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Development of calibration algorithms for selected water content reflectometry probes for burned and non-burned organic soils of Alaska

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Abstract. Water content reflectometry is a method used by many commercial manufacturers of affordable sensors to electronically estimate soil moisture content. Field-deployable and handheld water content reflectometry probes were used in a variety of organic soil-profile types in Alaska. These probes were calibrated using 65 organic soil samples harvested from these burned and unburned, primarily moss-dominated sites in the boreal forest. Probe output was compared with gravimetrically measured volumetric moisture content, to produce calibration algorithms for surface-down-inserted handheld probes in specific soil-profile types, as well as field-deployable horizontally inserted probes in specific organic soil horizons. General organic algorithms for each probe type were also developed. Calibrations are statistically compared to determine their suitability. The resulting calibrations showed good agreement with *in situ* validation and varied from the default mineral-soil-based calibrations by 20% or more. These results are of particular interest to researchers measuring soil moisture content with water content reflectometry probes in soils with high organic content.

Additional keywords: aspen, black spruce, duff, feather moss, fire-disturbed soils, soil moisture, sphagnum moss, TDR, water content reflectometers, WCR, white spruce.

Introduction

Field monitoring of soil moisture is necessary for a variety of research and management applications. Water content reflectometry (WCR) instruments are in widespread use for this purpose because of their low cost, ease of use and non-destructive sampling capability. Time Domain Reflectometry (TDR) is a well-established method of measuring soil water content in soils (Topp *et al*. 1980; Roth *et al*. 1992; Ferré *et al*. 1996; Kellner and Lundin 2001) and is regarded as providing reliable measurements with relatively robust calibrations (Chandler *et al*. 2004), but such instruments are prohibitively expensive. Both the TDR and WCR rely on soil dielectric properties as the basis to estimate volumetric moisture content (VMC), but they operate at different frequencies, with the former operating at frequencies up to 1 GHz and the latter operating between 15 and 45 MHz (Chandler *et al*. 2004). Variations in soil solution composition, clay content and organic content, which affect electrical conductivity, have a greater effect on soil dielectric properties at low sampling frequencies (Chandler *et al*. 2004). As the WCR probes are more sensitive to soil type, salinity and organic content than TDR probes, calibration to specific soil types is often necessary.

The use of WCR probes for soil-water monitoring purposes is routine for many researchers and natural resource managers; however, the probes are often used without proper calibration to the high organic content of boreal soils. WCR probes are generally designed and tested by the manufacturer for mineral soils and are distributed with such a mineral-soil-based default calibration algorithm. However, laboratory tests of the CS615 WCR for different mineral soil types showed the default calibration to work well for coarse-textured soils, but as clay content or electric conductivity increased, there were substantial deviations from the default curve (Seyfried and Murdock 2001).

Due to slow decomposition rates in boreal regions, thick organic layers over mineral soil are common. These organic soils are characterised by high porosity, low bulk density and high conductivity compared with mineral soils (Roth *et al*. 1992), all of which affect WCR measurements and render the default mineral soil calibration unsuitable. The high porosity of the organic soils leads to a larger range in water content than for mineral soils (5–95% for moss detritus; Kellner and Lundin 2001). Default calibrations are not developed for this large range in water content. Kellner and Lundin (2001) found the relationship between bulk density and the dielectric constant of the soil

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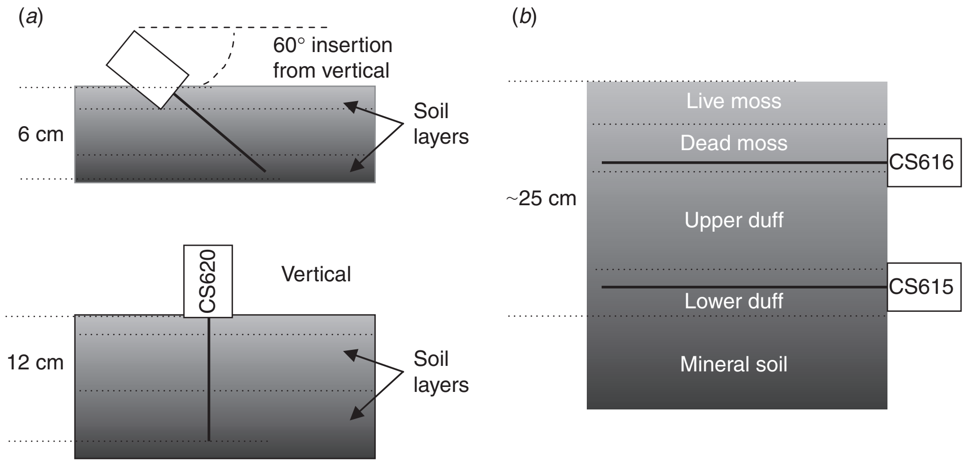

Fig. 1. Transverse section of soil sample showing: (*a*) vertical- and 60°-insertion methods of the HydroSense CS620 probe to obtain 6- and 12-cm soil moisture measurements (methods used in field and laboratory); and (*b*) horizontal-insertion method used in the laboratory for calibration of field-deployable CS615, CS616 and CS625 water content reflectometry (WCR) probes. Typical soil horizons are shown for an unburned moss-covered soil profile from the ground surface down.

as a function of soil water to be weak. However, high porosity affects probe contact with the soil medium. Although a general TDR calibration for peat soils was given by Kellner and Lundin (2001), it is not applicable to WCR probes due to frequency differences. Further, each WCR probe-type operates slightly differently, requiring probe-type-specific calibrations.

A calibration study was launched in 2003 to develop algorithms specific to organic boreal soils in both burned and non-burned boreal forest ecosystem types. The WCR probes used for calibration included Campbell Scientific's CS620, CS615, CS616 and CS625 (comparable with the CS616) (Logan, UT). Although no longer manufactured, the CS615 probes have been and continue to be used in the field for boreal studies by many scientists from a range of organisations (United States Geological Survey (USGS), United States Forest Service (USFS), Long term ecological research (LTER), University of Alaska Fairbanks (UAF)). With the exception of the CS620 (HydroSense instrument), these probes are field-deployable, designed to remain on site for long periods of time attached to a datalogger or similar device to capture time series data. The field-deployable instruments are typically inserted horizontally into specific soil horizons by researchers after a soil pit has been dug. Cost typically limits the number of probes deployed within a particular site, and distance to the datalogger restricts the spatial extent of measurements. In contrast, the handheld CS620 HydroSense instrument is designed for immediate soil moisture testing, and therefore can be used to quickly collect a distributed set of samples to characterise the spatial variability in surface soil moisture across a test site. Soil pits are often not used for the handheld instrument; rather, it is commonly used to sample surface soil moisture, and is inserted vertically or at an angle into the soil from the surface down. Thus there are trade-offs for using handheld *v.* field-deployable instruments, but a combination of the two can provide a greater understanding of the spatial and temporal soil moisture dynamics of a test site.

To use these instruments in the organic soils of our Alaska test sites, it was critical to develop calibration algorithms specific to the burned and non-burned soil profiles. Although uncalibrated data can be used to assess temporal changes *within* a given soil type or location, absolute VMC is unknown and comparisons *between* soil types or locations cannot be made with only relative changes in reflectometry as reference. This work presents methods used to create calibration algorithms specific to the soils within our study sites for the various probes.

