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Water and nutrient fluxes as indicators for the stability of different land use systems on the Terra firme near Manaus

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5) Field calibration of time domain reflectometry in an Amazonian rainforest soil with variable bulk density: sources of error and influence of land-use

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Introduction

Time domain reflectometry (TDR) is increasingly used as a technique for the determination of the volumetric water content of soils (q). The technique is based on the determination of the dielectric constant (e) of the soil through the measurement of the speed of the propagation of electromagnetic waves. The method is especially useful for non-destructive and rapid determination of soil moisture at different sampling points as well as the repeated measurement of soil moisture at the same point, including measurements close to the soil surface. It also avoids the radiation hazards involved in the use of the gamma radiation and neutron moderation techniques.

In view of the large differences observed for the values of e between water (81 F m^{-1}), air (1 F m^{-1}) and the major mineral constituents of soil (3-5 F m^{-1}) and frozen water (ice) (4 F m^{-1}) when measured at a standardized signal frequency and temperature, it was initially believed that a single universal equation could be found relating q to e (Topp et al. 1980). However, later work showed that various factors may influence the measurement of e, so that site-specific calibrations are required for obtaining a reasonable accuracy of the soil water determinations, especially on clayey soils and soils with low bulk density (r). These factors can be divided into two groups:

a) technical characteristics of the measurement device, such as the length of the rods, length and resistance of the wire connecting the probe to the measurement device, signal frequency and distance between the rods (Hook & Livingston, 1995; Petersen et al., 1994; Zegelin et al., 1992)

b) characteristics of the investigated medium, such as soil structure and consequently its bulk density (ρ) (Malicki et al., 1996, Dirksen & Dasberg, 1993; Roth et al., 1992, Herkelrath, et al., 1991); texture (Bohl & Roth, 1994); temperature (Pepin et al., 1995); vertical heterogeneity of soil water content (Topp & Davis, 1985; Baker & Lascano, 1989) and presence of magnetic minerals (Roth et al., 1992).

Several of these factors, such as temperature and bulk density, can not only vary between sites, but also within small distances at the same site, for example as a result of different plant species present or differences in the soil management (tillage, mulching, etc.). Such small-scale differences would be especially expected within heterogeneous land-use systems such as agroforestry, where plant species with contrasting characteristics with respect to growth, light interception, litter production, root distribution and management are typically associated. A similar situation may occur in heterogeneous natural vegetation communities such as savannas and some forest types. In research and monitoring projects which aim to analyze the soil water dynamics with a high level of accuracy in such heterogeneous situations, such potential sources of error of the TDR technique have to be taken into account and to be excluded through appropriate calibration, if necessary.

The objective of the present work was to calibrate the TDR technique for the determination of volumetric water content for a Xanthic Ferralsol with high clay content under conditions of differing bulk density within heterogeneous land-use systems in western Amazonia, Brazil. The study was part of a larger work on water and nutrient fluxes within these land-use systems.

Materials and methods

The study was carried out within a field experiment comprising different mono and polycultures of perennial crops at the experimental station of the Centro de Pesquisa Agroflorestal da Amazônia Ocidental (EMBRAPA-CPAA) at Manaus, Brazil (3°8'S; 59° 52'W, 40m above sea level, 2200 mm annual precipitation). The soil is a Xanthic Ferralsol in the FAO/UNESCO system ("latossolo amarelo muito argiloso" according the Brazilian classification) with about 60-70% clay. Soil samples were collected close to trees of cupuaçu (*Theobroma grandiflorum*) and Peach palm (*Bactris gasipaes*) which were grown either in monoculture or in association, as well as under the leguminous cover crop, *Pueraria phaseoloides*. Samples were also collected close to two relatively common tree species in the adjacent primary forest, *Bactris gasipaes* (a palm) and

Eschweilera spp. All samples were collected at 40 cm from the trunk of the respective tree. In addition, a soil pit was opened within the experiment (association of cupuacu and Peach palm) and samples were taken from the soil depths 30 cm, 90 cm and 150 cm. The sampling positions and the respective bulk densities and water contents are summarized in Table 1. The samples were collected during both the dry and the rainy season of the year 1996 for obtaining a wide range of soil water contents.

The TDR measurements were carried out with a commercial deviceof the type EASY TEST®, Lublin, Poland, with the following technical specifications: pulse rate 250 ps, probes with two transmission rods of 100 mm length and 2 mm diameter, with 16 mm distance between the rods. For the measurements, the probes were inserted vertically into the soil (0-10 cm).

