Comparing electronic probes for volumetric water content of low-density feathermoss.

Pier P. Overduin, Kenji Yoshikawa, Douglas L. Kane, Jennifer W. Harden

P. P. Overduin, K. Yoshikawa, and D. L. Kane, Water and Environmental Research Center, Institute of Northern Engineering, University of Alaska Fairbanks, P.O. Box 755860, Fairbanks, Alaska 99775-5860, USA.

J. W. Harden, U.S. Geological Survey, 345 Middlefield Rd., MS 962, Menlo Park, CA 94025, USA.

ABSTRACT

Feathermoss is ubiquitous in the boreal forest and across various land-cover types of the arctic and sub arctic. A variety of affordable commercial sensors for soil moisture content measurement have recently become available and are in use in such regions, often in conjunction with fire-susceptibility or ecological studies. Electromagnetic sensors available include frequency and time domain designs with variations in wave guide and sensor geometry, the location of sensor electronics and operating frequency. Few come supplied with calibrations suitable or suggested for low bulk density soils high in organics. We tested seven of these sensors (CS615, ECH2O, GroPoint, Vitel, Theta, TDR, Watermark) for use in feathermoss. Sensors installed in live, dead and burned feathermoss samples, drying in a controlled manner, were monitored continuously and compared to gravimetric determinations of moisture content. Almost all of the sensors tested were suitable for measuring the moss sample water content over a range of water contents from dry to field capacity, and we present a unique empirical calibration for each sensor for this material. Differences in sensor design lead to changes in sensitivity as a function of volumetric water content. These differences will affect the spatial averaging over the soil measurement volume. Sensitivity analysis shows that empirical calibrations are required for different soil types.

INTRODUCTION

1.1 *Electromagnetic Techniques for Measuring Volumetric Water Content*

Since the 1960s, electromagnetic techniques have been studied and used for measuring the volumetric water content of porous media. Most applications in the geosciences have been in mineral soils, for which both empirical relationships (for example, Ledieu et al., 1986; Topp et al.; 1980, Stein and Kane 1983) and theoretical models (for example, Roth et al., 1990) exist for estimating volumetric water content from the bulk relative dielectric permittivity. A few empirical relationships exist for soils high in organic content (Herkelrath et al., 1991; Roth et al., 1992), but not for mosses other than cultivated peat derived from *Sphagnum* moss (Myllys and Simojoki 1996). Based on their review of calibration equations, Jacobsen and Schønning (1995) suggested that organic soils might require special treatment.

Under the assumption that all moss tissue has a common dielectric constant, differences in the bulk dielectric constant of mosses at the same volumetric water content are due to differences in volumetric fractions of air and moss in the sampling volume, i.e. to differences in bulk density and to differences in the distribution of water between bound and free states. Moss differs from low bulk density soils in that the solid phase is composed mostly of organics with highly polar surfaces and a significant portion of the soil water is incorporated into the moss as inner-cellular solution, which may have a different dielectric constant than that of free water. Both factors can be expected to increase the proportion of water in a bound state relative to mineral soils with similar characteristic particle size and therefore to decrease the apparent relative dielectric permittivity of the bulk soil for a similar water content.

Assuming a representative volume element of soil, a general relationship between the real part of the dielectric permittivity, ϕ, and the volumetric water content, θ, should exist for a porous medium with spatially homogeneous composition, porosity and texture. In practice, however, the apparent relative dielectric permittivity of the medium is also affected by sensor measurement frequency and geometry and medium structure, density, and water content (Topp et al., 1980). An empirical calibration lumps together the influences of the medium and of the sensor on the measurement. Most calibrations presented in the literature deviate from Topp's relationship (Topp et al., 1980; for example, Jacobsen and Schønning, 1995) and soil texture is generally invoked as the cause of the deviation. Attempts have been made to extend the applicability of TDR calibration curves by soil characteristics such as bulk density (e.g. Malicki, 1989). In practice, this will not eliminate the necessity of sampling the material, or similar materials, in which water content measurements are to be carried out in order to create suitable calibration curves.

