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Calibration of time domain reflectometry for forest soil humus layers

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Time domain reflectometry (TDR) has become a widely used method for determining the volumetric water content of soils. However, due to the differences in bulk density and surface area, the relationship between the dielectric constant and water content in organic soils is very different from that in mineral soil. It is therefore impossible to have a universal calibration suitable for all soil types. In this article we describe the relationship between the apparent dielectric constant (K_a) and volumetric water content (θ_v) for homogenized and undisturbed humus layers (Of + Oh) from forested soil using three empirical models. There was a clear relationship between the K_a and θ_v and this relationship was best described ($R^2 = 0.968$) with a logarithmic equation of the form $\theta_v = a\ln(K_a) - b$. Accurate determination of sample volume was the main source of variation in the calibration, having a greater effect on the calibration results than differences in bulk density.

Introduction

During the last 20 years, a time-domain reflectometry (TDR) has become a widely-used method for measuring the soil water content. The TDR is easy to use and gives reliable and accurate results without disturbing the soil (Hoekstra and Delaney 1974, Davis and Chudobiak 1975, Davis and Annan 1977, Topp *et al*. 1980, Ledieu 1986). The basis of TDR measurements is the apparent dielectric constant (K_a) of the soil, which changes with moisture content.

Topp *et al*. (1980) established an empirical relationship between K_a and the volumetric water content (θ_v) for soils ranging from sandy loam to clay. However, this relationship does not apply to organic soils and layers such as peats and forest floors (Topp *et al*. 1980, Herkelrath *et al*. 1991). Smith and Tice (1988) and Dasberg and Hopmans (1992) showed that the K_a/θ_v ratio is also different for fine-textured mineral soils. Few calibration equations have been published for organic soils (Herkelrath *et al*. 1991, Pepin *et al*. 1992, Roth *et al*. 1992, Börner *et al*. 1996, Myllys and Simojoki 1996, Schaap *et al*. 1996, Shibchurn *et al*. 2005), but are required if TDR is to be used to monitor changes in the amount of plant available water in the forest floor, the layer in which much of the fine root biomass is located (Pietikäinen *et al*. 1999).

In this study, we report such a calibration for mor humus layers (Of + Oh) from podzolic forest soils. Three calibration models are compared and the effect of variation in bulk density and sample volume is evaluated. We also report on spatial variation and sample numbers and their affect on the accuracy of the determination of water content over a forested area.

Material and methods

The humus layer (Of + Oh) was sampled at a 130-year-old mixed Scots pine and Norway spruce stand in southern Finland (61°48´N, 24°19´E, 151–153 m above sea level). The ground vegetation consisted mainly of *Vaccinium myrtillus* with some *Oxalis acetosella*. The field layer consisted of mosses (*Pleurozium schereberi* and *Hylocomium splendens*). The soil is classified as a haplic podzol (FAO 1990) and developed on a sandy glacifluvial deposit with a texture varying from coarse to fine sand. Soil physical, chemical and biological properties have been described in detail earlier (Mecke and Ilvesniemi 1999, Pietikäinen *et al*. 1999). The carbon concentration of the humus layer averages 48.6% and its pH ($CaCl_2$) is 2.79 (Pietikäinen *et al*. 1999). The annual precipitation averages 709 mm and the annual mean temperature is 2.9 °C (Climatological statistics in Finland 1991).

The humus layer samples were collected in October when the soil was partly frozen. Undisturbed samples of the forest floor were cut from each corner of four 2 × 2 m quadrants (circa 200 × 300 mm in area and between 40 and 100 mm thickness). The 16 samples were kept frozen until measured. In the laboratory, vegetation and the litter layer (Ol) were removed from each sample and the remaining humus (Of + Oh) layer was placed on a tray. Each tray with a humus layer sample was then placed in a tank that was carefully filled with water such that the humus layer sample was submerged. The samples were kept in this state for 24 hours, after which the tray plus sample was removed from the tank and weighed to determine the water content. The exact dimensions of the humus layer samples were measured to calculate the sample volume and subsequently the volumetric water content.