Near this point were the measurements of e had been taken with the TDR probes, we collected soil samples with a volumetric ring of 5 cm height and a volume of 100 cm^3 from the soil depth 0-5 cm for the determination of bulk density (r) and volumetric water content by oven-drying at 105° C until constant weight. The water content which, was determined in this way (q_{Grav}) was considered the "true value" for the calibration of the TDR device.

The EASY TEST® device has a built-in calibration to present directly the volumetric soil moisture q_{TDR} in %. From these values, e was calculated according to the calibration equation given by the manufacturer. For mineral soils with 1,4 g cm^{-3} $< \rho <$ 1,8 g cm^{-3}, this equation is as follows:

if $e \leq 36$ => $q_{TDR} = 10{,}64\sqrt{\varepsilon} - 15{,}82$ (1)

and if $e > 36$ => $q_{TDR} = 17{,}54\sqrt{\varepsilon} - 57{,}21$

For mineral soils for which ρ differs by more than ± 0,2 g cm^{-3} from these margins, the manufacturer suggests the use of the following correction equation given by Malicki et al. (1996):

$$q_{TDR}(e,r) = \theta(\varepsilon,\rho) = \frac{\sqrt{\varepsilon} - 0{,}819 - 0{,}168\rho - 0{,}159\rho^2}{7{,}170 + 1{,}180\rho} \qquad (2)$$

In addition to these equations, the suitability of the equation given by Topp et al. (1980) for the soils of this study was tested:

$$q_{TDR} = -5{,}3 \times 10^{-2} + 2{,}92 \times 10^{-2} e - 5{,}5 \times 10^{-4} e^2 + 4{,}3 \times 10^{-6} e^3 \; . \qquad (3)$$

As the correspondence between the q_{TDR} values estimated with these equations and the "true" q_{Grav} was unsatisfactory in all cases, new calibration equations were calculated relating the measured e to q_{Grav}. The following regression models were tested:

$$q_{TDR} = b_0 + b_1 e \qquad (4)$$

$$q_{TDR} = b_0 + b_1 e + b_2 e^2 \qquad (5)$$

$$q_{TDR} = b_0 + b_1 e + b_2 e^2 + b_3 e^3 \qquad (6)$$

For the adjustment functions between the soil moisture estimates with different equations, we determined the coefficients (b_i) and their statistical significance, the coefficients of multiple determination (R^2) and adjusted determination coefficients ($\bar{R}^2$), and the standard errors of the mean (SE) (Table 2). The adjusted regression coefficients ($\bar{R}^2$) were calculated for allowing the comparison of models with unequal numbers of variables (Jacobsen & Schojonning, 1993; Draper & Smith, 1981). Multiple regression with r and e as independent variables and q_{Grav} as the dependent variable was computed through stepwise selection of the coefficients, which contributed significantly to the model (Draper & Smith, 1981).

Results

Fig. 1 shows the values for e and the corresponding volumetric water contents as determined directly from the soil cylinders q_{Grav}. Fig. 2 gives the deviations between the "true" volumetric water contents q_{Grav} and the water contents as determined by TDR (q_{TDR}), either by direct reading from the display of the EASY TEST® device (i.e. using the built-in calibration equation), or by calculating the water content from e with the equations given by Topp et al. (1980) and Malicki et al. (1996), respectively. As can be seen, the matching of q_{Grav} by q_{TDR} is generally unsatisfactory.

For obtaining a better accuracy of the TDR measurements for this site, new regressions were calculated between e and q_{Grav}, using the linear, quadratic and cubic regression models given above (Table 2). There were only small differences in the goodness of fit between linear and quadratic equations, whereas cubic equations contained some non-significant coefficients. We recommend the quadratic equation for the relationship between e and q_{Grav} as the most suitable one because of a slightly higher ($\bar{R}^2$) and a smaller SE compared with the linear model (Tab. 2, Figs. 3 and 4).

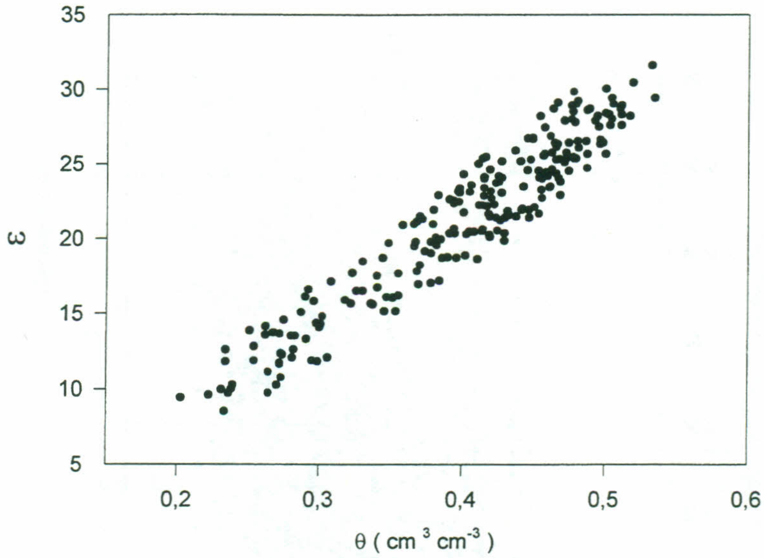

Fig. 1: Relationship between the apparent dielectric constant of soil (ε) and its volumetric moisture content (θ)