Alaska soil types are representative of a broad range of burned organic conditions and also of common non-burned, aspen and spruce–moss ecosystem soil types, making this dataset and calibration algorithms notable to the broader scientific community. The soil-specific algorithms developed are qualitatively and statistically compared to determine which of the soil types we have defined are similar enough to use a single algorithm, towards the end of creating general organic soil calibration algorithms.

Methodology

Study sites

From 2003 to 2005, soil samples were harvested from 20 different study sites, all located within a 150-km radius of Fairbanks, Alaska. The sites included organic soil profile development under sphagnum moss (*Sphagnum* spp.), feather mosses (*Pleurozium* or *Hylocomium* spp.), and some non-moss groundcovers. The sites were from both recently burned (1–15 years post fire) and non-burned, mature forest study areas, including ecosystems dominated by black spruce (*Picea mariana*), aspen (*Populus tremuloides*), and white spruce (*Picea glauca*). For detailed information about the study sites, see Bourgeau-Chavez *et al.* (2007).

Soil types

Most of our sites were moss-dominated spruce forests. The typical non-burned Alaskan spruce boreal forest organic soil sample has the following main soil horizons with increasing depth as taken from the surface (see Fig. 1*b*): live moss, dead moss, upper duff, lower duff and mineral soil (Norum and Miller 1984; Wilmore 2001; Jandt *et al*. 2005). The distinction between these layers is important for fire weather and fire danger measurements as *per* Norum and Miller (1984) and B. Wilmore, unpubl. data. The live moss is the green portion on top, which is typically only 2 or 3 cm deep. The dead moss layer is moss that is no longer green, but does not visibly show signs of decomposition. The duff is dead moss that shows signs of decomposition. It is divided into an upper and lower part. The upper duff is partially decomposed and has visible stems, but it is decomposed to the point that the original plant species is not readily identifiable. The lower duff is fully decomposed, and has a darker colour and a more soil-like consistency. Another common characteristic of the duff layer is the presence of fungal hyphae (very fine hair-like strands, usually white or very light grey). There are also cases where the lower duff will contain material with a grey ash-like appearance. An ash-like property indicates the presence of volcanic ash, fire ash, or mineral material; a mixture of mineral and organic material of these lower duff horizons is consistent with organic C contents of 20 to 25% (Harden *et al.* 2000). The mineral soil in these Alaska sites is typically very fine-grained and can usually be differentiated from lower duff by colour and consistency differences.

The burned organic soil sample is similar to the unburned sample, except the live moss layer is replaced by a partial to completely burned upper layer. Burn severity dictates which layers remain; a severe burn may reach the lower duff and in extreme cases expose the mineral soil.

Instrumentation description

The WCR units used in this study consist of a probe attached to a power supply and a local display unit (CS620) or datalogger (CS615, CS616, CS625). Probes consist of two stainless steel rods connected to a circuit board. The circuit board enables the probe, monitors probe output, and is a conduit for power. The CS620 units used in this study had 12 cm-length steel rods; all other probes had 30 cm-length steel rods. Design of the CS616 and CS625 probes is essentially equal according to manufacturer specifications and are assumed equal in this investigation (Campbell Scientific, Inc. 2003).

The method of operation consists of the embedded electronics contained within the probe head sending a signal down the probes, the probes acting as waveguides. The return time of the signal is the period (τ). Ideally, in WCR, the period of the electromagnetic wave is a function of wave guide length (L) the speed of light (c) and the electrical permittivity (ε) of the surrounding medium (Overduin *et al*. 2005).

$$\tau = \frac{L\sqrt{\varepsilon}}{c} \tag{1}$$

Electrical permittivity of the surrounding medium is defined as:

$$\varepsilon = \varepsilon_0 \kappa_e \tag{2}$$

where the constant ε_0 is the permittivity of free space and κ_e is the dielectric constant of the medium. κ_e for soil is a composite of the dielectric properties of the soil constituents, namely: organic and inorganic matter, liquid water and air. Of these, water is the dominant source of variance in electrical permittivity. This allows us to compare τ with volumetric moisture content θ. Empirical or dielectric mixing models are often used to relate water content to measured electrical permittivity (Roth *et al*. 1992; Kellner and Lundin 2001; Overduin *et al*. 2005; and others). Rather than a physically based approach, we focus here on empirically calibrating the probe period output (τ) to percentage volumetric moisture content (% VMC) for practical application. The general form of this relation is shown in Eqn 3, where A, B and C are derived from the calibration data.

$$\theta = \mathrm{A}\tau^2 + \mathrm{B}\tau + \mathrm{C} \tag{3}$$

Volumetric moisture can be measured from gravimetric moisture through the bulk density of the soil sample.

The dielectric permittivity of soil minerals and soil water, as well as the electrical conductivity of the soil solution all vary as a function of temperature. The role of temperature in the electrical permittivity of water is well established (see Weast and Astle 1982) and the field-deployable Campbell Scientific probes come with temperature correction algorithms (Campbell Scientific, Inc. 1996, 2001, 2002, 2003). Temperature fluctuations are not expected to influence permittivity measurements in our laboratory measurements, as they were taken at room temperature (nominally 20–22°C).

Harvesting soil samples

Two or more soil samples were harvested from each of the study sites for laboratory experimentation, with a total of 65 samples collected over 3 years. A large rectangular soil sample was collected so that the individual soil horizons could be probed horizontally with the 30-cm probes to maintain soil matrix homogeneity. The organic soil sample extraction was performed using a specially made rectangular furnace duct (sample cut area: 20.3 by 35.5 cm). Care was exercised during the extraction process to not compact the organic soil layers. The samples were then measured for dimensions, packaged in plastic tubs, and shipped back to the laboratory for experimentation.

Validation samples for HydroSense CS620 only

For validation of the laboratory-developed HydroSense calibration algorithms, at least one or more small cylindrical soil samples were also collected for each of the study sites examined. The cylindrical sample extraction was performed using a 14.5 cm-diameter standard circular furnace duct.

At the time the small samples were collected in the field, the soil surrounding the sample was probed with the HydroSense to obtain probe period for validation. The samples were then measured for dimensions and weighed wet. Then, they were packaged and shipped back to our laboratory, where they were completely dried in a convective drying oven and reweighed. The VMC was calculated from Eqn 4 below. Occasionally water was observed in the hole after extraction of the soil sample; thus, for the saturated samples, field-measured probe period from the HydroSense will likely show a higher moisture content than that estimated from gravimetric destructive sampling. A total of 66 small cylindrical samples were harvested, producing data points that were reserved as validation.

Laboratory measurements and calibration algorithm development

Laboratory sampling procedure

The organic soil calibration of the Campbell Scientific WCR probes occurred in a controlled laboratory setting. The calibration process consisted of submerging the samples in water for 24–48 h to complete saturation in a mesh cage designed to hold the samples. The standing water was decanted off and initial weight and probe measurements taken. The sample was then allowed to slowly air-dry and systematic probe measurements and corresponding gravimetric weights were taken. When the samples dried to roughly the 5% volumetric moisture content level, the sample was placed in a laboratory oven where they were dried at 105°C for 48–96 h until all the moisture in the sample was removed. A final dry weight was then measured and the volumetric moisture content was calculated for each measurement using the equation:

$$\theta = \frac{Ww}{Wsd} \times \frac{BDs}{BDw} \times 100 \tag{4}$$

where θ, percentage VMC; Ww, weight of water in grams; Wsd, weight of dry soil in grams; BDs, bulk density of soil (g cm^{-3}); BDw, bulk density of water, 1 g cm^{-3}.