More than 23 studies of the TDR technique in a wide variety of materials are available in the literature. Third-order calibration curves for peat moss, litter or soils high in organic or measured carbon content are available from Herkelrath et al., (1991), Ledieu et al., (1986), Myllys and Simojoki (1996), Pepin et al., (1992), Roth et al., (1992), and Topp et al., (1980). Mineral soil calibrations (e.g. Dasberg and Hopmans, 1992; Jacobsen and Schønning, 1995; Ledieu et al., 1986; Malicki and Skierucha, 1989; Nadler et al., 1991) predict higher relative dielectric permittivities for volumetric water contents above 0.4 m^3 m^{-3}, consistent with the prediction made above. Below this value, the regions bounded by organic and mineral calibrations overlap.

Sensor type influences the calibration through sensor geometry and frequency, both of which affect the spatial weighting function applied to the soil volume (Ferré et al, 1996; Nissen et al., 2003; Zegelin et al., 1989). Both the measurement volume and spatial weighting are dependent on sensor design (Ferré et al., 1996; Knight 1992; Zegelin et al., 1989; Pepin et al., 1992). Ferré et al (1996) showed that sensor output averages variations in water content along the wave guides for uncoated wave guides but not for coated wave guides. For all sensor designs, the soil volume proximal to the sensor wave guides is more heavily weighted in averaging of the apparent relative dielectric permittivity. Thus, the density of plant tissue immediately adjacent to the tines of the sensor exerts a disproportionately large influence on sensor output. Thicker tined-sensors, which shift and compact more of the solid soil matrix (moss tissue) on insertion may have a tendency to change the character of this near-tine material to a greater degree, particularly in a low bulk-density material.

Since TDR was developed and gained common usage as a means of measuring volumetric soil water, numerous other devices exploiting the sensitivity of the relative dielectric permittivity to soil water content have appeared on the market. They have the advantage of being cheaper and simpler to employ than TDR. While TDR measurements are only slightly influenced by the nature of the soil (Ledieu et al., 1986), most inexpensive commercially available sensors, both time domain and capacitance, provide calibrations relating sensor output directly to volumetric water content for use in a limited number of media. As with the empirical relationships in the literature, none provide calibrations with a finer distinction than mineral vs. organic soils.

Feathermoss is virtually ubiquitous in the boreal forest and common in higher latitudes. Its presence is sensitive to changes in environmental conditions and particularly to changes in water content. The water content of moss cover in both of these regions is also important because it determines boreal forest fire susceptibility, and because the thermal properties of the surface layers are highly sensitive to water levels (Yoshikawa et al., 2003). The bulk thermal conductivity and heat capacity of this surface layer have been shown elsewhere to play a pivotal role in controlling permafrost persistence or degradation (Yoshikawa et al., 2003).

Feather mosses include species from a number of genera, all of which share similar morphological characteristics, such as prostate growth habit and branched stems. Dry bulk densities for feathermoss species have been reported in the literature (Table 1) and cover a range from 0.01 to 0.05 kg m^{-3}. Feathermoss changes in bulk density within live and decomposing layers, as well as generally over depth. As an indication of their variability, values for dry bulk density from a number of sources are plotted with sample depth in Figure 1. Higher dry bulk densities are recorded with greater depth, and reflect the accumulation of dead moss tissue beneath the living layer.

In this paper, we test the suitability of a number of electromagnetic devices for measuring the volumetric water content of feathermoss. These sensors are used in feathermoss in Arctic (Romanovsky and Osterkamp, 2000; Hinkel et al., 2001) and sub-Arctic (Harden et al., 2004) soils. The differences between sensor calibrations and the influence of their design are important considerations when planning field measurements and when comparing data derived from different sensors or sensors measuring water content in differing materials. This has particular relevance to climate gradient and remote-sensing studies that seek to compare results from different ecosystems or to ground-truth spatially distributed data.