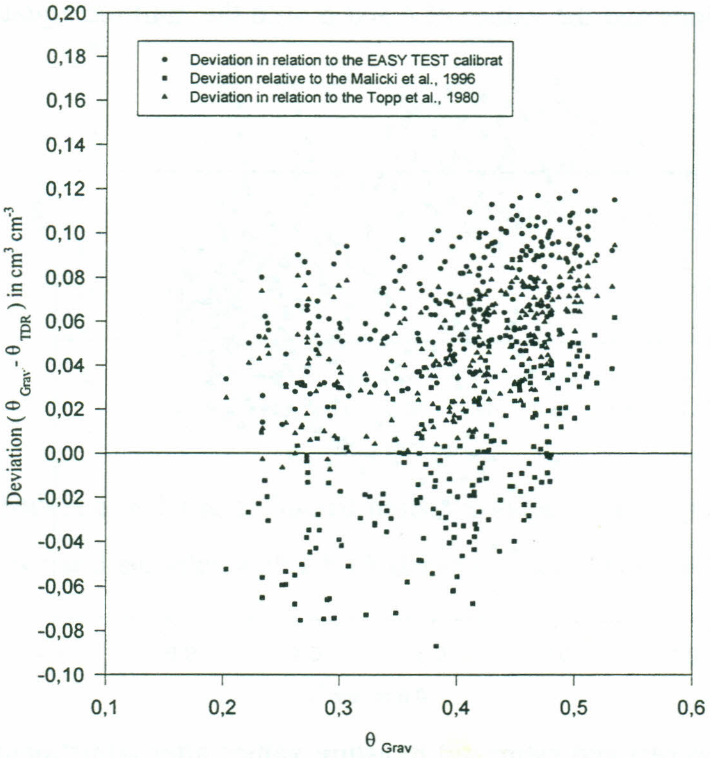

Fig. 2: Deviations between the real soil moisture (θ Grav) and the estimated soil moisture as obtained by measuring the dielectric constant of the soil (ε) and adjustment of the measured values by tree equations (θ TDR)

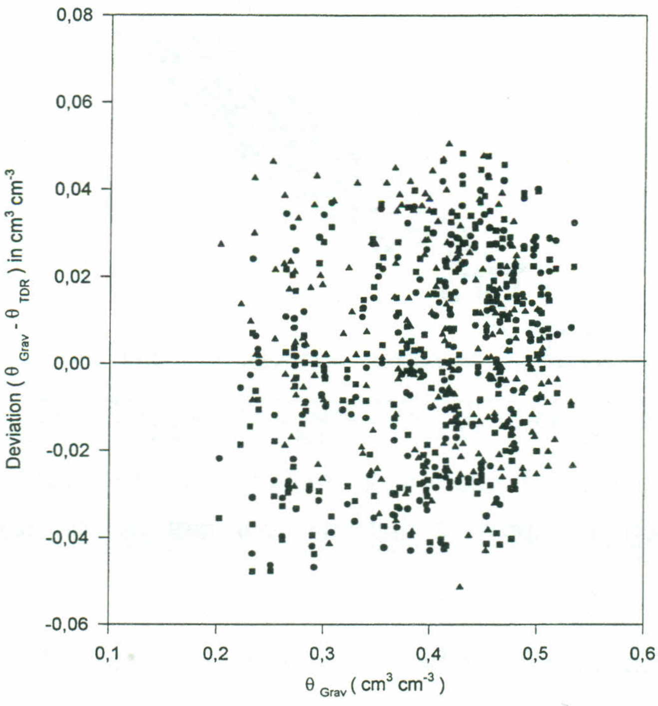

Fig. 3: Deviations between real and estimated soil moisture after adjusting the ε values with the linear and quadratic equations and the values of ε and ρ with the multiple equation