Ww is calculated as:

$$Ww = Wsw - Wsd \tag{5}$$

where Wsw, weight of wet soil in grams.

WCR measurements of harvested samples

Probing was conducted from the surface down for the CS620 (Fig. 1*a*) and horizontally for all other instruments (CS615, CS616, CS625; Fig. 1*b*). Two instruments of each WCR probe-type were used in the experimentation. The handheld CS620 was inserted at two angles for probing of 6-cm (60° angle from vertical) and 12-cm depths (vertical). With this surface-down probing methodology, the probes were often crossing multiple soil horizons in the burned samples, and sometimes into mineral soil (Fig. 1*a*). As the moisture estimate is integrated over the length of the probe, there is potential for profile discontinuities to affect probe period. Separate calibrations were developed for these two surface soil depths, mainly because the soil horizons vary with depth, and the 6-cm insertion was not always crossing over different soil horizons; it depended on the soil profile and burn severity (for those sites that were burned). The 12-cm samples were generally crossing over into mineral soil in the burned sites more frequently than the 6-cm measurements. In the statistical section, we evaluate the differences in these two probe-depth calibrations for the same soil types.

Soil-profile types of the surface-down sampling (CS620)

Of the 65 large soil samples harvested for laboratory experimentation, 39 were used for calibration of the surface-down probing of the HydroSense instrument. With the surface-down sampling, it was important to categorise the soil samples to soil-profile type based on non-burned or burned conditions. The calibration algorithms were then developed by soil-profile type. Samples that were similar in vertical profile (including variation in depth of organic soil, type of organic soil on the surface and amount of live moss) were grouped. Note that not all samples taken from a particular site would fall into a given soil-profile type. This is especially true of the burned sites, where variation in burn severity results in spatially varied organic soil depths remaining post burn, and also soil-profile type. For example, a site may range from singed moss in one area to burned lower duff, or burned to mineral soil in another area of the burn. The samples were divided into eight soil-profile types.

1. Live feather moss. These samples include soils that are unburned and composed of a thick layer (> 12 cm) of live feather moss over dead feather moss, upper duff or both. Lower duff and mineral soil begin at depths greater than 12 cm.
2. Live sphagnum moss. These samples are unburned and composed of a thick layer (> 12 cm) of live sphagnum moss over dead moss, upper duff or both. No lower duff is found in the upper 12 cm of the sample.
3. Lightly burned moss (sphagnum or feather). These samples are lightly burned but composed of a thick layer of dead or burned moss and/or upper duff. There is no lower duff or mineral soil in the upper 12 cm of the sample.
4. Severe recent burn or mineral soil. These samples have the least amount of organic soil horizons (< 5 cm depth). These samples are composed of pure mineral soil or fresh burns that have less than 1.5 cm of dead moss and upper duff. The majority of these samples are composed of lower duff and/or mineral soil.
5. New regenerating moss. These samples have between 5 and 10 cm of organic soil on the surface. The samples are composed of a very thin layer of live moss (less than 1 cm), a layer (0.5–2 cm) of dead moss and upper duff, underlain by lower duff and mineral soils. Generally, this group represents soils that were burned but are in the early process of regenerating.
6. Middle regenerating moss. These samples have more than 10 cm of organic soil on the surface. The samples are composed of a thin layer of live moss (0.5–2 cm), a thicker layer of dead moss and upper duff (2–3.5 cm) underlain by lower duff and mineral soil. These samples are from past fires that either were relatively light or are regenerating back to a full moss layer.
7. Older regenerating moss. These samples have a thick organic layer on the surface. They are composed of a thicker layer of live and dead moss (1.5–3.5 cm) and a layer of upper duff (2–5 cm) and then are underlain by lower duff and mineral soil. These are generally areas of older fires that are in the latter stages of regenerating back to a full moss mat.
8. Burned aspen. These samples are from relatively recently (within last 15 years) burned aspen stands. They consist of litter and shallow organic soil layers over mineral soil.

Soil horizons evaluated for horizontal sampling (CS615, CS616, CS625)

Of the 65 harvested rectangular soil samples, 26 were used for development of calibration models for the horizontal-insertion methodology. CS616 and CS625 calibrations were developed for the following soil horizons (as in the typical soil sample of Fig. 1*b*): live moss, dead moss, burned moss, upper duff, lower duff and mineral soil. Unfortunately, only six of the large soil samples used to calibrate the CS616 and CS625 probes were available for use in the calibration of the CS615 probes, as many samples had been discarded before receipt of the CS615 probes. As none of the remaining six samples had a live moss layer sufficient for testing, the layers for which calibration algorithms were developed for the CS615 are dead feather moss, upper duff, lower duff and mineral soil.

General organic soil calibration algorithms

Investigation of the development of general organic soil calibration algorithms for the individual probe types was also conducted. Although the calibrations developed for individual soil layers or profile-specific types are probably most useful, there are instances where a generic calibration for organic soils may be helpful. For surface-down-probing in areas with heterogeneous soil profiles, a single generic calibration may be of use for all types of probes, especially if the exact soil-profile type is unknown.

Owing to the porous nature of live mosses, we expected that separate general algorithms would be required for live moss *v.* humic soils with both the surface-down and horizontally inserted WCR instruments. Further, because the laboratory wetting of sphagnum moss was difficult compared with feather moss or humus, we assumed it would likely require a separate calibration algorithm. We therefore developed the general algorithms based on these assumptions and then evaluated the suitability of these general equations for each soil type or horizon in the model comparison section.

Algorithm model development

Calibration algorithms were developed for each soil type and probe type and probe sampling depth using quadratic regression least-squares as in Eqn 3. These algorithms were evaluated based on the resulting coefficients of determination (R^2), standard errors (s.e.) of the estimate, and 95% level of significance ($P < 0.05$) for optimisation. The best equations were sought that did not overfit the data, and only equations with significant coefficients are presented.

Model comparisons

Statistical evaluations of model differentiation were conducted to determine when it was appropriate to generalise calibration equations and where type-specific models were required. To test for model similarities, goodness-of-fit statistics were computed from a residual analysis of dependent datasets holding a reference regression model constant. Comparisons were made within probe model and, in the case of the HydroSense, sampling within and between depth class (6 or 12 cm). Algorithm comparison was conducted by choosing one of the soil-profile type calibration algorithms (or general algorithm) as reference and then testing its goodness-of-fit on data from each of the remaining soil types and probing depths in a cross-validation procedure.

Each test statistic explains a different part of the model fit: R^2 the overall variance explained, s.e. identifies the estimated confidence interval and t tests evaluate the hypothesis that a coefficient is not significantly different than zero. It is common for these statistics to covary. However, overall model fit is explained in the R^2 and s.e. whereas coefficient tests target model form (i.e. linear, non-linear), and hence nothing precludes a non-linear model from explaining significant variation in a linear dataset. Furthermore, these tests do not identify a single superior model, but indicate physical similarities between soil types as measured by the WCR probes. Combining these datasets and creating a new model will explain more variation in the new dataset with reduced error than swapping coefficients.

Results

Most calibration algorithms were developed in the form of Eqn 3 and the results are presented with coefficients in this quadratic form (Tables 1–3). In a few cases, a linear model was a better fit to the data (the A term is not significant) and for the mineral soils with the CS616 field-deployable probes, an exponential model was the best fit (the B term is not significant). This is comparable with the form of the default mineral soil calibration equations that are delivered with the field-deployable WCRs. The results are presented via the probe types and sampling methodology, starting with the surface-down sampling methodology of the HydroSense handheld instrument, and later presenting the horizon sampling methodology of the field-deployable probes (CS615, CS616, CS625). Note that the number of sample points (n) in the tables refers to the number of paired % VMC and probe period, and not number of harvested soil samples. Thus each harvested soil sample would have multiple soil moisture sample points (n) measured from it, and each test site had two or more soil samples harvested for monitoring soil moisture.

