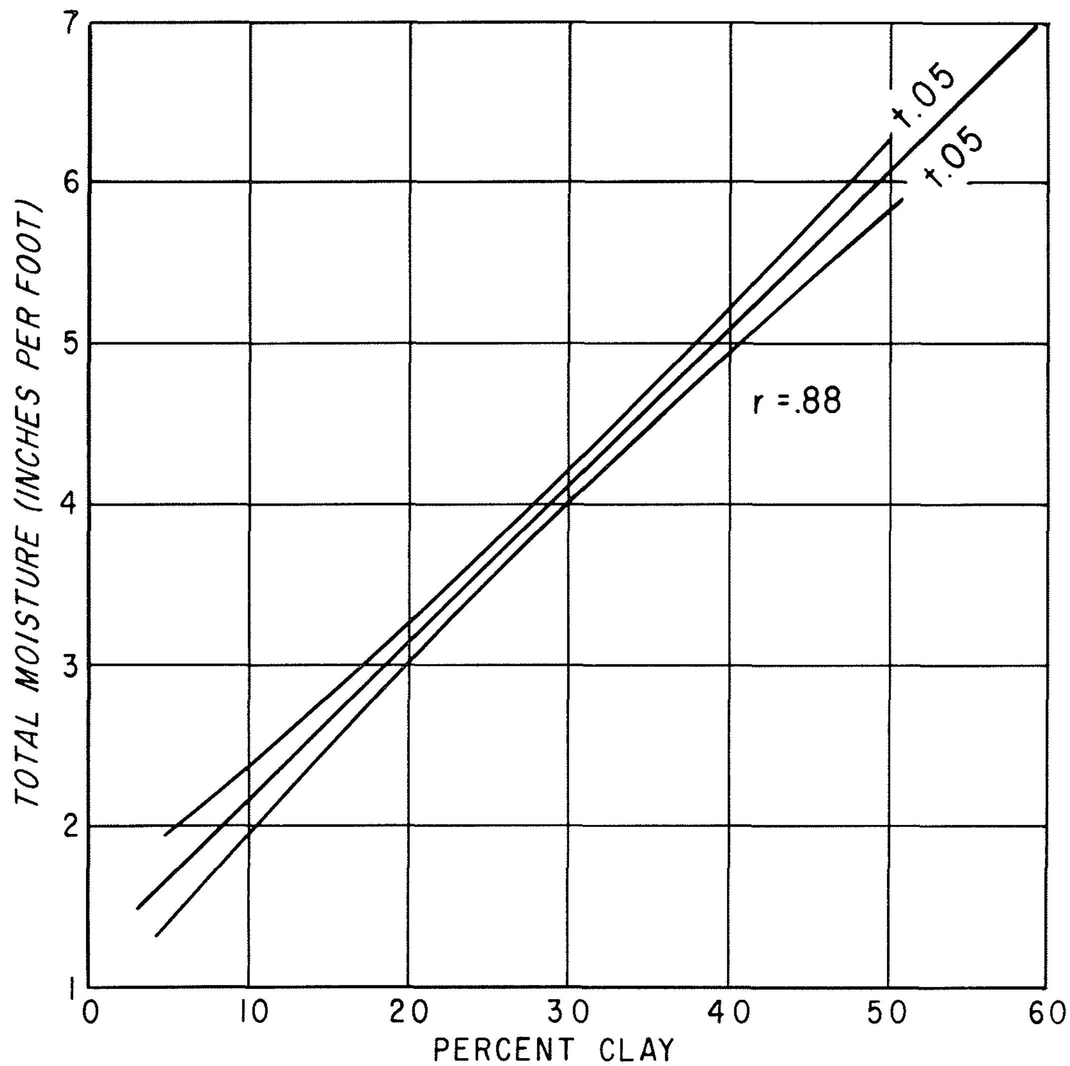

Figure 2.--Relationship of total water to clay content.

Using the same statistical model as in the analysis of total moisture content, the components of variation in clay content were estimated (table 2). Comparison with table 1 reveals that where clay content differs significantly, total moisture is also generally significantly different. Thus, clay content appears to be responsible for much of the variation in moisture volumes.

Table 2.--Components of variance in percent clay content by soil depths[1/]

Component of variation	Depth in feet							
	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8
	Components of variance in clay content							
Between blocks	42.70	40.19**	66.81	247.58**	155.88**	166.63*	128.32	50.50
Between plots within blocks	-	-	-	-	2.12	17.50	7.50	21.00
Between positions within plots	49.25*	-	46.75	-	-	-	11.25	15.00
Between determination at the same position	9.06	22.50	28.75	36.75	55.55	24.75	10.00	11.00

1/ Dash indicates that the best estimate of the component is 0.
* Significantly different from 0 at the .05 level as determined from analysis of variance table.
** Significantly different from 0 at the .01 level as determined from analysis of variance table.

