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COMPARISON OF NEUTRON MOISTURE GAUGES WITH NON-NUCLEAR METHODS TO MEASURE FIELD SOIL WATER STATUS

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Abstract. The neutron moisture gauge was compared with the gravimetric-core soil sampling technique, tensiometers and resistance blocks in relation to temporal stability, field variability, spatial dependence and number of samples needed for a given level of accuracy. The variance of field water content measurements with neutron moisture gauges was lower than that of the gravimetric sampling, which therefore required 2 to 6 times as many samples as the number of measuring sites of the gauges to attain the same level of accuracy. The space dependence of the measurements made with the subsurface gauge varied depending on average field soil water content. No space dependence was evident when the water content was lower than 0.2 $cm^3 cm^{-3}$ (50 % saturation). Measurements with the tensiometers and resistance blocks manifested, however no spatial dependence and therefore randomly selected measuring sites can be adapted to field research work where these methods are to be utilized. Soil water content measurements estimated with neutron moisture gauges showed well defined temporal stability which implies that soil water status of an entire field can be assessed with measurements limited to a few sites. The measurements with both tensiometers and the resistance blocks are time variant owing to their relatively smaller measuring domains as compared to neutron gauges. Therefore, it is not possible to calibrate the measuring sites of the tensiometers and resistance blocks as to assess soil water status of the entire field as it could be done with the neutron gauge.

INTRODUCTION

The neutron scattering method has received world-wide popularity in soil water studies because it can provide very quick and non-destructive measurement of field soil water content. However, traditional non-nuclear methods such as gravimetric sampling, tensiometers and resistance blocks are still being used, for the same purpose, in a field research work. Since the pioneering works of Gardner and Kirkham [5] and Van Bavel [28, 29], a wide range of research has been done for the evaluation and improvement of the neutron scattering method [1,6,9, 10-13,20,24,27]. Similar attention has been given to the development of tensiometers [17-19,22,23] and of resistance blocks [2,3,16,21,25]. Tensiometers work only in the wet range of soil water content, up to soil water matrix pressure of -80 kPa [18]. The resistance blocks complement the tensiometers and work only in the dry range. Gravimetric sampling is the oldest traditional method used to measure soil water content. It is the standard method against which all the other methods are to be calibrated. However, it is very laborious and the results can only be available after a minimum of one day. Different merits of the methods mentioned above vary depending on specific objectives of scientists who use them.

This work compared neutron moisture gauges with tensiometers, resistance blocks and with gravimetric sampling in estimation of field-mean soil water content in regard to temporal stability, field variability, spatial dependence and number of sampling or measuring sites for a given accuracy.

METHODS AND MATERIALS

The data, subject to discussion here, was compiled from field tests conducted in 1985 and 1986. Measurements were made along field transects so that geostatistical methods could be used in the comparison of the different methods. The spare interval of measurements (i.e., lag distance) in 1985 and 1986 field transects were 1.5 and 3 m, respectively. Each year, the field transects were laid down in different sites of a 5 hectare-research field. Measurements made for comparison purpose were independent of the measurements for calibration. The experimental soil is classified as Typic Eutohrepts with coarse clay loam texture. It is an alluvial soil with compacted gravelly clay zone at about 0.5 m depth. The surface layer of 0.4 to 0.5 m appears rather stony with gravel content of about 30 %.

Neutron gauge calibration and comparison

Two types of neutron moisture gauges, surface and subsurface types were used in the field tests. They were Troxler 3411 series, combined water and density gauge, and CPN 503 DR, respectively.

Measurements made with neutron subsurface gauge were compared with those made with tensiometers and resistance blocks in 1986. The experimental plots of 3 x 3 m, where the different methods were compared, were planted alternately to maize, and the remaining plots were left bare.

Neutron access tubes were installed in the center of the plots. Tensiometers and resistance blocks were installed at 30 cm depth, 50 cm from the access tubes. Calibration of the neutron gauge was done at the end of growing season, in September 1986. The calibration was completed in two stages: 1). When soil water content was relatively dry (0.12-0.20 $cm^3\ cm^{-3}$), and 2). When it was relatively wet (0.25-0.30 $cm^3\ cm^{-3}$). After neutron gauge measurements were made, in each case the measuring sites were excavated to collect gravimetric samples. The second set of measurement was obtained following irrigation to increase soil water content to wet range (over 0.20 $cm^3 cm^{-3}$). At each stage, 20 (equally divided in bare and maize planted plots) gravimetric core soil samples were collected, with concurrently made neutron count rate measurements, using both surface and subsurface neutron gauges.