Surface-down sampling (CS620 HydroSense)

For the Hydrosense probes, calibration algorithms were developed for the eight defined soil-profile types for (1) 60° surface-angle insertion (6-cm depth); and (2) vertical insertion (12-cm depth, Table 1) with the exception of the live sphagnum, burned aspen and lightly burned moss, which had minimal sampling points at 12-cm depth. This is because some samples were too shallow for 12 cm probing owing to conditions at harvest (permafrost at shallow depths or rock layers), compaction during shipping or both.

Quadratic regressions were good fits to all of the soil-profile types for the HydroSense. The calibration algorithms developed have low spread about the fitted lines of % VMC to probe period (example plots in Fig. 2). The range in standard errors for all moss-covered soil type equations was fairly low, 2.6 to 4.86, and all equations were significant at much below the 5% level of significance. Overall, all of the calibration algorithms had coefficients of determination (R^2) greater than 0.86, with most profile soil types showing R^2 values greater than 0.94 (Table 1). Notice that Fig. 2 and Table 1 present both probing depths (6 and 12 cm).

Example plots of calibration data for specific soil types in the surface-down sampling (Fig. 2) show that when the top soil horizon of the vertical profile was greater than the 12-cm probe depth (e.g. live feather moss, Fig. 2*a*), the measurements appear qualitatively similar at both 6- and 12-cm probing depths.

Table 1. List of calibration algorithms for the surface-down sampling with the CS620 HydroSense moisture probes

6- and 12-cm depth moisture equations are provided. Refer to Eqn 3 for algorithm form. The general organic soil calibration equations are based on all data but the live moss soil-profile types. Also presented are the coefficient of determination (R^2), standard error of the estimate in % VMC (s.e.), significance (P) and sample size (n, number of paired probe and moisture points)

	Soil-profile type	Probe depth (cm)	A	B	C	R^2	P	n	s.e.
1	Feather moss	6	−0.01149	3.902	−234.49	0.95	<0.05	117	4.0
2	Feather moss	12	−0.00597	2.839	−186.98	0.96	<0.05	111	3.98
3	Recent burn or mineral soil	6	−0.02689	7.100	−391.39	0.98	<0.05	95	3.17
4	Recent burn or mineral soil	12	−0.02874	7.554	−417.25	0.97	<0.05	63	4.22
5	New regenerating moss	6	−0.01505	4.675	−273.08	0.95	<0.05	44	4.86
6	New regenerating moss	12	−0.01747	4.918	−278.78	0.98	<0.05	38	2.71
7	Mid regenerating moss	6	−0.02375	6.516	−364.66	0.95	<0.05	68	3.73
8	Mid regenerating moss	12	−0.01408	4.356	−255.77	0.98	<0.05	55	3.30
9	Older regenerating moss	6	−0.00707	3.024	−189.09	0.98	<0.05	31	2.62
10	Older regenerating moss	12	−0.02022	5.565	−311.49	0.97	<0.05	82	3.09
11	Burned aspen	6	−0.03868	9.987	−550.48	0.99	<0.05	19	11
12	Live sphagnum	6	−0.03085	7.031	−354.85	0.94	<0.05	67	3.38
13	Lightly burned moss	6	−0.03424	7.849	−400.44	0.86	<0.05	67	4.81
14	General calibration	6	−0.018	5.243	−300.6185	0.94	<0.05	374	5.00
15	General calibration	12	−0.015	4.673	−273.9543	0.93	<0.05	243	5.49

Table 2. List of calibration algorithms for horizontal sampling with the CS616 field-deployable moisture probes

Refer to Eqn 3 for algorithm form. The general organic calibration equation is also presented, based on only the non-mineral soil types. Also presented are R^2, s.e. (% VMC), P and sample size (n, number of paired probe and moisture points)

	Soil horizon	A	B	C	R^2	P	n	s.e.
1	Live moss	0	6.729	−97.850	0.97	<0.05	19	0.92
2	Dead moss	0	3.734	−52.939	0.88	<0.05	122	6.22
3	Burned moss	0	6.045	−88.469	0.93	<0.05	30	1.81
4	Upper duff	−0.066	5.748	−68.034	0.85	<0.05	124	5.81
5	Lower duff	−0.064	6.577	−83.099	0.89	<0.05	187	7.33
6	Mineral soil	0.083	0	−16.726	0.97	<0.05	99	4.31
7	General	−0.043	5.387	−68.443	0.88	<0.05	482	6.65

Table 3. List of calibration algorithms for horizontal sampling with the CS615 field-deployable moisture probes

Refer to Eqn 3 for algorithm form. The general organic soil calibration equation is also presented, based on only the non-mineral soil types. Also presented are R^2, s.e. (% VMC), P and sample size (n, number of paired probe and moisture points)

	Soil horizon	A	B	C	R^2	P	n	s.e.
1	Dead moss	0	113.690	−76.662	0.91	<0.05	20	6.22
2	Upper duff	−59.453	189.910	−102.340	0.87	<0.05	48	5.75
3	Lower duff	−82.866	261.204	−146.448	0.77	<0.05	62	10.33
4	Mineral soil	0	110.740	−84.777	0.98	<0.05	32	3.92
5	General	−75.452	237.821	−130.626	0.78	<0.05	130	9.03

However, for more heterogeneous types (e.g. new or middle regenerating moss, Fig. 2*b*), the calibration curves appear to deviate between the 6- and 12-cm measurement depths, indicating the need for separate algorithms.

Fig. 3*a* and *b* shows all of our sample points from all eight burned and unburned organic soil-profile types plotted together, for 6- and 12-cm depths respectively. Plotted with these data points is the Campbell Scientific (CSI) default calibration curve for mineral soil that is programmed into the WCR (CS620 HydroSense). Also plotted are the general organic soil calibration algorithms that we developed based on all the non-live-moss organic soil-profile types combined for each sampling depth. The 6-cm general organic soil calibration algorithm is fairly robust, with a coefficient of determination of 0.94, s.e. of 5.0% VMC (Fig. 3*a* and Table 1, line 14). The algorithm developed for the 12-cm probing depth also had a strong coefficient of determination (0.93) and the s.e. is similar (5.5% VMC, Table 1, line 15).