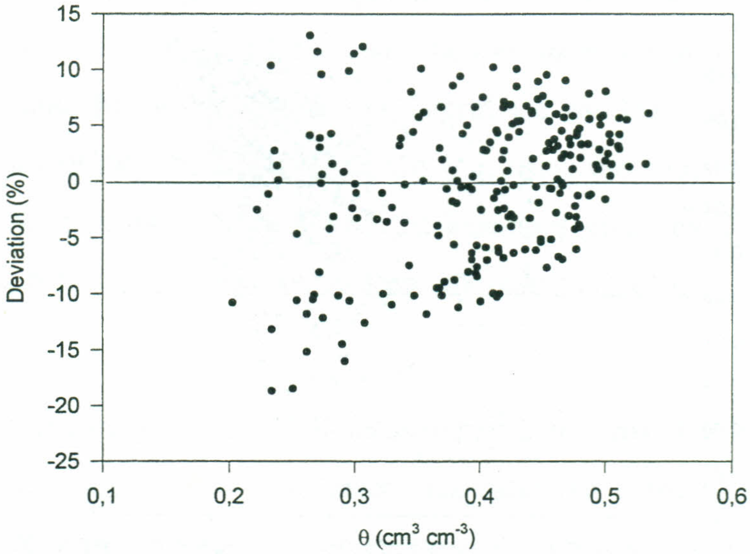

Fig. 4: Deviations between real and estimated moisture values after adjustment with the quadratic equation as related to soil moisture content

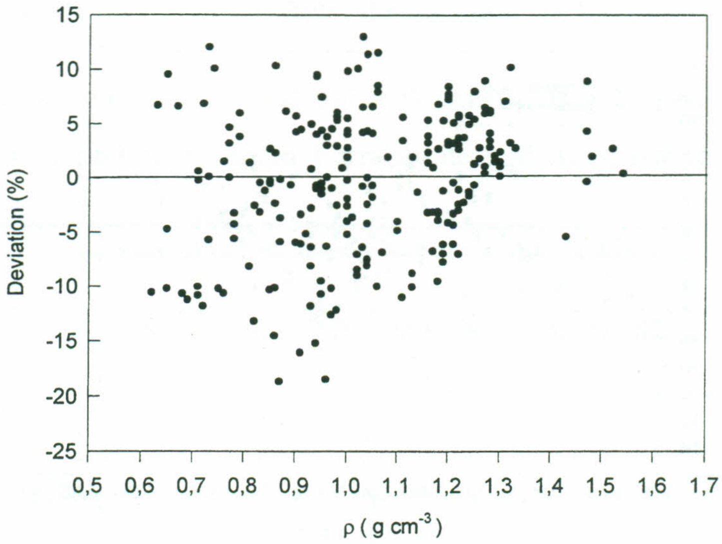

Fig. 5: Deviations between real and estimated moisture values after adjustment with the quadratic equation as related to soil bulk density

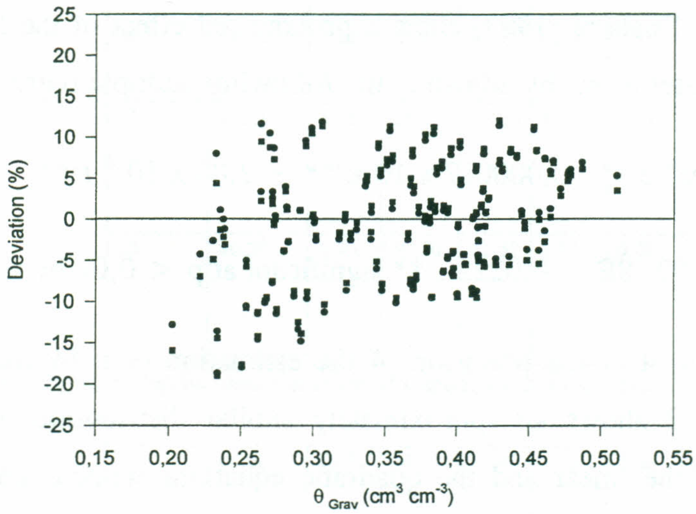

Fig. 6: Deviations between real and estimated moisture values after adjustment with the linear and quadratic equations for soil samples with a bulk density of less than 1,1 g cm-3