The K_a value at 20 °C was measured by inserting two parallel wave guide rods (length 175 mm, diameter 5 mm, distance between the rods 50 mm) horizontally into the humus layer samples and by connecting them with a Tektronix 1502 C cable tester. The K_a values were similarly determined after drying the sample in an unventilated oven at 50 °C to increasing states of dryness. Thus, for each sample, K_a values were determined for ten water contents, which ranged from 0.7 $m^3\ m^{-3}$ down to 0.0 $m^3\ m^{-3}$. Drying in high relative humidity conditions was done to ensure as uniform drying throughout the humus layer sample as possible.

We also used air-dried and homogenized (SM2000 cutting mill, Retsch GmbH, Haan, Germany) humus layer material collected from a similar type of forest for comparison with the results from the undisturbed humus samples. The air-dry homogenized humus layer material was first wetted thoroughly with distilled water, mixed and allowed to saturate for 24 hours before being used to fill a single rectangular plastic container (200 × 100 mm, thickness 200 mm). The K_a values were measured at ten levels of decreasing water content as described above. Four pairs of parallel wave guide rods were inserted into the sample giving four replicate K_a values for each level of water content. After recording the K_a values for each water content level, the humus layer material was removed from the container, dried, mixed and repacked to precisely the same volume each time. This was done in order to maintain the same bulk density throughout the experiment and to ensure uniform moisture content throughout the sample.

At the end of the experiment the dry mass of both undisturbed and homogenized samples was determined by drying the sample at 105 °C for 24 hours.

The relationships between the K_a and θ_v values were described by fitting equations presented by Ledieu *et al*. (1986) (Eq. 1) and Topp *et al*. (1980) (Eq. 2), and a logarithmic model by the authors (Eq. 3). The three models used were:

$$\theta_v = a\sqrt{K_a} - b, \tag{1}$$

$$\theta_v = a + bK_a + cK_a^2 + dK_a^3, \tag{2}$$

$$\theta_v = a\ln(K_a) - b. \tag{3}$$

The least squares method was used in the fitting.

Bulk densities (BD) of the samples were calculated using the volume of the sample at saturation and the oven-dry weight of humus measured at the end of the experiment. The amount of mineral material in the sample was determined by ashing at 550 °C for three hours. The ash content, BD and porosity of the humus layer samples are presented in Table 1.

Results and discussion

The measured K_a values of the homogenized humus layer samples were closely related to measured soil water contents and the between-rod variation in K_a values was small, particularly at lower water content levels (Fig. 1).

Within a single undisturbed humus sample θ_v increased with increasing K_a almost as smoothly as with the homogenized samples, but the shape of the K_a-θ_v curve differed between separate samples (Fig. 2). When all measurements of 16 humus samples are combined (Fig. 3), this between-sample variation causes large variations in the K_a/θ_v ratio.

The K_a values measured in the Of and Oh horizons range typically from 5 to 10 during the growing season. The corresponding volumetric water content values calculated with Eq. 3 with parameters from pooled undisturbed samples and from the homogenized sample range from 0.17 to 0.30 $m^3 m^{-3}$ and from 0.15 to 0.31 $m^3 m^{-3}$, respectively (Table 2). In that moisture range, both calibration materials resulted in fairly similar values. However, in the extreme drought, for $K_a = 4$, parameter values measured with undisturbed humus resulted in 43% higher volumetric water content than those of homogenized humus layer material.

At higher water contents, K_a values for undisturbed humus samples were generally greater than for the homogenised sample at the same water content. At the volumetric water content of 0.6 $m^3 m^{-3}$, the K_a values for undisturbed humus layer samples were, on average, 54% higher than those in the homogenized sample. This difference is probably due to differences in pore space between the two sample types. The mean bulk density of the undisturbed samples was 0.102 g cm^{-3} and that of the homogenized humus layer sample was 0.340 g cm^{-3}.