METHODS

Seven electronic sensors were tested and included two time domain reflectometry sensors: the TDR100 (Campbell Scientific, Inc.) with the CS605 TDR probe and the GroPoint (Environmental Sensors Inc.). Four capacitance (sometimes referred to as frequency domain reflectometry or FDR) sensors were also included: the CS615 probe (Campbell Scientific, Inc.), the ECH$_2$O probe (Decagon device, Inc.), the Hydra Vitel probe (Stevens Water Monitoring Systems Inc.), and the Theta ML2x Delta-T probe (Delta-T devices, Inc.), as well as a device based on measured electrical resistance, the Watermark sensor model 200SS (Irrometer Co.). Other than the latter device, each sensor has unique wave-guide geometry, frequency and electronics, details of which are given in Table 2. The CS615, ECH$_2$0, GroPoint, Hydra Vitel probe, Theta probe and carry on-board electronics, while the TDR probe is a simple wave-guide. The wave-guide geometry is important for the ease of installation, disturbs the soil matrix on installation to different degrees and changes the soil volume over which the measurement is made. Finally, the ECH$_2$0 probe is unique among the electromagnetic sensors tested here, because its tines are encased in a sensor board.

Methods were selected to demonstrate that the seven soil water sensors listed in Table 2 were effective in determining the water content of the live and dead part of feathermoss. Bulk samples of forest floor feathermoss were harvested in spring (May and June) from three locations around Fairbanks, Alaska (Birch Hill, University Ski Trails and Delta Junction). Each block contained a mix of feathermoss species, in each case predominantly of *Pleurozium* and *Hylocomium* species. Both live and decomposing moss was collected in each case. A sample of burned, partially charred moss from the Tanana River flood plain, Alaska was also used for TDR calibration. The four feathermoss samples were discriminated by layer (live or dead) and cut to known volume. Live and dead moss layers are usually distinguished on the basis of color, the presence of litter and the relative proportion of fibric moss tissue. In practice, we found a division of lesser cohesion between more loosely bound live moss tissue and the underlying, more tightly matted dead moss tissue, which roughly corresponded to the division based on color. Each layer was over 0.1 m thick.

The seven sensors were placed in the sample block in parallel orientation, extending from the insertion side of the block into its interior. Feathermoss sample blocks were set in an upright position and allowed to soak for more than 24 hours before measurements began. The saturated feathermoss samples, including sensors, were lifted out of the water in mesh baskets, drained to approximately field capacity and weighed during drying in a 30ºC forced air oven using an electronic balance. Sensor cables were supported to avoid their influence on the measured weight and the sensors remained inserted in the samples for the duration of the experiment. Balance output was recorded every 5 minutes. Temperature data within the oven and the moss samples was recorded using thermistors at 5-minute intervals during the experiment. Sensor output was measured simultaneously with all seven sensors at five-minute intervals during drying until the sample block reached a stable weight over a twelve-hour period. The volume of the sample block varied with water content and was estimated using its dimensions at a number of points during the drying process.

All sensor output signals were logged with a CR10X datalogger (Campbell Scientific, Inc.). TDR waveforms were analyzed with a computer algorithm based on Heimovaara and Bouten (1990), but including an endpoint determination algorithm that accounts for signal attenuation with increased travel time. All waveforms were analyzed visually, following the recommendations of Dasberg and Hopmans (1992). The Vitel sensor outputs three voltages for soil water content determination and one for sensor head temperature, so that temperature compensation to dielectric and conductivity values can be performed. The manufacturer provides an algorithm for this compensation. The CS615 sensor outputs a single period measurement from which the bulk soil dielectric constant may be calculated using an empirical polynomial calibration. The manufacturer-supplied calibrations are for 20 ±C and a correction coefficient has been developed for measurement temperatures of 10 to 30 ±C (Campbell Scientific, Inc., 1996). Output from the ECH_2O (single voltage), GroPoint (single current) and Watermark (single resistance) sensors were left untreated.