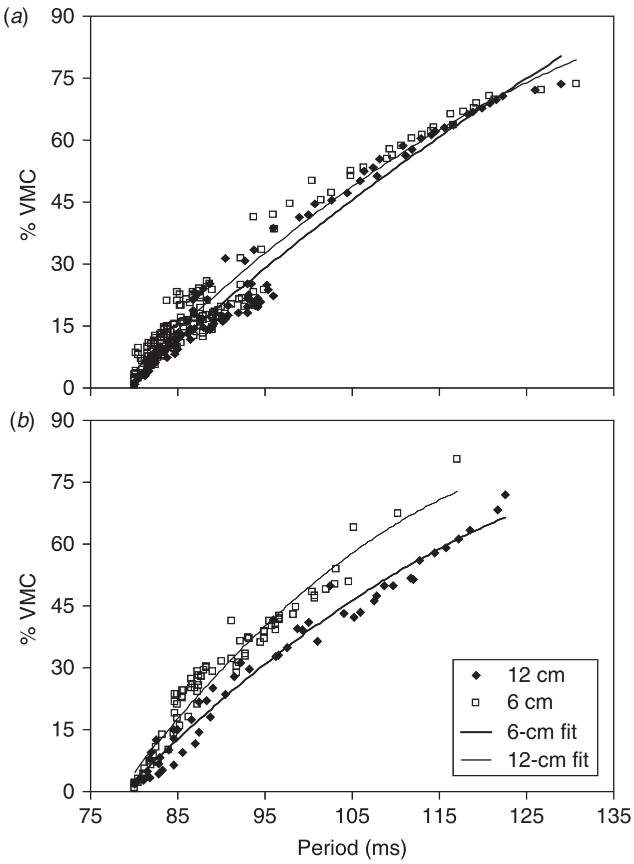

Fig. 2. Plots of 6- and 12-cm volumetric soil moisture (% VMC) *v.* HydroSense probe period in milliseconds for: (*a*) feather moss (Table 1, lines 1–2) and (*b*) middle regenerating soil (Table 1, lines 7–8) profile types.

Fig. 3*a* shows that using the CSI default curve that was designed for mineral soils in a surface-down probe insertion at our test sites would result in an underestimation of actual soil moisture for all organic soil types with the exception of live sphagnum, which is underestimated up to a period of 105 and VMC of 38% (Fig. 3*a*), and lightly burned moss, which is underestimated up to VMC of 45%. Similar observations for the live sphagnum and lightly burned moss at 12 cm also occur in Fig. 3*b*.

Horizontal sampling

CS616 and CS625 results

Table 2 lists all algorithms developed for the CS616 and CS625 probes. Although the table follows the quadratic form presented in Eqn 3, the organic soil calibration algorithms developed include simple linear and quadratic fits to the data, while an exponential curve fit the mineral soil best. All algorithms were found to be significant at the 5% level (Table 2), with strong coefficients of determination ($R^2 = 0.85$–0.97), and fairly low standard errors of the estimates (0.92 to 7.33% VMC).

Fig. 4*a* shows all the data points plotted for the CS616 and CS625 probe calibration. It is evident that there is much more spread in these data than were in the surface-down-probing HydroSense calibration. The duff layers and dead moss show the greatest spread. Note that burned moss and live moss samples are clustered at the low end of the plot, although there is a small amount of spread about these samples and they are fairly linear. The probe sample size was rather low for live feather moss ($n = 19$, Table 2, line 1) and this was mainly due to the fact that the moss samples simply did not hold much water, even after submersion. Similarly, burned moss had only 30 probe sample points as it also resists wetting. Fig. 4*a* also presents the general algorithm for the organic soil horizons. This algorithm is significant at a P level much less than 5%, has a coefficient of determination of 0.88 and a standard error of 6.7% VMC (Table 2, line 7).

For reference, the default Campbell Scientific mineral soil calibration curve for the CS616 and CS625 is plotted in Fig. 4*a*. All of the sample points are well above this default calibration. Even the measured values for the mineral soil horizon (closed black squares in Fig. 4*a*) are markedly of greater % VMC than would be predicted with the default CSI calibration. In the high-moisture regime, the difference between the derived calibration and the default calibration of our mineral soil is roughly 27% VMC and trails quadratically to 3% difference in the dry regime.

CS615 results

Fig. 4*b* displays all of the data points collected for the CS615 sensors, by soil horizon. Also plotted are the Campbell Scientific (CSI) default calibration curve for mineral soil and a general organic soil calibration curve based on all organic soils.

All of the horizon-specific algorithms are significant at the 5% level (Table 3), and they all have high coefficients of determination (0.77 to 0.91 for the organic layers and 0.98 for mineral soil). The standard error ranges from 5.75 to 10.33% VMC for the organic layers, and is 3.92% VMC (Table 3, line 4) for mineral soil.

The coefficient of determination for the CS615 general organic soil calibration algorithm (0.78) is lower than for the CS616 probes (0.88), with the lower duff measurements being the prime driver (Fig. 4*b*, Table 3, line 5). The standard error was also much greater for CS615 (9.0) than for the CS616 general algorithm (6.7), yet the model was significant ($P < 0.05$).

Algorithm comparisons results

Statistics for the algorithm comparisons are presented in Tables 4–7, with Tables 4–5 for the surface-down sampling technique and Tables 6–7 for the horizontal-insertion technique. At the bottom of each table are the statistics for the respective general organic soil algorithm compared with each soil type. For Tables 4–5, depth-class comparisons are presented for each soil-profile type. In all comparison tables (Tables 4–7), statistics are only shown for significant equations, i.e. t tests of coefficients that had a probability of 0.05 or less and the coefficient of determination (R^2) was at least 0.40.

Surface-down-sampling comparison of algorithms

Tables 4 and 5 respectively present the 6- and 12-cm depth algorithm comparisons. These tables show all of the coefficients for the reference model to itself (highlighted in grey) as significant; thus the quadratic equation is a good fit for all soil-profile types. However, when data are compared from different