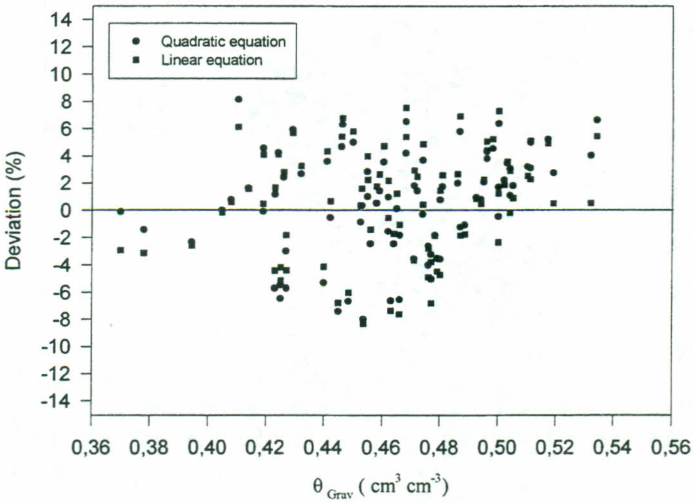

Fig. 7: Deviations between real and estimated moisture values after adjustment with the linear and quadratic equations for soil samples with a bulk density of equal to or more than 1,1 g cm-3

According to Topp et al. (1980) and Herkelrath et al. (1991), the presence of organic matter in the soil can lead to a subestimation of e, whereas Malicki et al. (1996), Roth et al. (1992), Roth et al. (1990) and Dirksen & Dasberg (1993) show a pronounced effect of the bulk density r of the soil on e. We tested the latter effect by adjusting the following multiple regression to the data:

$$q = 0{,}156204 + 8{,}7 \text{ x } 10^{-4} e^{2}{**} - 0{,}000017 \text{ x } 10^{-5} e^{3}{**} + 2{,}08 \text{ x } 10^{-2} r^{2}{**} \qquad (7)$$

($R^2 = 0{,}9212$, $\bar{R}^2 = 0{,}9202$, SE = 0,0222 , ** significant at $p < 0{,}01$ by F test).

This is a slight improvement of the precision of the estimation of q by inclusion of r into the equation (Table 3). Fig. 3 shows an approximately similar distribution of the errors of this adjustment with those of the linear and the quadratic equations without considering r. Similar adjustments have been calculated by Tommaselli & Bacchi (1996) and by Jacobsen & Schjonnig (1993), who also found slightly better adjustments when including r into the equation. In contrast, Malicki et al. (1996) obtained a significant improvement of precision by including r.

Fig. 5 indicates that the adjustment is better for samples with $r > 1.1$ g cm^{-3} than for soil with lower bulk density. So, we calculated separate adjustment equations for the groups of soil samples with $r < 1.1$ g cm^{-3} and $r = 1.1$ g cm^{-3} , using the same models as above. Again, the best adjustments were obtained with the linear and the quadratic equations (Table 3). When compared with the test of model identity (Graybill, 1976), both the linear and the quadratic equations were significantly different for the two soil density classes at $p < 0{,}01$, so that improved precision of the adjustment can be attained by using these equations in cases where r is either known or can be estimated for a soil under study. In other cases, the equation for the whole data set can be used.

Table 1: Volumetric soil moisture and soil bulk density as measured close to different plant species (40 cm) and soil depths in a Xanthic Ferralsol near Manaus, Amazon

Sampling point	tq(%) - volumetric soil moisture					r - soil bulk density (g cm^{-3})			
	n	Mean	SD.	Min	Max	Mean	SD	Min	Max
Primary forest									
Matá-matá *(Eschweilera spp)*	19	34,10	6,49	25,40	47,70	0,78	0,11	0,62	0,98
Bacaba *(Oenocarpus bacaba)*	18	41,44	5,81	30,20	48,70	0.81	0,10	0,63	1,00
Cultivated area									
Peach palm (*Bactris gasipaes*) for fruit	20	26,71	3,15	22,20	33,00	0,94	0,13	0,73	1,22
Peach palm for palmhearts	38	34,68	7,26	20,27	47,75	0,91	0,10	0,71	1,16
Cupuaçu (*Theobroma grandiflorum*)	33	41,81	2,61	34,67	46,68	1,10	0,21	0,91	1,54
Pueraria (*Pueraria phaseoloides*)	20	36,20	2,90	30,80	42,50	1,05	0,06	1,18	0,93
Soil profile, three depths (associacation of cupuacu and Peach palm)									
30cm	26	43,62	3,07	34,50	47,40	1,23	0,06	1,06	1,33
90cm	27	48,27	3,05	40,80	53,40	1,21	0,06	1,05	1,30
150cm	25	48,28	3,05	44,50	53,20	1,22	0,06	1,14	1,29

where n: number of samples and SD = standard deviation of the mean

Table 2: Coefficients of the regression equations for the adjusted models, either for the whole data set or for two groups of samples separated according to their bulk density (r)