For TDR, the measured travel time of the is related to the permittvity:

$$t > \frac{L\sqrt{\phi}}{c}$$

where t is the travel time, ϕ is the relative dielectric permittivity, L is the length of the TDR wave guides and c is the speed of light in free space ($2.997 \propto 10^{8}$ m s^{-1}). For the CS615 sensor, the measured response is a period from which the bulk dielectric constant may be calculated:

$$\upsilon > 2\left(t_{cir} \, , \, \frac{2L\sqrt{e}}{c}\right)$$

where υ is the period output, t_{cir} is delay of the circuit components, L is the probe length, c is the speed of light. The Vitel Hydraprobe is delivered with binary versions of proprietary software that calculates soil water content from 3 sensor output voltages and sensor temperature from the fourth voltage. Output values include the real and imaginary parts of the soil dielectric constant, the soil conductivity, water content and temperature. We make the assumption that the sensor response is accurately represented by the calculated real part of the dielectric constant before temperature correction. The Delta-t Theta probe operation has been described by Miller and Gaskin (1999). The measured quantity for the sensor in a datalogging mode is a voltage for which Delta-t provides a linear and a cubic calibration to relative dielectric permittivity:

$$\sqrt{\phi >}4.44\mathrm{V}\ ,\ 1.10$$

and:

$$\sqrt{\phi >}4.70\mathrm{V}^{3}\ .\ 6.40\mathrm{V}^{2}\ ,\ 6.40\mathrm{V}\ ,\ 1.07$$

where V is the sensor output voltage. The linear relationship is used for calibrations relating the dielectric constant and volumetric water content. Similarly, the ECH_2O form of the empirical calibration suggested by the manufacturer is a linear relationship between sensor output voltage and volumetric water content. GroPoint sensors are not delivered with an algorithm for calculating dielectric constant from sensor output, but a linear function is applied to the current output of the device.

RESULTS AND DISCUSSION

Calibrations

For all probes, excepting the Watermark, calibration curves were generated relating the gravimetrically-determined volumetric water content to sensor output over a range of 0.025 – 0.15 m^3 m^{-3} for live moss tissue and from 0.025 – 0.20 m^3 m^{-3} for dead moss tissue. Figure 2 shows these results except for the Watermark sensor. The given volumetric water contents range from near field capacity to air-dry values. The field capacities for the live, dead and burnt mosses were approximately 0.15, 0.20 and 0.20 m^3 m^{-3}, respectively. The rapid change in water content on removal of the sample block from the water hampered the determination of field capacity and of the bulk dielectric at water contents near field capacity. In practice, the field capacity depends on the nature of the underlying material. Least squares 2nd or 3rd order polynomial fits of the data for each of the sensors, excepting the Watermark, were performed. The polynomial coefficients and correlation coefficients are listed in Table 3, along with the probe output domain, expressed as a range of dielectric constant or sensor output values, for each relationship.

The Watermark sensor output decreased measurably up to volumetric water contents of 5% and 7% for live and dead moss, respectively. At higher water contents, the probe output is essentially independent of changes in water content. The Watermark probe distinguishes between the air-dry and near-saturated states of the moss.

The differences between sensor outputs under similar dielectric constant conditions suggest that the volume of sensitivity, which is the volume of bulk sample over which the probe measures a spatially weighted average dielectric constant, and spatial weighting within this volume, affected sensor output. For all of the sensors, sample volume proximal to the sensor tines is heavily weighted. Sensor insertion into the sample displaces moss. In contrast to mineral soil matrices, compression of the moss around the sensor causes a localized increase in bulk density proximal to the sensor tines. Although the range of tine diameters for the sensors presented here is small (2.5 to 6 mm), this effect would to an underestimate of water content increasing with tine diameter. Ferré (1996) showed that such effects are not independent of tine spacing, diameter and coating and of heterogeneities in the distribution of water around the sensor itself. Sensor dimensions play a larger role in moss than in mineral soils due to probe contact and air void effects, particularly for sensors using lower measurement frequencies than TDR, at which the apparent dielectric permittivity is more sensitive to bulk density (Hallikainen et al., 1985).