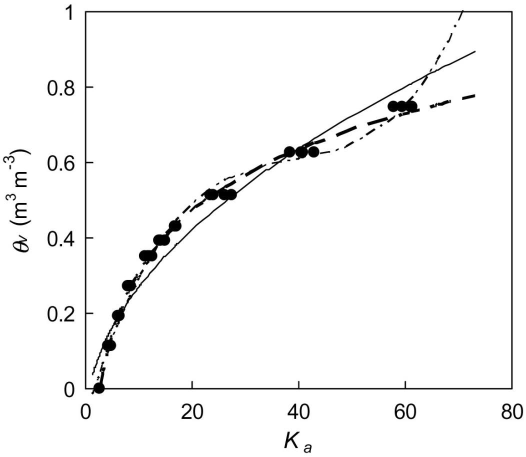

Fig. 1.The relationship between K_a and θ_v in homogenized humus layer material. Solid black line represents Eq. 1, thin dashed line Eq. 2 and thick dashed line Eq. 3 fitted to data. Black dots represent the replicate measurements of four wave guide rods.

Since the soil water content is expressed as a volumetric water percentage, both measured amount of water and volume of the undisturbed humus sample can include measurement errors. When the humus is near water saturation, a proportion of water can be easily lost by leaking before weighing. This can cause variations in the wet end of the curve. The volume of the undisturbed humus samples was calculated based on the dimensions of the samples. However, the samples were not perfectly rectangular, which may have resulted in some error in the determination of the volume. In addition, the volume of the undisturbed samples measured at saturation

Table 1. Physical properties of the humus samples used in the calibration.

Humus	Ash content (%)		Bulk density (g cm^{-3})		Porosity ($m^3 m^{-3}$)	
	Mean	S.D.	Mean	S.D.	Mean	S.D.
Undisturbed	21.62	22.43	0.10	0.021	0.67	0.095
Homogenized	–	–	0.34	–	0.75	–