The neutron gauges callibrated in 1986 were compared with the gravimetric core sampling. The gravimetric data used in the comparison were collected in 1985, in a different site of the field. Measurements, used in the comparison, were made along the field transect, laid on a bare soil, at 1.5 m equally spaced measuring sites.

Autocorrelation analysis

Autocorrelation analysis described by Davis [4] was used to determine if soil water content measurements made with the different methods are spatially correlated. The relation to calculate autocorrelation coefficients $r(h)$ is given by:

$$r(h) = C(h)\, C(0)^{-1} \qquad (1)$$

where $C(h)$ is the estimated autocovariance of measured values of one given property X separated by a number h lags (one lag being the distance between two consecutive measurements) and $C(0)$ is the estimated sample variance. For one dimensional case, the autocovariance is given by:

$$C(h)=(\sum X_i-\overline{X})\,(X_{i+h}-\overline{X})(n-h-1)^{-1} \qquad (2)$$

where $\overline{X}$ is the sample mean, n is the total number of the measuring sites, X_i and X_{i+h} are any measured values along the experimental transect.

Sample number determination

Two methods were used for sample number determination. The first method is based on the assumption that the measurements are normally distributed, and that the accurate estimation of its variance is known. The number of samples (N) necessary to be within the d units of the field mean with (1- α) % confidence is [7,8,14]:

$$N = [Z\sigma/d]^2 \qquad (3)$$

where Z is $(X - \mu/\sigma)$, σ^2 is the population variance, μ is the population mean and d is half width of the confidence interval. For values of $\alpha = 0.1$, Z is 1.64.

The second method [8], is recommended for situations where there is no accurate estimation of variance. This method yields a conservatively high sample number; but, it gives a higher assurance that the mean will indeed fall within d units of the mean [8]. The sample number N is given as:

$$N = \frac{t\alpha^2, n-1F\alpha, n-1, n-1s^2}{d^2} \qquad (4)$$

where t is Student's t with $(n-1)$ degrees of freedom, $\alpha$is the assumed probability that half width of the confidence interval will not be exceeded; F is the tabulated variance ratio with identical degrees of freedom (n-1) for both the numerator and denominator of the F distribution function, and s^2 is the sample variance.

RESULTS AND DISCUSSION

Accuracy and spatial dependence

Field soil water content measurements, estimated with tensiometers and resistance blocks were mostly confined within the limits of 95 % confidence interval (±0.06 cm^3 cm^{-3}) of the neutron moisture gauge estimations (Fig. 1). The field mean values of water contents measured with tensiometers and resistance blocks deviated slightly from those estimated with neutron moisture gauge (Fig. 1). The deviation can further be reduced if one can invest the same effort in their calibration as spend in the calibration of the neutron moisture gauges.

Figure 2 compares autocorrelograms of soil water content measurements, made with subsurface neutron gauge and tensiometers. Neither soil matrix pressure nor soil water content, which are respectively measured directly and indirectly with the tensiometers, show spatial dependence. However, the neutron gauge measurements manifest a distinct spatial dependence over a distance of 3 lags (9 m). This implies that the measurement domains of the two methods, tensiometers and the neutron gauges, are not the same. While the measurements with the neutron gauge are spatially correlated within a distance of 9 m, the tensiometer measurements show a random distribution. The spatial dependence, manifested in neutron gauge measurements, has both advantages, and conversely, some conseqences, which must be considered in agricultural research: 1). A single measurement made with a neutron gauge represents relatively larger area in the field, which is a circular area with a radius of 9 m, than that of tensiometers. 2). Soil water characteristic curves can be determined with concurrent use of tensiometers and the neutron gauge in field conditions. In this case, tensiometers can be installed at any convenient distance, up to 9 m for this field, from the neutron access tubes. 3). Field experiment designs must consider spatial dependence of water content measurements, and a distance of more than 9 m in the experimental soil used in this study, must be allowed between the centroids of the experimental plots, where water content measurements are made with neutron moisture gauges.