The question facing someone using any of these sensors in moss is what sort of calibration is necessary and sufficient to achieve a particular uncertainty. One can choose between calibrating for the specific material into which the sensor is to be installed, which is appropriate to permanent installation in a particular soil horizon. If the sensor is to be used in a handheld fashion in the field inserted from the surface, however, a wider range of materials will need to be included in the calibration. Based on the data presented here, we recommend separate calibrations for live and dead horizons, i.e. for differing stages of decomposition.

The feathermoss TDR calibrations presented here lie within the range of the low bulk density and organic media calibrations listed in the Introduction. The TDR graph of Figure 2 includes data for a block of charred dead feathermoss. This sample was dark, brittle and dusty, with a bulk density of over 0.12 kg m^{-3} for a 10 l sample. The TDR calibration curves suggests that burning feathermoss changes the apparent dielectric constant of the moss, presumably as a result of changes in the moss structure and perhaps the formation of carbon deposits. In this study, live and dead moss output values approached each other at low water contents, but diverged with increasing water content. Probe output, or measured dielectric constant, was lower for live feathermoss than for dead at most volumetric water contents, for all tested probes except the ECH_2O and the GroPoint sensors, for which sensor output values for live and dead moss were closer than ±6% (20 mV). This is generally consistent with the difference in bulk densities (live 0.022; dead 0.06 kg m^{-3}) observed.

RECOMMENDATIONS

We present calibration curves for six sensors in live and dead feathermoss. For all six, calibration curves for the calculation of volumetric water content from measured dielectric constant or sensor output, depending on sensor type, were created in live and dead feathermoss over a volumetric water content range of approximately 0.02 to 0.2 m^3 m^{-3}. Calibration in multiple samples of the medium in which each sensor is to be used is advocated, whereby the uncertainty in the calibration is probably affected by spatial variability of the moss bulk density. The selection of samples for calibration should be determined by the intended use of the sensor. Sensor output in live and dead feathermoss layers at the same volumetric water content differ by more than 10% measured water content. Site-specific calibrations must therefore also record the horizons in which the sensors are being used, a consideration relevant to measurements made from the ground surface.

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List of Tables

Table 1. Bulk density ranges for feather and *Sphagnum* mosses from the literature.

Table 2. The physical and operating characteristics of the sensors.

Table 3. Calibration coefficients for relating sensor output or measured dielectric to volumetric water content in live and dead feathermoss. The coefficients for the expression:

$$\text{volumetric water content} = a\,\mathrm{x} + b,$$

are given, where x is either sensor output or the square root of the dielectric constant, as listed in Table 2. The range of sensor output or dielectric constant for which the sensors were calibrated in feathermoss is given the rightmost columns (units are listed in Table 2).

List of Figures

Figure 1. Bulk density as a function of depth for live and dead feathermoss layers from Delta Junction, Alaska - Manies et al.; Manitoba, Canada - O'Neill et al., (1995) and the Frostfire experiment in Alaska - Harden et al., (2004).

Figure 2. Variation in measured dielectric constant (CS615, TDR, Theta and Vitel sensors) or sensor output (ECH$_2$O and GroPoint) with volumetric soil water content for six sensors for live and dead feathermoss. The TDR graph shows additional data from a sample of charred feathermoss.

