# Theta probe calibration for forest floor duff

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Raaflaub, L. D. and Valeo, C. 2009. **Theta probe calibration for forest floor duff**. Can. J. Soil Sci. **89**: 315–318. The Theta Probe is calibrated for duff (forest floor organic matter) water content using samples collected from six boreal forest stands. Values of $a_0 = 1.0$, $a_1 = 5.8$ and uncertainty in duff water content of $\pm 0.09\ m^3 m^{-3}$ were determined. Results were consistent regardless of tree type or duff depth.

**Key words:** Porous media moisture, duff, calibration, Theta Probe, boreal forest

Raaflaub, L. D. et Valeo, C. 2009. **Étalonnage de la sonde Thêta pour l'humus forestier**. Can. J. Soil Sci. **89**: 315–318. Les auteurs ont étalonné la sonde Thêta pour établir la teneur en eau de l'humus (matière organique du sol forestier) au moyen d'échantillons recueillis dans six peuplements de la forêt boréale. Ils ont obtenu les valeurs $a_0 = 1{,}0$, $a_1 = 5{,}8$ et une incertitude de $\pm 0{,}09\ m^3$ par $m^3$ pour la teneur en eau de l'humus. Ces résultats sont cohérents, peu importe le type d'arbre ou l'épaisseur de la couche d'humus.

**Mots clés:** Teneur en eau des médias poreux, humus, étalonnage, sonde Thêta, forêt boréale

Reliable measurements of soil water content are necessary both for direct monitoring and for hydrological model development and verification. This is especially true for the organic layer of the forest floor, known as duff, where water content values can be used to predict the potential risk of forest fires (Van Wagner 1987). Duff is highly porous (Fosberg 1977), which can make duff water content challenging to measure using non-destructive techniques because of difficulties in establishing effective duff-sensor contact. This is confounded by the fact that duff is heterogeneous both vertically and horizontally. There are many techniques and devices that can be used to measure soil water content but the Theta Probe manufactured by Delta-T Devices Ltd., Cambridge, UK, is one of the more popular available due to its low cost, ease of use, and small sampling volume. The Theta Probe does require calibration and few studies have investigated the calibration of the Theta Probe for duff. Wilmore (2001) does provide a calibration for duff under a black spruce canopy. However, the duff in that study was on average over 20 cm thick and was subject to permafrost, conditions that are not prevalent for all duff types. In addition, the calibration was based on only two samples without any examination into measurement accuracy. This study determines the calibration parameters for duff when using the Theta Probe to detect water content; and establishes the measurement accuracy.

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## Theta Probe

The Theta Probe (model ml2x), is a fixed frequency (100 MHz) impedance probe that has been designed to measure water content in both mineral and organic soils. It is composed of a central transmission line surrounded by three equidistant outer electrodes that act as coaxial shield conductors (Gaskin and Miller 1996). The four stainless steel electrodes are 60 mm long and occupy a volume 26.5 mm in diameter. This results in a sampling volume of approximately 75 cm$^3$, centred along the central electrode. The probe measures the dielectric constant of the soil, which is a combination of the dielectric constants of the individual components of the soil: solid matter, water, and air (Whalley 1993). Because the dielectric constant of water is approximately 20 times greater than that of the solid matter, the soil's dielectric constant is primarily dependent on its water content. The manufacturer's specified relationship between sensor measured voltage ($V$) and the dielectric constant ($\varepsilon$) for the Theta Probe is (Delta-T Devices Ltd. 1999):

$$\sqrt{\varepsilon} = 1.07 + 6.4V - 6.4V^2 + 4.7V^3 \quad (1)$$

where $V$ is in volts. This relationship was established using materials of known dielectric constant. While it is possible to use a linear relationship instead of the third order polynomial, this is not recommended for organic soils where the water content may be greater than 0.5 m$^3$ m$^{-3}$.

The volumetric water content of a soil, $\theta$, and the square root of its dielectric constant can be related using a linear relationship (Whalley 1993):

$$\sqrt{\varepsilon} = a_0 + a_1\theta, \quad (2)$$

where the coefficients $a_0$ and $a_1$ depend on the particular composition of the soil. General calibration values provided by the manufacturer for organic soils are $a_0 = 1.3$ and $a_1 = 7.7$. These coefficients are optimal for a soil with an organic content of 40% carbon and a bulk density range of 0.2–0.7 Mg m$^{-3}$, but are also recommended for use with soils that have organic contents >7% carbon and bulk densities <1.0 Mg m$^{-3}$.