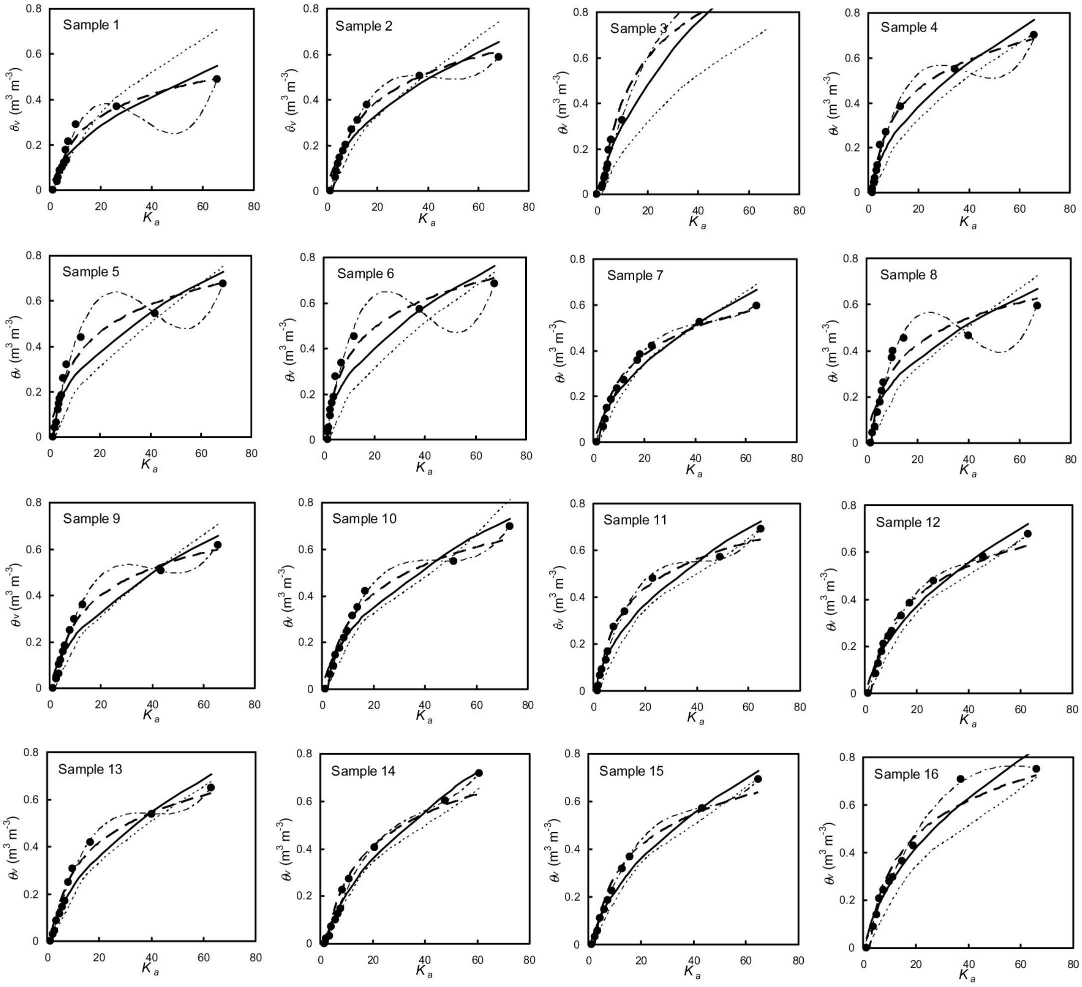

Fig. 2. The relationship between K_a and θ_v in each undisturbed humus layer sample. Black dots represent the measurements of wave guide rods. Solid black line represents Eq. 1, thin dashed line Eq. 2 and thick dashed line Eq. 3 fitted to data. Thin dashed line represents Topp *et al*. (1980) calibration for mineral soil.

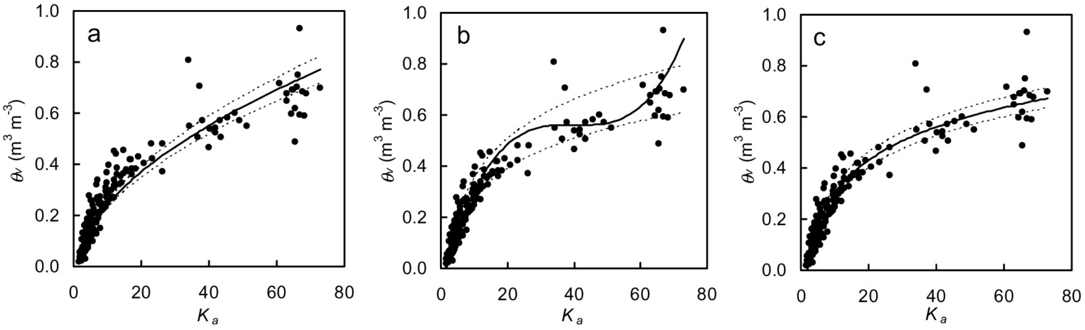

Fig. 3. The relationship between K_a and θ_v in pooled undisturbed humus layer samples. (**a**) Eq. 1, (**b**) Eq. 2 and (**c**) Eq. 3. Solid black line represents the fitted equation and dashed lines the 95% confidence lines for the respective equation.

was assumed to be the same over all ten water content levels, although considerable shrinkage at lower water contents was observed. At the four highest water content levels, the dimensions of the sample remained almost unchanged, but significant shrinkage occurred at six lower water content levels, when the original volume shrank by about 25%. This shrinkage can be different between different samples, causing variations at the dry end of the curve. Because all results are calculated using the volume of a moist sample, the actual volumetric water content in a smaller humus volume is higher than the calculated value. In a homogenized sample the measurement of the amount of water was accurate and the volume of the sample remained unchanged. In this case also the variation in the relation between K_a and θ_v was small as compared with that for undisturbed samples.