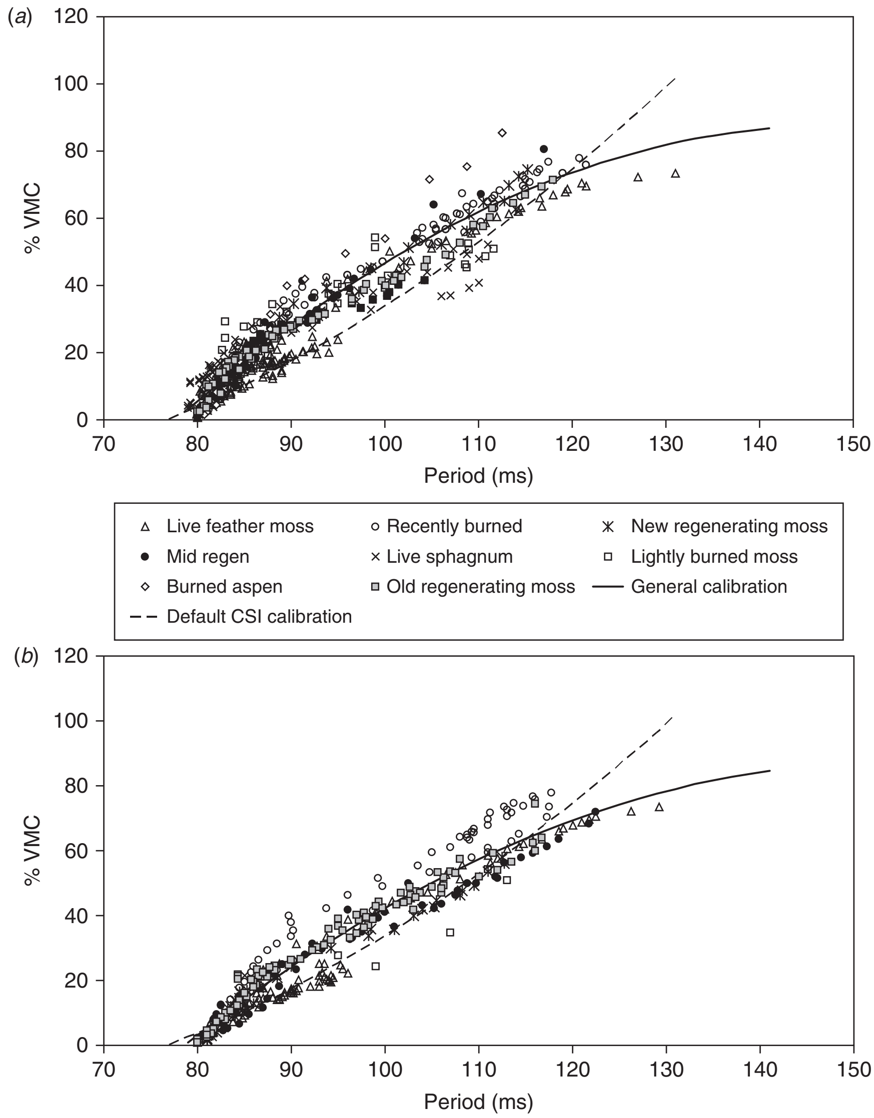

Fig. 3. Plots of: (*a*) 6-cm and (*b*) 12-cm laboratory-measured volumetric soil moisture (% VMC) *v.* respective 6- and 12-cm HydroSense probe period in milliseconds for all soil-profile types. Coefficients and statistics are in Table 1, lines 1, 3, 5, 7, 9, 11, 12 and 13 for 6-cm probing and lines 2, 4, 5, 6, 8 and 10 for 12-cm surface-down probing. Also plotted are the general calibrations developed for the HydroSense at each depth (Table 1, lines 14 and 15) and the default Campbell Scientific, Inc. (CSI) mineral-soil calibration curve. Note that burned aspen, live sphagnum and lightly burned moss data were not collected for 12-cm depths.

soil types, some coefficients lose significance or the coefficient of determination drops below 0.40. For example, for 6-cm live sphagnum (Table 4, line 38) and lightly burned moss (Table 4, line 40) soil-profile types as reference, all of the other soil types except these two (Table 4, lines 39 and 41) as testing models have non-significant coefficients. The R^2 and s.e. help to determine which soil types are most similar and can be used interchangeably. In the case of live sphagnum as reference, the coefficient of determination merely decreases from 0.94 (Table 4, line 38) for the reference to 0.92 (Table 4, line 39) for the testing model and the standard errors of the estimates differ by only 0.5% VMC. Thus the models for live sphagnum and lightly burned moss are similar and can be combined. For the burned aspen model (Table 4, line 42), none of the testing models had significant coefficients. Thus the burned aspen model is unique, but it is likely that the small sample size ($n = 19$) does not adequately represent the population variability.

The general model for 6-cm probe measurements shows good fits for all non-sphagnum (R^2 values of 0.91–0.98, Table 4, lines 43–48) soil types except burned aspen. Goodness-of-fit tests show the 6- and 12-cm general equations to be similar

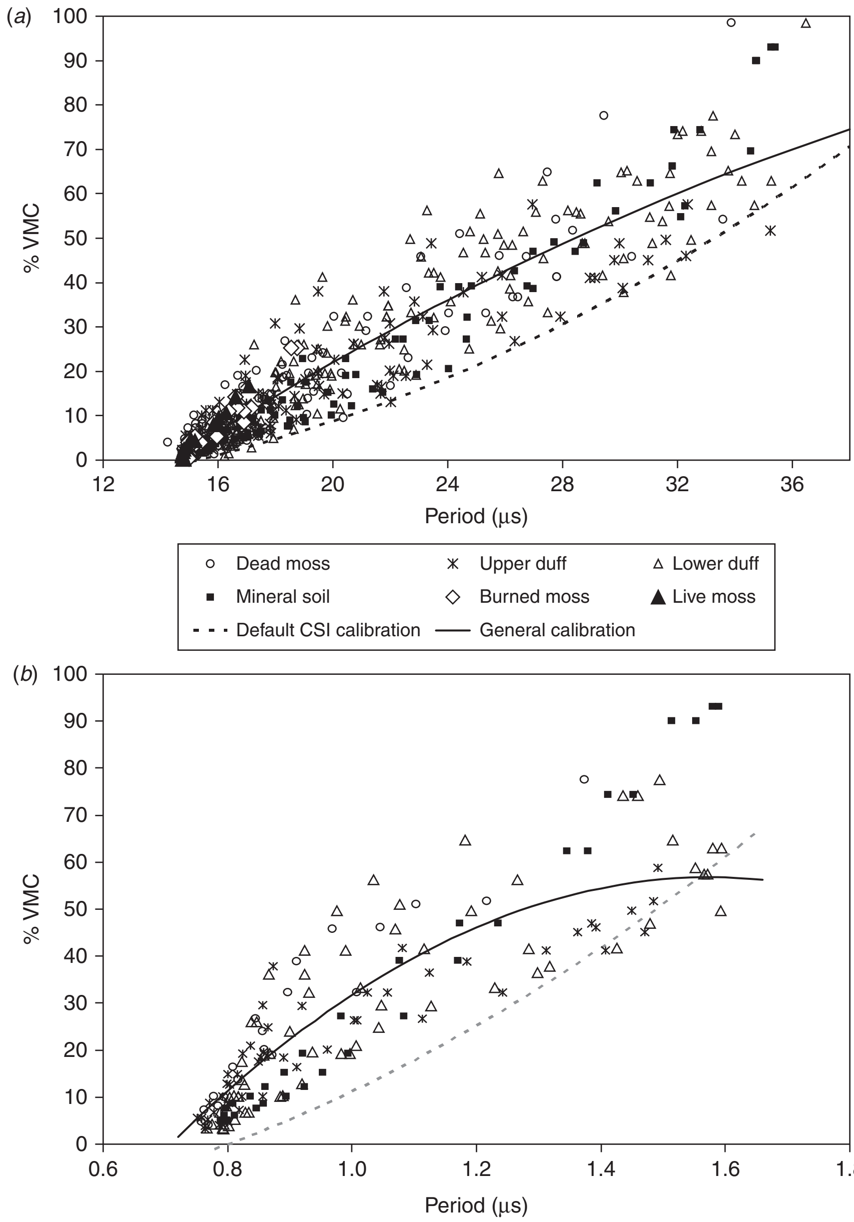

Fig. 4. Plots showing experimental laboratory results for: (*a*) CS616 probe period (µs); and (*b*) CS615 probe period (µs) *v.* volumetric soil moisture (% VMC) for all soil horizons. Also plotted are the general organic soil calibration curves for each probe and the default Campbell Scientific, Inc. (CSI) mineral-soil calibration curves for each probe type. Refer to Table 2 for calibration statistics for the CS616 and Table 3 for CS615. Note that CS615 calibrations were not developed for the live-moss or burned-moss horizons.

(Table 4, line 49). All other 6 cm-depth soil types are statistically similar to four or more other soil-profile types and the suitability of using one equation over another can be gleaned from this table.

For the 12 cm-depth models (Table 5), the results are somewhat different. Although some of the relationships are similar, (i.e. feather moss has good correspondence to non-sphagnum soil types (Table 5, lines 1–5)), many more of the testing models show non-significant coefficients. Comparisons of the 12-cm general organic soil model with some of the soil-specific 12-cm models had poor results (Table 5, lines 19–23). Thus, using the general calibration algorithm for 12-cm depth probing is not as robust as the 6-cm general equation. However, all of the soil-profile type-specific calibration algorithms for the 12-cm probing depth were significant and should be used when possible (Table 1).