These data are strong empirical evidence that where clay content is homogeneous, moisture variance will be small; and, conversely, if it is variable, moisture variance will be large. To illustrate this, data were grouped by clay content classes (assuming random sampling) and the standard error of moisture volume was calculated. Figure 3 illustrates graphically the theoretical consequences of an increasing range in clay content on the number of samples required for given standard errors. If the range in clay content increases from $\pm$ 5 percent to $\pm$ 10 percent, about twice as many samples are required to obtain a given error.

The study findings suggest that experimental error will be large for this series if total moisture volume is used to compare treatment responses. The interdependence of clay content and moisture volume precludes use of the latter as a valid indicator of soil moisture stress, unless the effect of textural differences can be removed through a covariance analysis. It is entirely possible for two soils to be at wilting, yet one contain a volume of moisture twice as great as the other simply because of differences in clay content.

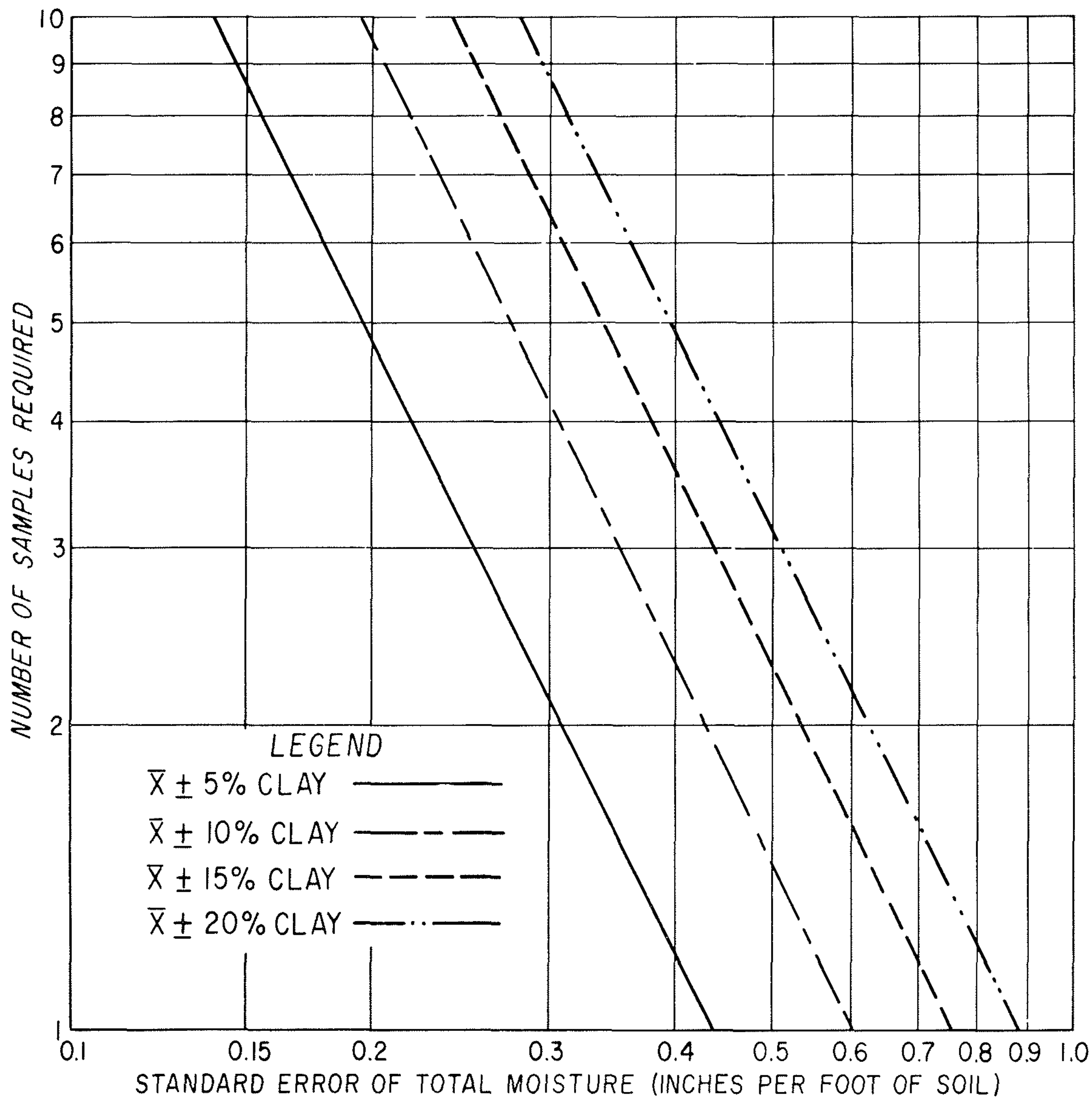

Figure 3.--Number of samples needed, for several ranges in clay content, to achieve certain standard errors of total moisture.