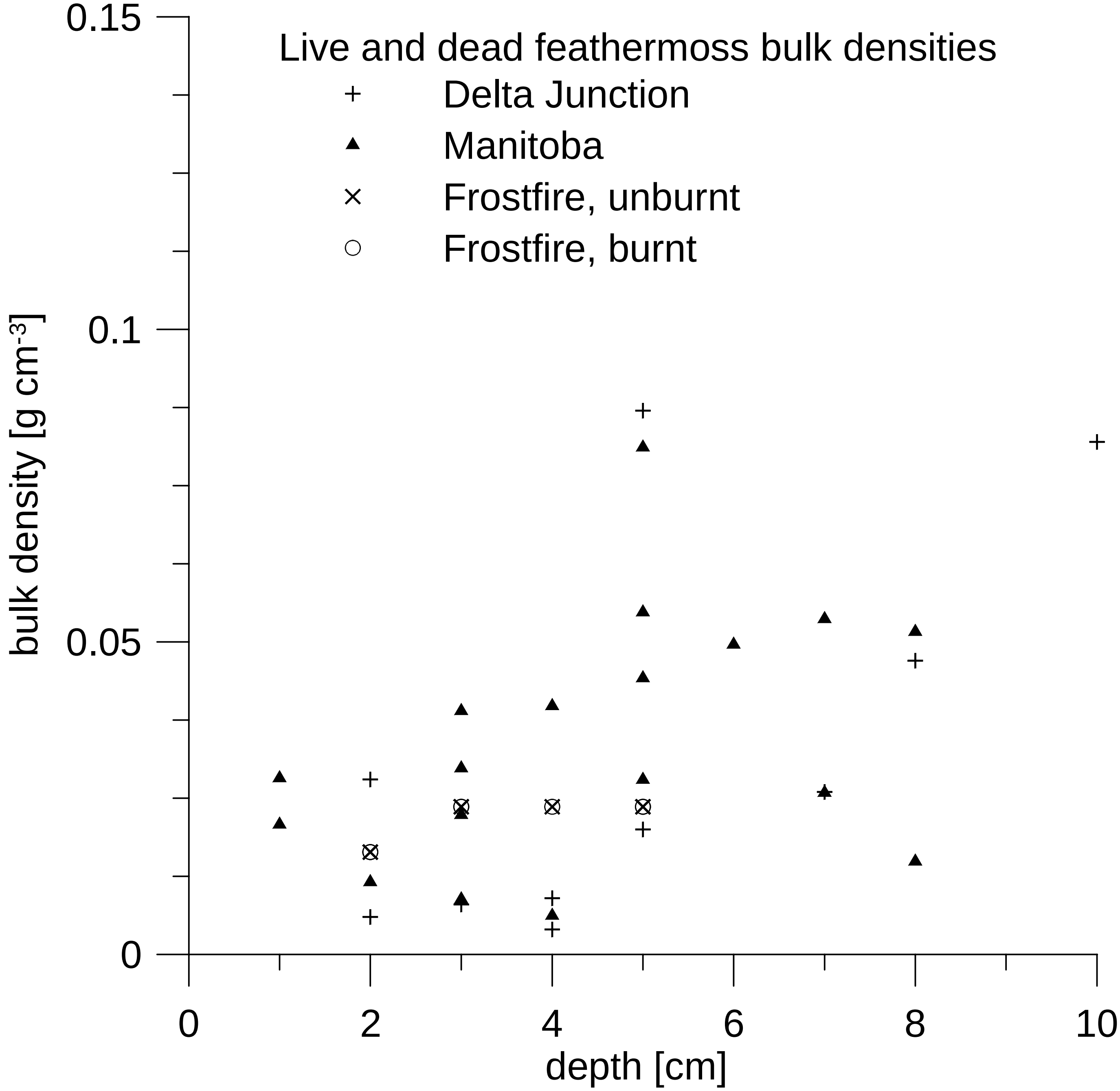