Spatial dependence of the neutron gauge measurements was more evident at high field soil water contents (0.20 cm^3 cm^{-3}), and it decreased as the water content decreased (Fig. 3). Autocorrelation coefficients

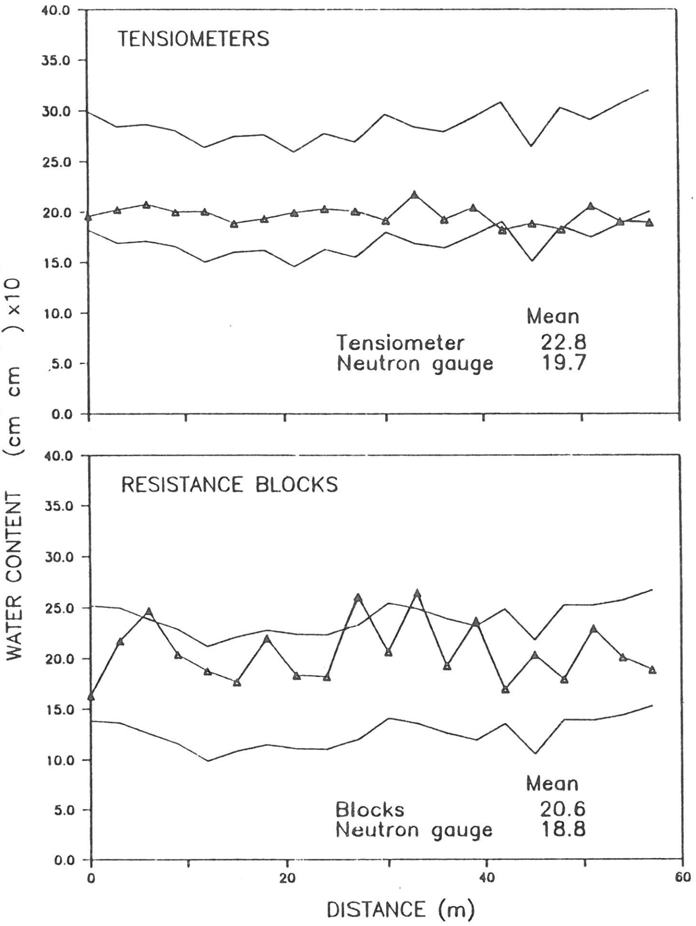

Fig.1. Spatial distribution of field soil water content at 30 cm soil depth, measured with neutron moisture gauge, tensiometers and resistance blocks. The solid lines show 95 % confidence interval of the estimates of soil water content measured with neutron gauges. The lines with data points are the estimates with tensiometers and the resistance blocks.

for lag=2, shown in Fig. 4, manifested a strong association with water content measurements. Therefore, the results suggest that highly heterogeneous nature of the physical soil properties, influencing water storage capacity of the experimental soil, became more apparent at high water contents, from 0.24 to 0.27 cm^3 cm^{-3} (over 75 % saturation), than lower water contents, from 0.11 to 0.18 cm^3 cm^{-3} (below 50 % saturation).

Both surface and subsurface neutron gauge measurements were compared with the destructive, gravimetric core-sampling method, in a separate site of the field other than the one where the neutron gauges were calibrated. The site was bare soil. Measurements were made at 1.5 m equally spaced measuring sites, along the field transects. For surface and subsurface neutron moisture gauges 30 and 48 measuring sites were used, respectively. The depth of measurements for the subsurface gauge was 30 cm. After neutron gauge measurements were completed, the sites were excavated to collect cylindrical core soil samples, with 10 cm height and 10 cm diameter. Spatial distribution of water contents, measured with neutron gauge and the gravimetric sampling are