While general coefficients are provided, the manufacturer still recommends soil-specific calibration to obtain more accurate soil water content values. Fortunately, since all ml2x Theta Probes are manufactured to respond to the dielectric constant in the same way, calibration needs to be done only once on one probe (Delta-T Devices Ltd. 1999). According to the manufacturer, if the general calibration parameters are applied, then volumetric water content values are quoted to be within $\pm 0.05$ m$^3$ m$^{-3}$. If a soil-specific calibration is conducted, the values should be within $\pm 0.01$ m$^3$ m$^{-3}$, but this is provided that the soil is highly homogeneous, that the probe is perfectly inserted into the soil completely, and that soil compaction is avoided while maintaining full contact with the probe. In practice, particularly in the field, these conditions are difficult to achieve; consequently, so is the quoted accuracy. Delta-T Devices Ltd. (1999) states that overall soil-specific calibration error comprises three error sources: the repeatability of probe readings ($\pm 0.01$ m$^3$ m$^{-3}$), calibration errors ($\pm 0.02$ m$^3$ m$^{-3}$), and soil variability and insertion errors ($\pm 0.04$ m$^3$ m$^{-3}$). This results in a more realistic soil-specific calibration error of $\pm 0.05$ m$^3$ m$^{-3}$. However, they do state that errors can be as large as $\pm 0.1$ m$^3$ m$^{-3}$.

The manufacturer suggests a two-point soil-specific calibration where two voltage readings are taken of a single soil sample: one when the sample is wet and the other after it has been oven dried. The sample must have a known volume so that its volumetric water content can be determined. The applicability of a two-point calibration on a single sample to a single soil type is questionable. Kaleita et al. (2005) found that a two-point calibration was inadequate for field calibration because of the inherent heterogeneity of the soil, and instead recommended that 20 samples be used. In addition, it was recommended that samples of varying water contents be used instead of oven drying a single sample because of the problems of contraction and fragility of some soils once oven dried. This is especially true of duff, which becomes very brittle when dried.

## Methodology

Field measurements took place during the summer of 2004 in the boreal forest region near Whitecourt, Alberta (lat. 54°08′N, long. 115°47′W, elevation 780 m). Measurements and samples were taken in a pure stand of lodgepole pine (*Pinus contorta* Dougl.), jack pine (*Pinus banksiana* Lamb.), black spruce [*Picea mariana* (Mill.) BSP.], white spruce [*Picea glauca* (Moench.) Voss], and trembling aspen (*Populus tremuloides* Michx.), as well as from a mixed stand that contained all five tree types. All stands were within 20 km of each other.

Thirty-three duff samples were used in the calibration of the Theta Probe. Two sampling locations were established for each stand, except for the trembling aspen stand where limited resources allowed for only one sampling location, resulting in 11 sampling locations. Duff at each of the 11 sampling locations was, on average, 10 cm thick. Over the total duff thickness three, 2.7 cm thick sampling layers were established: upper, middle and lower. The upper layer was considered the top 2.7 cm of duff and lower layer was the bottom 2.7 cm of duff closest to the mineral soil. The middle layer was the 2.7 cm of duff equidistant from the upper and lower layers. The exception to this was the black spruce stand where the bottom of the duff layer was never found. This stand was essentially a bog, with the water table located only 40 cm from the ground surface. Lower layer samples for black spruce, therefore, were considered just above the water table. In all cases moss and litter were removed from the surface of the duff before sampling began.

Field measurements of voltage were made with a Theta Probe and recorded using a Delta-T Moisture Meter (hh2). The duff next to the selected sampling location was removed to allow for the horizontal insertion of the Theta Probe into each of the three duff layers at the sampling location. In an attempt to minimise the affect of poor duff-sensor contact, three replicate probe insertions and horizontal voltage measurements of the duff were made for each layer and then averaged. The average voltages were converted into dielectric constants using Eq. 1. Following the Theta Probe measurements, a vertical duff core was extracted from the site of the voltage measurements using a metal cylinder of 5.3 cm diameter and 2.7 cm depth. The volume of the extracted sample was slightly smaller than the volume occupied by the Theta Probe because of a 0.7 cm difference in sample diameter and probe length. This difference was unavoidable due to equipment limitations, but was not considered to be a major factor in the results mainly because of the high variability in the three voltage measurements as discussed in the results. Duff thickness was checked at all stages of measurement and extraction to ensure minimal compaction. After extraction, the duff samples were weighed, oven dried at 105°C for 24 h, and then weighed again. The volumetric water contents were determined by dividing the mass of the water (wet mass – dry mass) by the volume of the container.

Linear relationships between θ and sensor calculated $\sqrt{\varepsilon}$ were developed for several different groupings of the samples in order to determine if, for example, tree type or duff layer require separate calibrations. The first set of relationships was developed based on tree type. Thus, a linear relationship was developed for all samples taken within a single tree stand type regardless of the duff layer the sample was extracted from. This resulted in six groups within the 33 samples and, thus, six relationships for this set. A second set of relationships was developed by distinguishing samples solely by duff layer (i.e., relationships for the upper, middle and lower duff layer). Orthogonal regression (Rao et al. 2007) was used to determine the linear relationships to account for the measurement error in both θ and $\sqrt{\varepsilon}$. A two-way analysis of covariance was used to test the influence of tree type and duff layer as well as their interaction ($\alpha = 0.05$).