Moisture Losses

An analysis of moisture losses or change in moisture content with time has distinct advantages over a comparison of total moisture content. Biologically, losses are more meaningful than total moisture. Considering the usual study objectives in hydrology, the quantity required is generally moisture loss (which may be termed change in moisture content, moisture deficits, change in storage, etc., as serves the descriptive needs of the individual).

Since the same soil mass can be remeasured, losses can be determined for each sampling point. Analysis of individual losses automatically includes covariance and reduces experimental error. Also, losses, since they are numerically less than total moisture content, give a smaller error in terms of moisture volume or inches per foot of soil if the coefficients of variation of the two are about the same.

Moisture losses were computed for the same depletion period used in the analysis of total moisture, and the contribution of each component to total variance in moisture loss was determined (table 3). Note that the only significant difference is in the 3- to 4-foot depth. This analysis, in terms of water loss, eliminated most of the variation observed when total moisture content was the basis for comparison (see tables 1 and 3).

A word of caution is needed at this point. The greatly reduced variation and near absence of significant differences between components does not mean that texture is unimportant when losses are being compared. Clay content is also related to moisture loss. The relationship is negative, strong in the surface foot (r = .87), but considerably less in lower horizons. The effects of textural variations disappear when losses from individual depths are summed, as in obtaining total loss from the 0- to 4-foot depth. Therefore, prospective experimental areas should be examined for homogeneity of soil texture, particularly if individual depths are to be compared.

Table 3.--Components of variance in soil moisture loss by soil depths[1/]

Component of variation	Depth in feet									
	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	0-4	0-8
	Components of variance in soil moisture loss									
Between blocks	0.0659	-	0.0108	0.1285*	-	0.0005	0.0001	-	0.0209	-
Between plots within blocks	.0015	-	.0190	-	0.0047	.0004	-	0.0002	.0342	0.1041
Between positions within plots	.0282	-	-	.0091	-	-	-	-	.0902	.0853
Between determinations at the same position	.0413	0.0521	.0797	.0346	.0286	.0032	.0039	.0024	.2874	.2826

1/ Dash indicates that the best estimate of variance is 0.
* Significantly different from 0 at the .05 level as determined from the analysis of variance table.

The number of samples required for an analysis of losses and total moisture is illustrated in figure 4. For a given precision level, an analysis by losses requires about one-tenth as many samples as a total moisture analysis. Again, these are theoretical values based on random sampling.