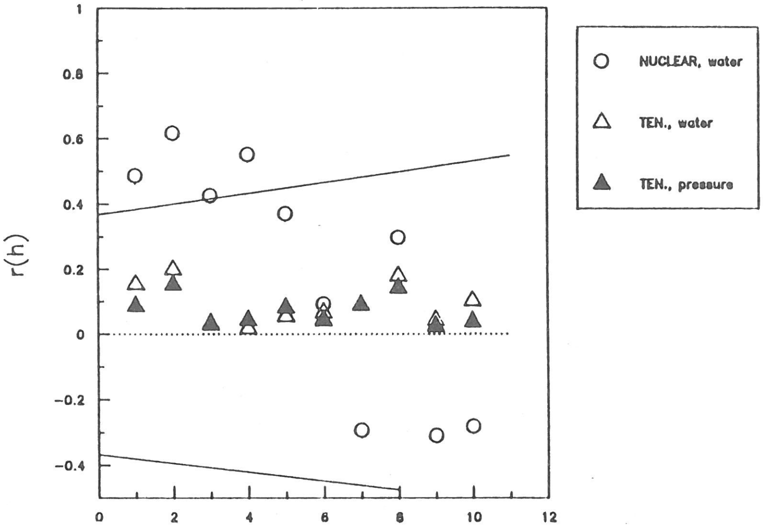

Fig. 2. Autocorrelograms of the neutron gauge and the tensiometer measurements. Solid lines show 95 % confidence interval of random variability.

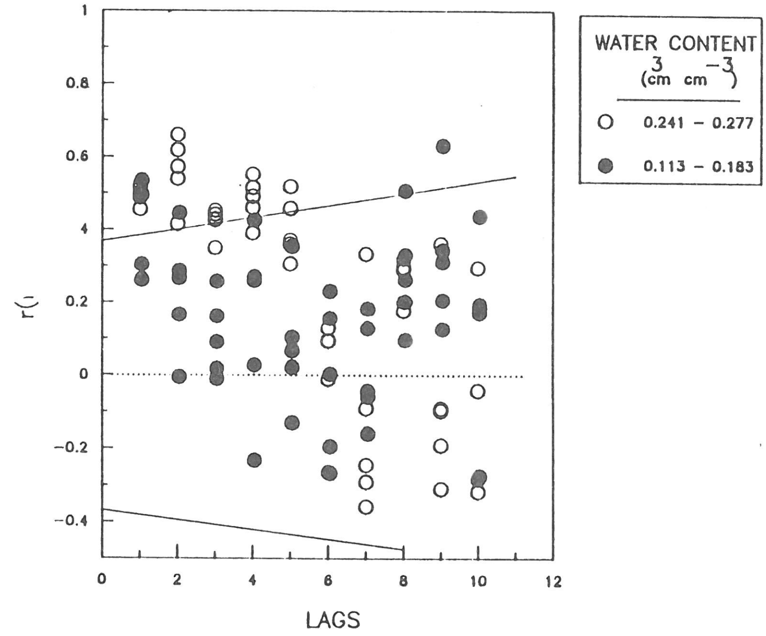

Fig. 3. Influence of soil water status (i.e., high or low water content) on spatial dependence of the water content measurements. Solid lines show 95 % confidence interval of random variability.

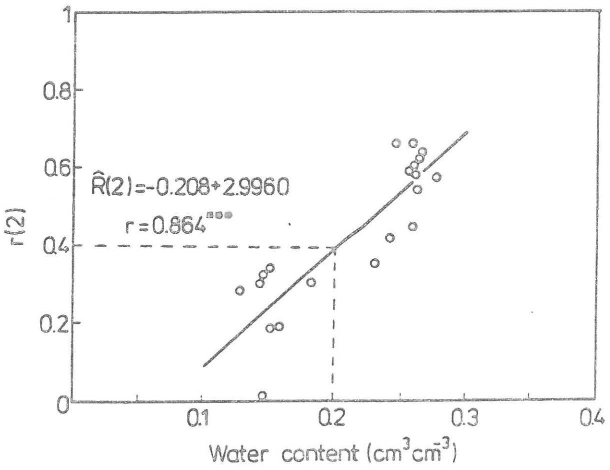

Fig. 4. Dependence of autocorrelation coefficient at lag = 2, r(2), on field soil water status. The marked area shows 95 % confidence range of random variability of field water content measurements.