In a comparison of the effect of probe depth on calibration equations, the analysis showed that 12 cm-depth equations are statistically similar to their 6-cm counterparts for the soil types of live feather moss (Table 4, line 9), recently burned or mineral

Table 4. CS620 HydroSense surface-down 6-cm probing depth comparison statistics of each soil-type-specific and general model as reference and all other models as testing data

Each reference model is listed in the first column and data formatted in bold are the comparison statistics of that model with itself, then all other significant ($P < 0.05$ and $R^2 > 0.40$) soil-type models are listed below that. Statistics include the R^2 and s.e. (% VMC). Also included are the statistics of each 6-cm model compared to each corresponding 12-cm model

	Reference model	Test model	R^2	s.e.
1	**Live feather moss**	**Live feather moss**	**0.95**	**4.00**
2		Recent burn or mineral soil	0.88	6.36
3		New regenerating moss	0.94	4.43
4		Middle regenerating moss	0.88	6.34
5		Old regenerating moss	0.93	4.90
6		Live sphagnum moss	0.72	9.69
7		Lightly burned moss	0.78	8.60
8		Burned aspen	0.57	12.07
9		12-cm live feather moss	0.94	4.95
10	**Recent burn or mineral soil**	**Recent burn or mineral soil**	**0.98**	**3.17**
11		Live feather moss	0.92	7.03
12		New regenerating moss	0.96	4.99
13		Middle regenerating moss	0.98	3.23
14		Live sphagnum moss	0.68	13.88
15		Lightly burned moss	0.77	11.70
16		Burned aspen	0.79	11.11
17		12-cm recent burn	0.97	4.46
18	**New regenerating moss**	**New regenerating moss**	**0.97**	**3.96**
19		Recent burn or mineral soil	0.98	3.41
20		Middle regenerating moss	0.98	3.42
21		Lightly burned moss	0.85	9.07
22		Burned aspen	0.80	10.62
23	**Middle regenerating moss**	**Middle regenerating moss**	**0.90**	**5.09**
24		Recent burn or mineral	0.90	5.20
25		New regenerating moss	0.91	4.93
26		Live sphagnum moss	0.79	7.60
27		Lightly burned moss	0.84	6.65
28		Burned aspen	0.64	9.86
29		12 cm mid regen	0.82	8.75
30	**Old regenerating moss**	**Old regenerating moss**	**0.98**	**2.62**
31		Live feather moss	0.96	3.70
32		Recent burn or mineral	0.92	5.21
33		New regenerating moss	0.97	3.03
34		Middle regenerating moss	0.92	5.20
35		Live sphagnum moss	0.82	7.89
36		Lightly burned moss	0.88	6.43
37		Burned aspen	0.47	13.67
38	**Live sphagnum moss**	**Live sphagnum moss**	**0.94**	**3.38**
39		Lightly burned moss	0.92	3.88
40	**Lightly burned moss**	**Lightly burned moss**	**0.86**	**4.80**
41		Live sphagnum moss	0.84	5.08
42	**Burned aspen**	**Burned aspen**	**0.99**	**3.11**
43	**General 6 cm**	**General 6 cm**	**0.94**	**5.00**
44		Live feather moss	0.91	5.47
45		Recent burn or mineral	0.98	3.64
46		New regenerating moss	0.98	3.33
47		Middle regenerating moss	0.92	4.73
48		Old regenerating moss	0.96	3.73
49		General 12 cm	0.92	5.95

soil (Table 4, line 17), mid-regenerating moss (Table 4, line 29), as well as for the general calibration equation (Table 4, line 49). Note that there were insufficient samples to compare 6- and 12-cm depth probing for live sphagnum, lightly burned moss and burned aspen soil-profile types. In a comparison of 6-cm equations with 12 cm-depth equations as reference, the general equation (Table 5, line 23), recently burned or mineral soil (Table 5, line 7) and old regenerating moss (Table 5, line 18) soil types had significant coefficients, with high R^2 and low s.e. Therefore, 6- and 12-cm probe depth models are essentially

Table 5. CS620 HydroSense surface-down 12-cm probing depth comparison statistics of each soil-type-specific and general model as reference and all other models as testing data

Each reference model is listed in the first column and data formatted in bold are the comparison statistics of that model with itself, then all other significant ($P < 0.05$ and $R^2 > 0.40$) soil-type models are listed below that. Statistics include the R^2 and s.e. (% VMC). Also included are the statistics of each 12-cm model compared to each corresponding 6-cm model

	Reference model	Test model	R^2	s.e.
1	**Live feather moss**	**Live feather moss**	**0.96**	**3.97**
2		Recent burn or mineral	0.77	9.88
3		New regenerating moss	0.93	5.23
4		Middle regenerating moss	0.95	4.50
5		Old regenerating moss	0.91	6.13
6	**Recent burn or mineral**	**Recent burn or mineral**	**0.97**	**4.22**
7		6-cm recent burn	0.98	3.51
8	**New regenerating moss**	**New regenerating moss**	**0.98**	**2.71**
9		Middle regenerating moss	0.97	2.94
10	**Middle regenerating moss**	**Middle regenerating moss**	**0.97**	**3.30**
11		Recent burn or mineral	0.78	9.75
12		New regenerating moss	0.97	3.68
13		Old regenerating moss	0.95	4.47
14	**Old regenerating moss**	**Old regenerating moss**	**0.97**	**3.09**
15		Recent burn or mineral	0.83	7.33
16		New regenerating moss	0.92	4.97
17		Middle regenerating moss	0.94	4.43
18		6-cm old regen	0.97	3.23
19	**General 12 cm**	**General 12 cm**	**0.93**	**5.49**
20		Live feather moss	0.93	5.38
21		Middle regenerating moss	0.95	4.52
22		Old regenerating moss	0.96	3.33
23		General 6 cm	0.91	6.46

Table 6. Horizontal-sampling CS616 and CS625 comparison statistics of each soil-horizon-specific and general organic soil model as reference and all other models as testing data

Each reference model is listed in the first column and data formatted in bold are the comparison statistics of that model with itself, then all other significant ($P < 0.05$ and $R^2 > 0.40$) soil-horizon models are listed below that. Statistics include the R^2 and s.e. (% VMC)

	Reference model	Test model	R^2	s.e.
1	**Live moss**	**Live moss**	**0.97**	**0.92**
2		Dead moss	0.42	13.5
3		Burned moss	0.88	2.40
4	**Burned moss**	**Burned moss**	**0.93**	**1.81**
5		Live moss	0.92	1.53
6	**Dead moss**	**Dead moss**	**0.88**	**6.22**
7		Burned moss	0.79	3.21
8		Live moss	0.76	2.59
9		Lower duff	0.88	7.65
10		Mineral soil	0.94	6.04
11		Upper duff	0.72	7.78
12	**Upper duff**	**Upper duff**	**0.85**	**5.81**
13		Dead moss	0.82	7.64
14		Lower duff	0.81	9.74
15	**Lower duff**	**Lower duff**	**0.89**	**7.33**
16		Dead moss	0.87	6.51
17		Mineral soil	0.91	7.33
18		Upper duff	0.75	7.46
19	**Mineral soil**	**Mineral soil**	**0.97**	**4.31**
20		Burned moss	0.51	4.87
21		Dead moss	0.85	6.94
22		Lower duff	0.83	9.08
23		Upper duff	0.69	8.23
24	**General**	**General**	**0.88**	**6.65**
25		Lower Duff	0.89	7.47

Table 7. Horizontal-sampling CS615 comparison statistics of each soil-type-specific and general model as reference and all other models as testing data

Each reference model is listed in the first column and data formatted in bold are the comparison statistics of that model with itself, then all other significant ($P < 0.05$ and $R^2 > 0.40$) soil-type models are listed below. Statistics include the R^2 and s.e. (% VMC)

	Reference model	Test model	R^2	s.e.
1	**Dead moss**	**Dead moss**	**0.91**	**6.15**
2		Mineral soil	0.84	12.33
3	**Upper duff**	**Upper duff**	**0.87**	**5.75**
4		Lower duff	0.70	11.93
5	**Lower duff**	**Lower duff**	**0.77**	**10.33**
6		Dead moss	0.77	10.02
7		Upper duff	0.75	7.89
8	**Mineral soil**	**Mineral soil**	**0.99**	**3.26**
9	**General**	**General**	**0.78**	**9.06**
10		Lower duff	0.77	10.48
11		Upper duff	0.80	7.07

equal for the recently burned or mineral soil. This is also true for the 6- and 12-cm depth models for older regenerating moss, and separate depth models are not needed. However, all other model comparisons show one or more non-significant coefficients or low R^2 for either the comparison of 6-cm data with the 12-cm reference model or vice versa.