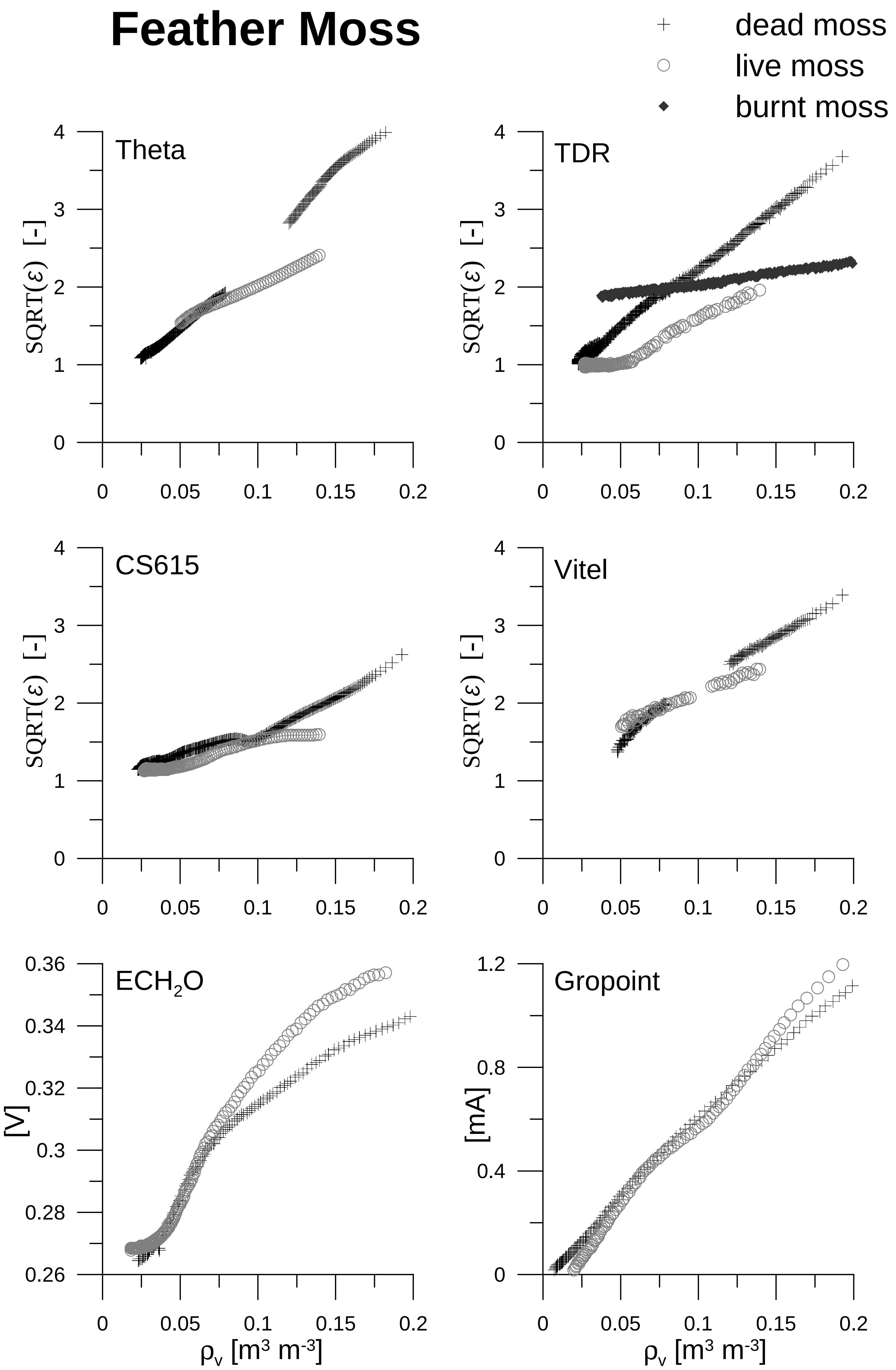