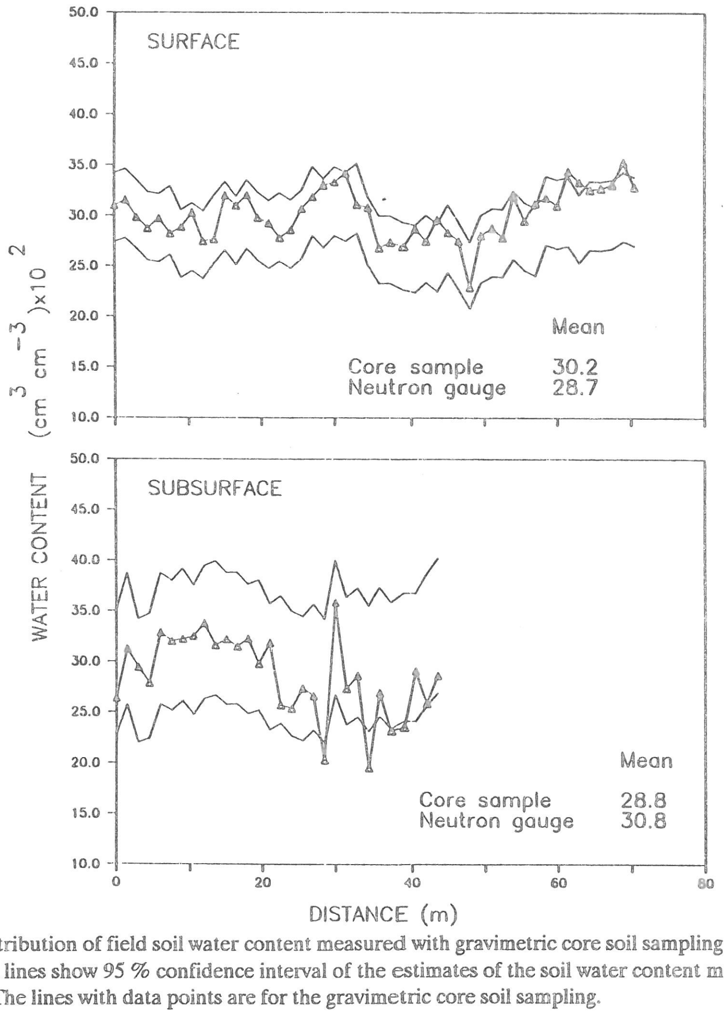

Fig. 5. Spatial distribution of field soil water content measured with gravimetric core soil sampling and the neutron gauges. The solid lines show 95 % confidence interval of the estimates of the soil water content measured with the neutron gauges. The lines with data points are for the gravimetric core soil sampling.

shown in Fig. 5. Soil water content estimations made with neutron moisture gauges follow very closely the spatial distribution manifested with the gravimetric sampling. There was no statistically significant difference ($P<0.05$) between the field mean estimation of water content with both, the neutron moisture gauges and the gravimetric sampling. Autocorrelograms, not shown here, indicated that water content measurements with both gravimetric sampling and the neutron scattering method had spatial dependence with similar autocorrelation distance, irrespective of the method of measurement, the gravimetric sampling or neutron gauge measurement.

To determine number of measuring sites or number of samples in different methods, for estimation of field mean water content to be ±10 % deviation of the true mean (i.e., population mean μ) with 90 % confidence, Eqs (3) and (4) are used. In cases where the data were space dependent, the sample mean and the variance were calculated using sub-sample sets with individual observations selected outside of the autocorrelation distance. For example, in comparison of subsurface neutron moisture gauge with the gravimetric sampling, only half of the total 30 measurements could be used to satisfy the prerequisite of the independent measurements to calculate the necessary statistics. Variance of water content measurements with neutron moisture gauge are rather small and therefore total number of measuring sites, to allow the true mean to be within ±10 % deviation of the sample mean, with 90 % confidence, vary within a very small range, from 1 to 4, or from 2 to 9, depending on whether Eqs (3) or (4) is used (Table 1). Variance of measurements with the gravimetric sampling, when compared with the neutron gauge measurements, is higher. Therefore, 2 to 6 times as many samples as the number of neutron gauge measuring sites are needed to attain the same level of accuracy (Table 1).