Presumably the detected variations in undisturbed humus samples were also partly due to the factors affecting the dielectric value of samples, such as differences in the bulk density, mineral soil content and pore space distribution. However, we assume that most of the variation in the K_a-θ_v relationship for the undisturbed humus layer samples was related to the sample volume determinations.

For the undisturbed humus layer samples the variation between samples was large (Fig. 2), but it can be assumed that this is also the case in the field. The spatial variation in the K_a-θ_v relationship may result in inaccurate estimates of water content for a forested area. From the data presented in Table 2, it is possible to estimate the standard error in humus layer water contents due to the TDR calibration parameter values. For example, the volumetric water content values calculated with Eq. 3 for each of the 16 individual samples for K_a = 5 ranged from 0.13 to 0.24 m^3 m^{-3} and have a standard error of 0.008. The range in water contents for K_a = 10 was from

Table 2. Statistical models and respective parameters fitted for undisturbed humus samples and homogenized humus.

Sample	Model										
	$\theta_v = a\sqrt{K_a} - b$			$\theta_v = a + bK_a + cK_a^2 + dK_a^3$					$\theta_v = a\ln(K_a) - b$		
	a	*b*	R^2	*a*	*b*	*c*	*d*	R^2	*a*	*b*	R^2
1	0.073	0.043	0.957	–0.090921	0.049392	–0.001602	0.000015	0.985	0.141	0.098	0.983
2	0.083	0.032	0.978	–0.055303	0.041715	–0.001010	0.000008	0.999	0.181	0.151	0.998
3	0.144	0.153	0.983	–0.035098	0.043519	–0.000669	0.000004	0.998	0.278	0.237	0.990
4	0.105	0.084	0.974	–0.068922	0.055361	–0.001536	0.000013	0.996	0.188	0.103	0.996
5	0.090	0.019	0.954	–0.074149	0.064987	–0.001849	0.000015	0.996	0.178	0.073	0.989
6	0.095	0.017	0.950	–0.057006	0.067129	–0.001984	0.000017	0.993	0.181	0.053	0.992
7	0.091	0.065	0.986	–0.036759	0.034038	–0.000723	0.000005	0.999	0.170	0.127	0.992
8	0.082	0.002	0.930	–0.103170	0.064250	–0.001920	0.000020	0.998	0.167	0.076	0.975
9	0.087	0.049	0.972	–0.071738	0.049412	–0.001303	0.000011	0.999	0.169	0.108	0.992
10	0.092	0.057	0.979	–0.065759	0.041809	–0.000940	0.000007	0.999	0.184	0.145	0.988
11	0.100	0.080	0.981	–0.048471	0.043921	–0.001083	0.000009	0.998	0.180	0.103	0.992
12	0.101	0.082	0.992	–0.042916	0.036767	–0.000794	0.000006	0.999	0.190	0.159	0.990
13	0.100	0.086	0.976	–0.076952	0.047351	–0.001201	0.000010	0.998	0.184	0.137	0.988
14	0.112	0.146	0.992	–0.069683	0.036634	–0.000781	0.000006	0.997	0.203	0.200	0.971
15	0.103	0.103	0.990	–0.060961	0.039328	–0.000857	0.000007	1.000	0.192	0.161	0.986
16	0.115	0.097	0.986	–0.015504	0.032575	–0.000424	0.000002	0.997	0.216	0.178	0.982
Average	0.098	0.070	0.974	–0.060832	0.046762	–0.001167	0.000010	0.997	0.188	0.132	0.988
Pooled*	0.098	0.069	0.959	–0.037205	0.039962	–0.000897	0.000007	0.933	0.182	0.120	0.968
HH**	0.116	0.097	0.988	–0.082170	0.047585	–0.001150	0.000010	0.990	0.236	0.238	0.999

*Pooled = pooled samples. **HH = homogenized humus.