b_0	b_1	b_2	b_3	R^2	$\overline{R}^2$	SE ($cm^3 cm^{-3}$)
q (e) - All data (n = 226)						
0,108794	0,013690**	-	-	0,9079	0,9075	0,02387
0,046367	0,020444**	- 0,000169**	-	0,9123	0,9115	0,02334
0,142527	0,0042070 ^{ns}	0,0000684 ^{ns}	-0,000014 ^{ns}	0,9133	0,9127	0,02326
q (e) - Bulk density lower than 1.1 g cm^{-3} (n = 134)						
0,105602	0,013687**	-	-	0,8929	0,8921	0,02396
0,068213	0,018129**	- 0,000122 ^{ns}	-	0,8944	0,8928	0,02388
0,143210	0,004446 ^{ns}	0,000664 ^{ns}	-0,000014 ^{ns}	0,8950	0,8926	0,02390
q (e) - Bulk density equal or higher than 1.1 g cm^{-3} (n = 92)						
0,178980	0,011077**	-	-	0,7621	0,7595	0,02135
- 0,077161	0,032686**	- 0,000446**	-	0,7833	0,7784	0,02049
-0,312368	0,06422^{ns}	- 0,001825^{ns}	0,000020^{ns}	0,7844	0,7771	0,02055

** and *: significant at the 1% and 5% probability levels, respectively, by F test; ns : not significant.

Discussion

Adjustment coefficients and goodness of fit depend, among other factors, on the range of water content values included in the calibration. In the present work, the volumetric water contents encountered in the field lay between 22% and 53%. Similar ranges have been obtained with the neutron probe technique by Cabral (1991) and Hodnett et al. (1996) in studies in primary forest, rubber (*Hevea brasiliensis*) plantations and pasture on similar soils in the Manaus region, and by Medina & Júnior (1987) in a study on the field capacity of these soils. So, our calibration is valid for the range of water contents, which are likely to be encountered in these soils under natural conditions in the field. In laboratory calibrations such as those by Topp et al. (1980) and Malicki et al. (1996), on the other hand, water contents have been created artificially which would not occur in the field. The use of an artificially increased range of water contents for TDR calibration can lead to changes in the adjustment functions principally due to variations in the relative contribution of free water and soil-bound water to e. At low soil moisture values, e increases slowly with increasing soil water content, but after passing a certain soil moisture threshold which depends strongly on soil texture, there is a pronounced increase in the inclination of this relationship. This is because the water molecules in a thin layer of water covering mineral particles are not free, but behave rather like ice molecules (e = 3,2; Bohl & Roth,1994).

The SE of the TDR measurements (Table 2) is approximately of the same magnitude as those found by other authors (Herkelrath et al., 1991, [0,02 cm^3 cm^{-3}], Bohl and Roth, 1994, [0,02 to 0,03 cm^3 cm^{-3} for mineral soils and 0,03 cm cm^{-3} to 0,07 cm cm^{-3} for organic soils], Topp et al., 1980, [0,013 cm cm^{-3}]). This comes unexpected, because the majority of calibration studies of the TDR technique encountered in the literature have been carried out in the laboratory, with sieved soils and by changing the water content of a single sample instead of measuring separate samples with different water content as in the present study. It was consequently to be expected to encounter a significantly reduced precision of the obtained adjustment in our study, especially if the voluntarily high variability between the sampling points with respect to soil management and vegetation is taken into consideration. Comparing the standard errors of water content and bulk density in the topsoil and the subsoil samples (Table 1) can assess the importance of this variability. Obviously, the variability of the physical properties of the soil decreases significantly with increasing soil depth, due to the reduced biological (e.g. root and soil faunal) activity.

The observation that the obtained adjustment of the data was better (the standard error was smaller) for samples with r=1,1 g cm^{-3} than for those with lower bulk density (Table 2) can be explained by comparing Figs. 6 and 7. It can be seen that in this soil, samples with higher r also had a higher water content, presumably because of a higher water holding capacity. In these samples, the variability of r is also less than in samples with lower r (Table 1), and this may have contributed to the increased precision of the adjustment.

The improved precision of the TDR technique for high water contents is probably related to a better contact of the rods with the soil and the reduced occurrence of discontinuities (such as air-inclusions and macropores) at high water content and bulk density which may cause difficulties in the determination of e (Baker & Lascano, 1989). It is also a consequence of the higher contribution of water in relation to other soil constituents (air, minerals) to e as has been demonstrated by Roth et al. (1990).