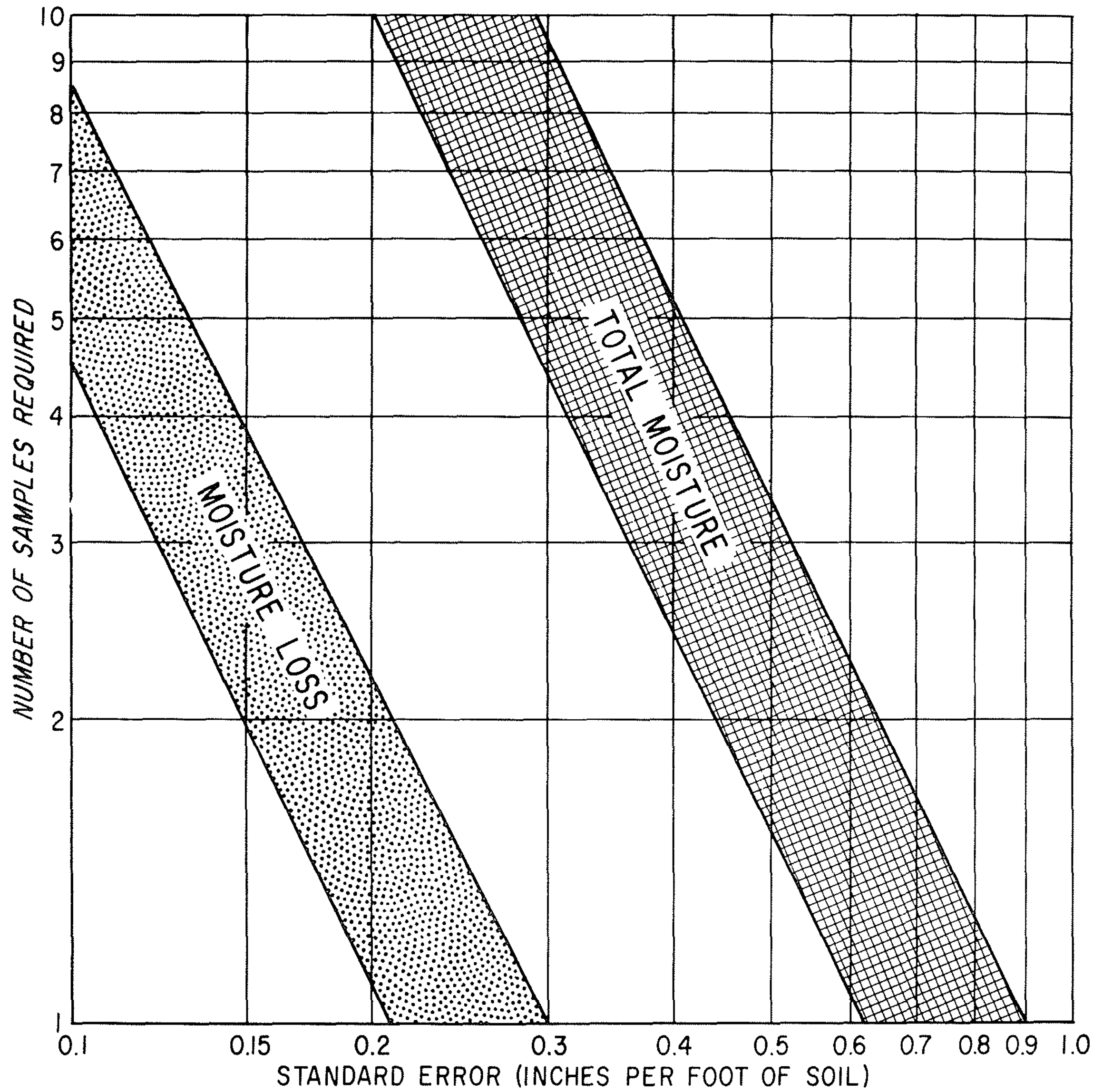

Figure 4.--Number of samples required to hold the standard error of total moisture and moisture loss to specific amounts. Upper and lower limits represent ranges in clay content of 40 and 20 percent, respectively. The curve is valid only to a depth of 5 feet.

Design Efficiency

One naturally wonders whether the design used could be improved. All evidence suggests losses as the most precise method of comparing moisture conditions and it, rather than total moisture, will be considered.

In the design, each block was divided into two strata (plots). Subsampling within strata provided a means of determining the contribution of these components to total variance--an unknown prior to the study. Within plots, only determinations at the same position made an appreciable contribution to total variance (table 3), and a more precise measure of loss would have been obtained if the four samples had been randomized within plots. The following tabulation shows the estimated gain in precision which would result from randomly sampling within plots.

Soil depth (Feet)	Precision gain (Percent)
0-1	40
1-2	0
2-3	0
3-4	21
4-5	0
5-6	0
6-7	0
7-8	0
0-4	24
0-8	23

The plots-within-blocks component contributed little to total variance, and stratifying blocks into plots decreased rather than increased precision. The between-blocks component contributed appreciably to variance in only two depths (table 3). Thus, it can be concluded that, in general, more information would be obtained by random sampling of the population.

If the population is sampled at random, how many samples are needed? This can be determined directly from figure 4 if variability of clay content of the soil and desired error are known.

Applicability of the data in figure 4 to other soils and areas is not known. However, since data are for soils of variable texture and density within depths, they may have application to soils of similar characteristics and should be conservative for more homogeneous soils. Until better data are available, figure 4 affords a useful guide in planning future studies.

SUMMARY

Results from this study lead to several tentative conclusions concerning use of the nuclear equipment to measure moisture in Piedmont soils.

1. The error of total moisture content determined by the neutron method is large, particularly where soils vary considerably in texture. Consequently, it is difficult to detect differences between treatment means unless covariance techniques are used to remove textural effect.

2. Analysis of moisture losses is, for several reasons, a more precise analysis for detecting treatment differences than total moisture content. For the same experimental precision an analysis by losses requires fewer samples than a total moisture content analysis.

3. The error of both total moisture content and moisture loss increases as the range of clay contents encountered increases.

4. For the area involved, random sampling of the moisture population would have been the best possible design for sampling moisture in the study area.

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