Number of samples required for tensiometers and resistance block measurements varies depending on whether soil

Table 1. Comparison of the different methods for number of samples required for a given level of accuracy [a]

Date	Method	Unit	Total No. of data	No. of data in space independent sub-set	m	σ	Eq. (1)	Eq. (2)
86/06/23	Nuclear	θ %[b]	20	10	24.2	3.45	2	5
	Tens.	ψ kPa[c]	19	-	-17.5(-11.0)[d]	49.8	44(1)[e]	96(2)[e]
86/07/13	Nuclear	θ %[b]	20	-	18.3	2.21	2	4
	Tens.	ψ kPa[c]	18	-	-70.8(-43.5)[d]	241.9	13(0.3)[e]	30(0.8)[e]
86/07/24	Nuclear	θ %[b]	20	-	14.6	3.39	4	9
	Block	ψ kPa[c]	19	-	-1022(-650)	134171	36(1)[e]	77(2)[e]
1985	Nuclear	θ %[b]	30	15	30.8	2.71	1	2
	Grav.	θ %	30	15	28.8	14.9	5	12
1985	Nuclear	θ %[b]	48	16	28.7	3.2	1	3
	Grav.	θ %	48	16	30.2	5.9	2	4

a - the accuracy is defined as to have field mean water content to be ±10 % deviation of the true mean with 90 % confidence; b - water content θ is measured as volume fraction of the total soil volume (10^2 $cm^3 cm^{-3}$); c - soil matrix pressure ψ measured with tensiometers (Tens.) and resistance blocks (Blocks) and given in kPa; d - soil matrix pressure in parenthesis is approximated pressure equivalent of 10 % deviation of the field mean water content which was measured with the neutron gauge; e - number of samples in parenthesis is based on water content equivalent of the matrix pressure.

matrix pressure or soil water content is measured. Although variance of matrix pressure measurements is very high, for both the tensiometers and resistance blocks, it is lower in units of water content when compared with neutron gauge measurements (Table 1). Therefore, in contrast to the gravimetric sampling, number of tensiometers and of resistance blocks needed are 2 to 6 times less than the number of neutron gauge measuring sites to attain the same level of accuracy as the neutron gauge measurements. However, having somewhat smaller number of measuring sites for the tensiometers or resistance blocks should not outweighed the well established advantages of the neutron scattering method. For example, with a single neutron access tube one can measure changes of soil water storage over the complete plant rooting depth; whereas, one would need several tensiometers and resistance blocks, depending on the rooting depth, installed to different depths.

Temporal stability

It is also of interest to compare different methods as regards to temporal stability, i.e., if the lowest, average, and the highest soil water content measurements always occur at the same site for a given method. Vachaud *et al.* [26] demonstrated the occurrence of such a feature for soil water content measurements, and explained the observed behaviour with the deterministic relation existing between soil water content and soil texture, i.e., a field location with the highest clay content remains the wettest at all times. Kirda and Reichardt [15] showed that temporal stability of water content measurements would not be perturbed even under different crops. The existence of temporal stability of water content measurements could allow the assessment of soil water status of an entire field with measurements made only at a few sites.

Temporal stability of soil water status as measured with different methods was compared using Spearman's rank correlation test [26]. The correlation coefficients between the ranks of the first day measurements (28 April for the neutron gauge and the tensiometers, 26 June for the resistance blocks) and the ranks of another 10 sets of data collected nearly at two-week intervals over the period of 3 months (May, June and July) were compared. Both in cropped and in bare soil plots the correlations were all significant ($P<0.05$); whereas, the correlation coefficients of the tensiometers and the resistance blocks were not sifgnificant (Fig. 6). Therefore, our results suggest that it is indeed possible to assess soil water status of entire field with neutron gauge measurements limited only to a few sites. However, this is not possible with tensiometers and the resistance blocks which have to be installed in randomly selected measuring sites, and in considerably higher number than the neutron gauges. The reason why tensiometer and resistance block measurements could not manifest temporal stability lays with the extreme textural variability of the experimental soil which was essentially an alluvial deposition, mixture of sand and gravel, and compacted packs of clay. The neutron gauge measurements gave an average water content integrated over a relatively larger 'sphere of influence' than tensiometers and resistance blocks therefore, the influence of soil variability on the temporal stability was minimal. However, this was not so for the tensiometers and resistance blocks which gave soil matrix pressure measurements as they reach in equilibrium with the very heterogeneous soil, partly sand and clay, and gravel. Therefore, the deterministic relation existing between soil water content and soil texture could not manifest itself for the tensiometers and resisitance blocks used in the experimental soil.