A source of random error in the described calibration procedure in the field is associated with the sampling and weighing of the volumetric rings, the results of which were taken as the "true" values of soil water content. The method is generally considered as reasonably precise, although care must be taken to avoid soil compaction and volumetric errors during the sampling with the rings, especially as the topsoil of our site possess very low bulk densities (Table 1) and are easily compacted, and volumetric sampling was made difficult by the high root contents of many topsoil samples (especially those taken under palms). So, part of the observed variability of the results is probably due to the cumulative effect of several small errors during the collection and processing of the samples. Larger errors, caused by defect probes, untypical soil conditions etc., were partially eliminated by excluding data which strongly differed from the bulk of the measurements. Such erroneous readings typically occurred in sequence, suggesting instrument failure, or were associated with very low r, presumably because of sampling disturbed soil (e.g. macrofauna channels).

Systematic errors in the calibration may have been caused by differences between the soil volume sampled by the TDR probes and by the volumetric rings. According to Baker & Lascano (1989), TDR probes measure the soil moisture uniformly along the rods. According to the EASY TEST manual, the soil volume sampled by this device is basically a cylinder around the two rods with a diameter of approximately 5 cm and a length of 13 cm. This corresponds to more than twice the volume sampled with the rings, and errors would have occurred in cases of a vertical moisture gradient within the sampled soil volume.

Dasberg & Hopmans (1992) analyze the effect of a waterfront infiltrating through the sampled soil volume during the TDR measurement. They conclude that this situation is not adequately treated by the algorithms programmed into TDR devices and recommend graphical interpretation of the obtained signal. This effect was not taken into consideration in our study, as the used device does not provide graphics of the signal. However, the importance of this effect under Amazonian conditions needs to be further investigated because of the frequent and heavy rainfalls in this region during an important part of the year. Errors may especially arise when measurements are taken automatically (i.e. also during rain events which was not the case in our study) and with long measurement rods. This problem could be reduced by horizontal installation of the probes in the soil, although at the price of higher disturbance of the site.

In our study, the measurements were taken immediately after installing the probes in the soil, which is one of the possibilities of use of the device indicated in the manual. Depending on the construction of the measurement probes, this technique may introduce errors due to the compression of the water around the steel rods during the installation (Jacobsen & Schjonning, 1993). With the probes used in our study, the effect is certainly of minor importance because of the small diameter of the rods (2 mm), but it may be relevant for rods with larger diameter.

As e is also a function of the temperature (Pepin et al., 1995), errors could be introduced into TDR measurements when comparing positions with different soil temperature. This effect is more likely to be important with high soil moisture, because e of water is affected more by temperature than e of the gaseous and solid phases. On the other hand, the temperature of dry soil changes more rapidly than that of wet soil according to changes in air temperature or incoming radiation because of its smaller heat capacity and conductance. In the present case, temperature effects were certainly no significant source of error because the points were measurements were taken were generally protected from direct radiation, and measurements of the topsoil temperature showed little variability between different points at this site (Cabral, 1996). However, more important temperature effects may occur in other situations, so that the measurement of soil temperature simultaneously with TDR measurements may be necessary in studies, which require a high level of precision.

Conclusions

Among the factors which have the potential to affect TDR measurements, soil bulk density, soil temperature and vertical gradients of soil moisture near the soil surface are the ones which are most easily influenced by the vegetation and by land-use practices. We have shown that, under the conditions of this study, the inclusion of bulk density into the TDR calibration improved the precision, which could be obtained with this method. Soil bulk density can change relatively rapidly as a consequence of soil management and may consequently exhibit considerable within-site heterogeneity in heterogeneous land-use systems such as agroforestry associations. In this study, important differences in bulk density were observed between the cultivated area and the primary forest, but also between plant species within the cultivated area (Table 1), the reasons of which will be discussed in subsequent papers. If such factors are not taken into account, bias may be introduced into comparisons of the soil water economy of sites, which differ in such characteristics.

It is certainly important to determine the important factors that may influence TDR measurements when using this technique for the first time at a site and/or in a land-use system or natural vegetation community. Possible sources of error can then be detected and be excluded, if necessary, through suitable calibration procedures in the field, taking the within-site heterogeneity into account. The purpose of the intended soil water measurements should however be kept in mind, as not every study requires a precision of the measurements which justifies the considerable investment in time and labor for a field calibration.

References

BAKER, J.M. & LASCANO, R.J. 1989. The spatial sensitivity of time domain reflectometry. *Soil Science*, **147**(5): 378 - 384.

BOHL, H. & ROTH, K. 1994. Evaluation of dielectric mixing models to describe the q(e) relation. In: *Symposium and workshop on time domain reflectometry in environmental, infrastructure and minig applications*. Evanston, 1994. Proceedings. Evanston, United States Department of interior bureau of mines, pp. 309-319 (Special publication SP 19-94).

CABRAL, O. M. R. 1990. Armazenamento de água no solo da floresta e de terra firme e seringal implantado. Master thesis, INPE, São José dos Campos - Brazil.