## Results

The relationship between the dielectric constant, which is indirectly measured by the Theta Probe, and the water content of the duff is presented in Fig. 1, with the grouping based on tree type highlighted. Orthogonal regressions based on the groupings tree type and duff layer all had significant slopes. For tree type, the analysis of covariance revealed that there was no significant difference in the six regressions ($P = 0.62$) and that the hypothesis that all slopes were equal was acceptable. The same was found for the three regressions grouped by duff layer ($P = 0.47$). The interaction between tree type and duff layer was also found not to be statistically significant ($P = 0.74$). Thus, a single calibration of the Theta Probe for all duff types and layers (based on the 33 samples) was created, and is depicted in Fig. 1. Concern could be raised regarding the impact of three water content measurements that were $> 0.5\ \mathrm{m^3\ m^{-3}}$, especially considering they were all from the same tree type. However, analysis of covariance verified that there was no significant difference in the regressions with $\theta > 0.5\ \mathrm{m^3\ m^{-3}}$ and $\theta < 0.5\ \mathrm{m^3\ m^{-3}}$ ($P = 0.53$).

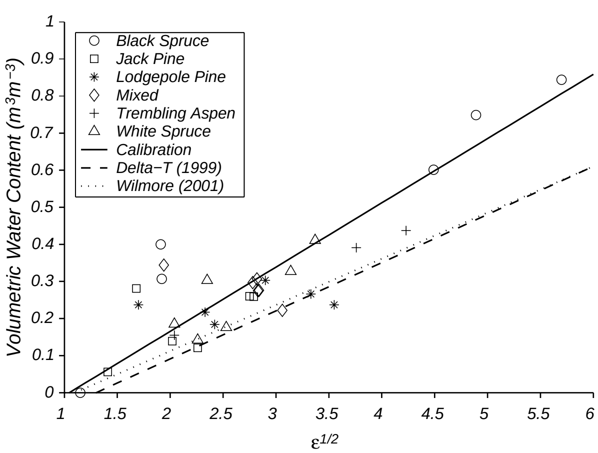


**Fig. 1.** Relationship between measurements of the dielectric constant, ε, and volumetric water content for duff collected from six tree stands. The resulting orthogonal regression calibration equation is provided along with the manufacture's suggested fit and that from Wilmore (2001).

The slope of the linear regression (using all 33 data points) was found to be significant ($P < 0.001$), with a coefficient of determination $R^2$ equal to 0.70. The relationship is:

$$\theta = 0.17\sqrt{\varepsilon} - 0.18. \tag{3}$$

The values of the coefficients, $a_0$ and $a_1$, were calculated by rearranging Eq. 3 into the form of Eq. 2. The coefficients with associated uncertainty are: $a_0 = 1.0 \pm 0.3$ and $a_1 = 5.8 \pm 0.6$. The measured coefficient $a_0$ is within the manufacturer's expected range (1.0–2.0), and includes the manufacturer's general calibrated value (1.3) within its uncertainty. The coefficient $a_1$, on the other hand, has a measured value that is outside the manufacturer's expected range (7.6–8.6), and does not include the manufacturer's general calibrated value (7.7) within its uncertainty. This difference results in a consistent under-estimation of duff water content, as evidenced by the difference between our calibration and the Delta-T Devices Ltd. (1999) calibration (Fig. 1). Wilmore (2001) also found that the generalised calibration provided by the manufacturer under-estimated duff water content in their study of black spruce duff. The difference in Wilmore's case was due to the disparity between the bulk density of duff and the optimized bulk density range for the general calibration, which is also suspected to be the reason for the difference in this study. However, the difference between the calibration done by Wilmore and Delta-T is smaller than the difference in this study, as shown in Fig. 1. The measured coefficient $a_0$ is comparable to Wilmore's (1.099); however, the measured coefficient $a_1$ is smaller than what was found by Wilmore (8.03). As stated previously, it is believed these differences could be related to differences in the nature of the duff in the two studies (thickness, density and permafrost conditions), as well as the limited number of samples (2) used in the calibration by Wilmore.

Uncertainty is a key issue in calibrating the Theta Probe for duff because of the material's high heterogeneity. Fig. 1 shows that there is a strong linear relationship between the dielectric constant and volumetric water content, but there is also a large amount of variability. The standard error of the linear fit was $\pm 0.09\ \mathrm{m^3\ m^{-3}}$, which is substantially larger than $\pm 0.05\ \mathrm{m^3\ m^{-3}}$ and even larger than the quoted ideal measurement error of $\pm 0.01\ \mathrm{m^3\ m^{-3}}$. Even the three replicate probe insertion voltage readings taken for each sample produced an average standard error of $\pm 0.04\ \mathrm{m^3\ m^{-3}}$. Such a high error may be attributed to the compressibility of duff, the difficulty in probe insertion, and the heterogeneity of duff over very small areas.

## Conclusion

Theta Probe calibration coefficients for duff were determined to be $a_0 = 1.0 \pm 0.3$ and $a_1 = 5.8 \pm 0.6$. Statistical testing indicated that duff sampled from specific tree types or depth do not require different calibrations but further testing is required because of the limited number of samples and the high heterogeneity of the duff even over small areas. The standard error associated with this calibration is $\pm 0.09\ m^3\ m^{-3}$. This error should be considered or propagated through models using these data.

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