CONCLUSIONS

From the results discussed above, the following can be concluded:

1. Field soil water content measurements with both the gravimetric core-soil

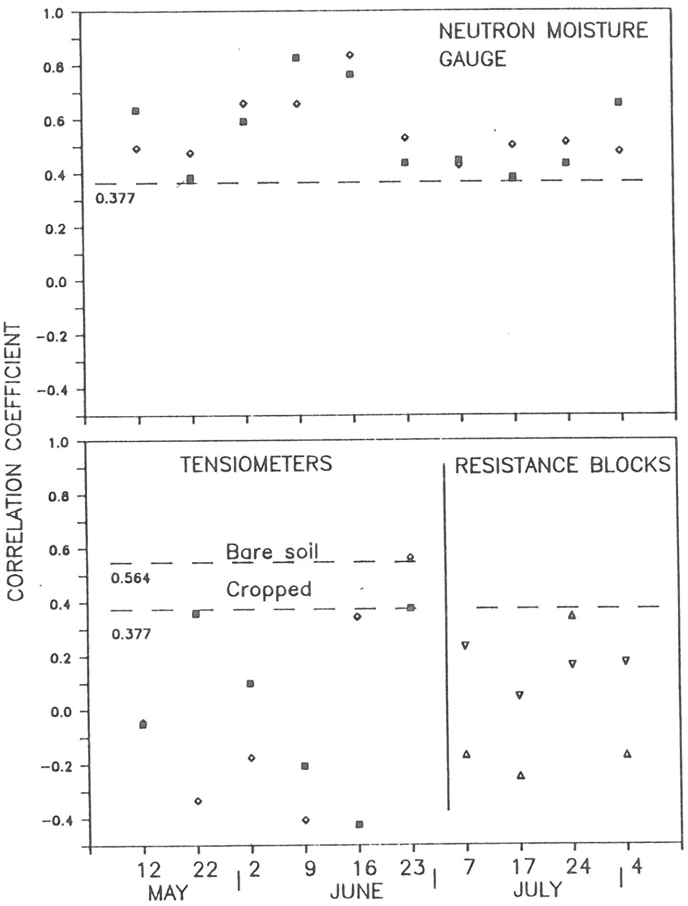

Fig. 6. Spearman's rank correlation coefficients between the first day of water content measurements (28 April for the neutron gauge and the tensiometers, 26 June for the resistance blocks) and of other measurement days. The solid and the open points designates measurements in cropped and bare soil plots, respectively. The broken lines indicate minimum correlation coefficient at 5 % significance (which was 0.377 for all measurements, except for the tensiometers in bare soil where it was 0.504).

sampling and the neutron gauge have the same spatial variance structure, i.e., the measurements with both methods are either space dependent or randomly distributed. If they are space dependent, it is not critical to take the core soil samples very close to the neutron gauge access tubes but the samples can be taken in any convenient distance within the limits of the autocorrelation length (i.e., the distance over which the measurements are correlated) during the calibration of the gauges, providing of course, that the spatial changes with respect to water content are not significant. If the measurements, however, do not show any space dependence the core samples during the calibration must be taken immediately adjacent to the access tubes.

2. Spatial dependence of the neutron gauge measurements varies depending on soil water content and it is increased as field soil water content increases to values higher than 75 % of soil saturation.

3. Field soil water content measurements estimated with neutron moisture gauges show temporal stability which persists irrespective

of whether the measuring sites are planted or left fallow. This implies that it is possible to assess soil water status of an entire field with neutron moisture gauge measurements limited to only a few sites. However, this is not possible with tensiometers and the resistance blocks owing to their relatively smaller measuring domains as compared to the neutron moisture gauge.

4. Users need relatively more numbers of samples with the gravimetric sampling than the number of the measuring sites of the neutron gauges to attain the same level of accuracy, i.e., to allow for example estimated field mean water content measurements estimated indirectly with tensiometers and the resistance blocks is lower than that of the neutron gauge measurements because the high variability observed in soil matrix pressure measurements can be eliminated in estimation of water content using soil water characteristic curves for the clay soil. Nevertheless, users would still need more units of tensiometers and resistance blocks than the number of the measuring sites of the neutron gauges to monitor changes of soil water status over the entire plant rooting depth which may be as deep as 1 to 3 m. One needs several units of tensiometers or resistance blocks to measure soil water content at different depths; whereas only one access tube would be adequate for the neutron moisture gauge.

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