CABRAL, O.M.R. 1996. Climatological observations recorded during the period 1993 to 1995 at Shift project site in Manaus, Central Amazônia. In: *Recuperação de áreas degradadas e abandonadas, através de sistemas de policultivo* (eds. Gasparroto, L. & Preisinger, H.), pp. 34-46. EMBRAPA - CPAA / Universidade de Hamburg, Manaus.

DASBERG, S. & HOPMANS, W. 1992. Time domain reflectometry calibration for uniformly and nonuniformly wetted sandy and clayey loam soils. *Soil Science Society of America Journal,* **56**:1341-1345.

DIRKSEN, C. & DASBERG, S. 1993. Improved calibration of time domain reflectometry soil water content measurements. *Soil Science Society of America Journal*, **57**: 660-667.

DRAPER, N. & SMITH, H. 1981. *Applied regression analysis*, 2.ed., New York, J. Wiley.

GRAYBILL, F. A. 1976. *Theory and application of the linear model*. Belmont, Wadsworth.

HERKELRATH, W. N., HAMBURG, S. P. & MURPHY, F. 1991. Automatic, real-time monitoring of soil moisture in a remote field area with time domain reflectometry. *Water Resources Research*, **27**: 857-864.

HODNETT, M.G., OYAMA, M.D., TOMASELLA, J. & MARQUES FILHO, A. de O. 1996. Comparisons of long term soil water storage behavior under pasture and forest in three areas of Amazonia. In: *Amazonian deforestation and climate*. (eds. Gash, J.H.C, Nobre, C.A, Roberts, J.M. & Victoria, R.L.), pp. 79-101. John Willey, New York.

HOOK, W.R. & LIVINGSTON, N. J. 1995. Propagation velocity errors in time domain reflectometry measurements of soil water. *Soil Science Society of America Journal*, **59**:92-96.

JACOBSEN, O.H. & SCHJONNING, P. 1993. A laboratory calibration of time domain reflectometry for soil water measurement including effects of bulk density and texture. *Journal of Hydrology*, **151**: 147-157.

MALICKI, M. A., PLAGGE, R. & ROTH, C. H. 1996. Improving the calibration of dieletric TDR soil moisture determination taking into account the solid soil. *European Journal of Soil Science*, 47:357-366.

MEDINA, B.F. & OLIVEIRA JUNIOR, R.C. 1987. Relações entre a capacidade de campo determinada in situ e em laboratório em latossolo amarelo, muito argiloso. *Revista Brasileira de Ciência do Solo*, **11**:91-95.

PEPIN, S; LIVINGSTON, N J & HOOK W. R. 1995. Temperature-dependent measurement errors in time domain reflectometry determinations of soil water. *Soil Science Society of America Journal*, **59**:38-43.

PETERSEN, L.W.; THOMSEN, A. MOLDRUP, P. JACOBSEN, O. H. & ROLSTON, D. E. 1994. High resolution time domain reflectometry: sensitivity dependency on probe-design. *Soil Science*, **159**(3): 149-154.

ROTH, C.H; MALICKI, M.A. & PLAGGE, R. 1992. Empirical evaluation of the relationship between soil dieletric constant and volumetric water content as the basis for calibrating soil moisture measurements by TDR. *Journal of Soil Science*, **43**:1-13.

ROTH, K., SCHULIN, R., FLUHLER, H. & ATTINGER, W. 1990. Calibration of time domain reflectometry measurements for water content measurement using a composite dielectric approach. *Water Resources Research*, **26**:2267-2273.

TOMMASELLI, J. T. G. & BACCHI, O. O. S. 1996. Calibração de um TDR utilizando modelos empíricos para cinco solos paulistas. In: *Congresso Pan Americano de Ciência do Solo*, 23., Águas de Lindóia, 1996. Sociedade Brasileira de Ciência do Solo, CD-ROM Solo-Suelo.

TOPP, G. C. & DAVIS, J. L. 1985. Measurement of soil water content using time- domain reflectometry (TDR): a field evaluation. *Soil Science Society of America Journal*, **49**: 19-24.

TOPP, G. C., DAVIS, J. L. & ANNAN, A. P. 1980. Electromagnetic determination of soil water content: measurement in coaxial transmission lines. *Water Resources Research*, **16**: 574-582.

ZEGELIN, S. J., WHITE, I. & RUSSEL, G. F. 1992. A critique of the time domain reflectometry technique for determining field soil-water content. In: *Advance in measurement of soil physical properties: bringing theory into practice* (eds Topp, G.C et al.), pp. 187-208. Soil Science Society of America, Madison. (Special publication, 30).