Live and dead feathermoss bulk densities
Delta Junction
Manitoba
Frostfire, unburnt
Frostfire, burnt
bulk density [g cm-3]
depth [cm]
0.15
0.1
0.05
0
0
2
4
6
8
10

Figure 1.



Feather Moss
dead moss
live moss
burnt moss
Theta
TDR
CS615
Vitel
ECH2O
Gropoint
SQRT(ε) [-]
[V]
[mA]
ρv [m3 m-3]

sample	Bulk density $[kg\ m^{-3}]$ live (# samples)	Bulk density $[kg\ m^{-3}]$ dead (# samples)
Feather moss species dry bulk density	**0.013 (6)**[†]	**0.049 (6)** [†]
	0.019 (6) [‡]	**0.041 (8)** [‡]
	0.040 (27) [§]	**0.092 (7)** [§]
	0.022 (23) [¶]	**0.06 (1)** [¶]
Sphagnum moss species dry bulk density	**---**	**0.108**[#]
	---	**0.8 – 100**[‡‡]
	0.0129 - 0.0314[§§]	
	0.0168 - 0.0406 [§§] **(capitulum)**	
	0.019 – 1.40 (corresponding to mat thicknesses of 3 – 47 cm) [§§]	

† – Trumbore et al. (1999); ‡ – King et al. (2002); § – O'Neill et al. (1995); ¶ – this study; # – Yoshikawa et al. (2004); ‡‡ – Yoshikawa et al. (2003); §§ – Kane et al. (1978).

Table 1.

type	Sensor	Characteristics			Dimensions [mm]		
		frequency [MHz]	wave shape	sensor output	sensor length	tine diameter	tine spacing (#)
Time Domain	**CS615**	55.5	sine	**1 pulse** [700 - 1400 ms]	288	3.2	28.5 (2)
	GroPoint	2 (0.5 microns)	pulse	**1 current** [0-5 mA]	205	6	25 (2)
	TDR100	3000 (130 ps)	pulse	**waveform** voltage *vs.* time	300	4.8	22 (3)
Frequency Domain	**ECH_2O**	2 (pulse)/6 (sine)	pulse/sine	**1 voltage** [400-1000 mV]	200	2.5/7.5	6 (3)
	Theta	100 MHz	sine	**1 voltage** [<1000 mV]	59	3.2	10 (2)
	Vitel	50 MHz	sine	**4 voltages** [<2500 mV]	57	4	8.6 (4)
Electrical Resistance	**Watermark**	DC	---	**1 resistance** [0.1-500 kΩ]	70	22.5	---

Table 2.

sensor	moss	coefficients			output domain†	
		a	*b*	R^2	x_{min}	x_{max}
CS615	dead	6.99×10^{0}	9.80×10^{-1}	0.981	1.18	1.58
	live	4.88×10^{0}	9.84×10^{-1}	0.966	1.14	2.63
ECH_2O	dead	5.00×10^{-1}	2.58×10^{-1}	0.937	270	357
	live	6.58×10^{-1}	2.52×10^{-1}	0.975	264	384
GroPoint	dead	5.92×10^{0}	1.00×10^{-2}	0.996	0.02	1.70
	live	6.69×10^{0}	8.08×10^{-2}	0.994	0.02	1.55
TDR	dead	1.55×10^{1}	6.83×10^{-1}	0.997	1.04	1.96
	live	8.05×10^{0}	7.46×10^{-1}	0.929	1.02	3.67
	burnt	2.69×10^{0}	1.77×10^{0}	0.983	1.86	2.34
Theta	dead	1.90×10^{1}	5.80×10^{-1}	0.995	2.40	5.80
	live	9.22×10^{0}	1.10×10^{0}	0.998	1.18	16.8
Vitel	dead	1.31×10^{1}	8.98×10^{-1}	0.993	1.70	2.43
	live	8.05×10^{0}	1.32×10^{0}	0.989	1.37	3.39

† – sensor outputs and units are listed in Table 2.

Table 3.