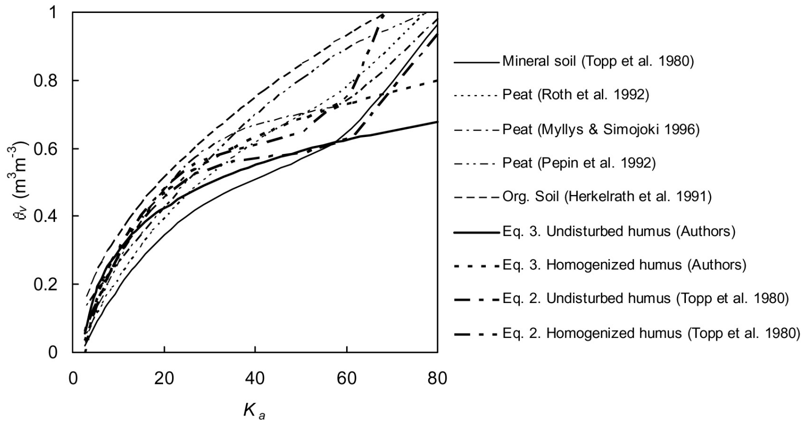

Fig. 4. The relationship between K_a and θ_v for organic soil presented in the literature and that for mineral soil by Topp *et al.* (1980). Eqs. 2 and 3 fitted to pooled data from undisturbed samples and homogenized humus layer material are also presented.

0.23 to 0.40 m^3 m^{-3} and the standard error was 0.01. Based on these values, we calculated the number of samples required for calibration to achieve 10% accuracy in the water content with a 95% confidence interval. For $K_a = 5$ the number of samples for calibration would be 14 and for $K_a = 10$ eight samples would be required.

When fitted to our humus data, the Ledieu's (Eq. 1) and Topp's (Eq. 2) calibration curves differed the most. Ledieu's equation underestimated water contents for K_a ranging from 10 to 40 in both undisturbed and homogenized samples. For very low K_a, Eq. 1 overestimated water contents significantly. Topp's polynomial equation, parameterized for our humus layer samples (Eq. 2), worked best for low K_a but overestimated water contents for K_a between 10 and 40, representing water contents between 0.3 and 0.55 m^3 m^{-3} (Fig. 2). The widely used calibration equation by Topp *et al.* (1980) for mineral soil can not be used for calculating the water content of organic soil layers because it systematically underestimates water content for $K_a < 10$. The logarithmic equation (Eq. 3) had a good fit at both low and high water contents. The relationship between K_a and θ_v in organic soil has been described by several models. Herkelrath *et al.* (1991), Pepin *et al.* (1992), Roth *et al.* (1992) as well as Myllys and Simojoki (1996) described the relationship for peat. The differences between the models, especially for low K_a, are considerable (Fig. 4). The change in water content for K_a ranging from 40 to 60 in the authors' log model (Eq. 3) and in the curves of Myllys and Simojoki (1996) is small as compared with that in the other curves presented in Fig. 4. The equations of Herkelrath *et al.* (1991) and Pepin *et al.* (1992) may overestimate the water content when there is more than 0.65 m^3 m^{-3} water in the organic material.

In our study, the best fit (highest linearity of residuals) was obtained for homogenized humus with Eq. 2 (Table 2). But as seen in Figs. 1 and 2, the polynomial model works well only at moderately dry conditions and its applicability to wetter conditions is considerably less reliable. However, water contents in humus layers under field conditions do usually not exceed 0.4–0.5 m^3 m^{-3}, and Eq. 2 would thus suffice. But when applied to peat, calibration using Eq. 2 should be carried out for a much wider range of θ_v due to the high porosity and so water contents of peat.

Conclusions

To use time domain reflectometry it is necessary to calibrate the relationship between K_a and θ_v separately for different types of soils. Calibrations to mineral soils should not be applied to organic soils and humus layers. There are also considerable differences between the equations, how well they describe the K_a-θ_v relationship in organic soil materials. The log model was able to predict the water content well both at high and low water contents. The most critical factor in determining a reliable K_a and θ_v calibration curve for humus layers is the accurate determination of sample volume.

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