Horizontal sampling (CS616 and CS625) comparison of algorithms

Table 6 presents the comparison of calibration models per soil horizon for the horizontally inserted CS616/625 probes. A comparison of upper and lower duff as reference and test models show that all coefficients are significant but the R^2 varies (0.75 to 0.89) as do the s.e. values (5.81 to 9.74% VMC, Table 6, lines 12, 14, 15 and 18). The plot of Fig. 4*a* shows these data as comparable, having a similar spread. Using the general organic soil algorithm as a reference model, it was statistically most comparable with the lower duff data, with significant coefficients $R^2 = 0.89$ and s.e. $= 7.47$% VMC (Table 6, line 25).

All three moss layers (burned, dead, live) had simple linear regressions as the best model, and burned moss and live moss had the most statistically similar models of these three (Table 6, lines 1–5) and can therefore be combined. In a comparison of burned and live moss with dead moss as reference, the variation explained is lower (0.79, 0.76 respectively, Table 6, lines 7 and 8) and the dead moss shows a larger range in VMC values and a greater spread in the data (Fig. 4*a*). Thus, it is better to keep the dead moss equation separate from live and burned moss.

Surprisingly, mineral soil and dead moss algorithms seem to be able to explain the data of each other, even though mineral soil had an exponential equation and the dead moss equation was simple linear. The data in Fig. 4*a* show that the mineral soil data have a distinct exponential form with less spread than dead moss data. This plot comparison illustrates the need for caution in analysing the statistics, particularly when the fitted curves vary in form (simple linear, quadratic, exponential) between two soil horizon types. In all cases, referencing the original data plots is very useful.

Comparison of algorithms (horizontal-sampling CS615)

The statistical comparison of all empirically developed calibration equations for the CS615 is presented in Table 7. The statistics tell us that the lower and upper duff models are similar enough to use interchangeably (Table 7, lines 4, 7) with all models showing significant coefficients, good R^2 (minimum 0.70) and acceptable s.e. values (0.7.07–11.93% VMC). The general model is useful for only the duff layers and has non-significant coefficients for dead moss and mineral soil (Table 7, lines 10–11).

The mineral soil horizon in comparison with dead moss as reference show comparable equations; however, the s.e. increases by almost a factor of four when using the dead-moss calibration for mineral soil, and the R^2 drops from 0.99 to 0.84 (Table 7, lines 2 and 8). The models should not be combined, as the data follow very different trends (Fig. 4*b*), with mineral soil having a very tight spread and quadratic fit and dead moss having higher VMC at the probe periods compared with mineral soil with a simple linear fit.

Discussion

In all of the calibration plots of probe period *v.* % VMC (Figs 3–4), it is noticeable that the default mineral calibration curves are at or near the lower bound of our sample points, demonstrating their lack of suitability for boreal organic soils. Kellner and Lundin (2001) also observed mineral soil calibrations for TDR probes to be at or below the lower bound of empirical data for peat (30–40-cm depth moss detritus) soils. Even our plot for the mineral soils evaluated in the present study (Fig. 4*a*, black squares) shows the data to deviate from the default CSI algorithm. These mineral soils were of fine texture with high bulk density, which could account for the differences between our measured data and the default CSI equation.

Results of the surface-down calibration algorithm comparisons (Table 4, lines 38–41) show that live sphagnum and lightly burned moss soil types are similar and equations are interchangeable. However, they differ from all other soil types. For feather moss, the comparisons with all non-sphagnum soil types was quite good (Table 4, lines 1–9 and Table 5, lines 1–5), though the general calibration shown in Fig. 3*a* does not appear to be a very good fit for live feather moss, because above 22% VMC, the samples fall well below this curve. This is true in Fig. 3*b* as well, for the 12-cm sampling depth. Therefore, it is not recommended to use the general organic soil algorithm for either live feather moss, live sphagnum, or lightly burned moss soil-profile types, as was predicted before the statistical analysis. For non-sphagnum soil types, the 6-cm general equation of Table 4 (lines 44–49) shows good fits, with high R^2 values and low standard errors for all soil types as well as for the 12-cm (non-live moss) general equation. Assessment of the data in Fig. 3*a* and *b* with Tables 4 and 5 shows that it better serves us to have three separate general calibration equations, one for live feather moss (Table 1, lines 1–2), one for live sphagnum or lightly burned moss (Table 1, line 12), and a third for all other organic soil-profile types (Table 1, line 14), although, when possible, the best algorithm to apply is the soil-profile-specific algorithm.

The surface-down algorithm comparison results indicate that the 6-cm HydroSense models have greater reliability than the 12 cm-depth models for surface-down sampling of surface soil moisture. As the 12-cm probe is likely crossing over multiple soil layers, more so than the 6-cm probe when sampling from the surface down, and because the 12-cm samples have greater variability in soil profile, this is not surprising. For most accurate results, shallower sampling of surface soil moisture is suggested when appropriate, especially for fire-disturbed soils.

Overall, the surface-down sampling plots for the HydroSense (Fig. 3) have a lower spread of data points than the horizon-specific sampling plots (Fig. 4). For the horizontal-insertion calibrations, there is much spread within the horizon-specific samples, especially for the lower duff horizons (Fig. 4). Kellner and Lundin (2001) also found a larger scatter in samples of more humified soil layers. The large spread in the empirical data for these horizons exhibits significantly different VMC values for the same probe output. It may be due to soil structural differences such as variability in the parent organic material comprising the duff layers. It is possible that there is simply a large range of densities among a specific soil-horizon type. In some cases, settling or compaction of some of the samples during shipping may affect the harvested sample's density in the laboratory, resulting in greater variability in probe measurements between harvested samples. Compression of the samples by repeated insertion of the probe in the laboratory and lack of good contact with the low-bulk-density material may also be a cause of error, as was also found in experimentation by Overduin *et al*. (2005) with feather moss. It is desirable to conduct further experimentation with the CS615 probes because our availability of samples was low (20–62, Table 3) and we would like to further investigate the large data spread within the duff and dead moss layers for both the CS615 and CS616 and CS625. Overduin *et al.* (2005) and Yoshikawa *et al*. (2004) have developed covers for the probes to improve contact with porous media. However, use of these covers would require new calibration algorithm development as it would alter the probe periods.

Despite the spread in our horizontal-insertion data, significant soil-horizon-specific algorithms were developed for each probe-type (Tables 2 and 3) with $R^2 > 0.85$, s.e. $< 7.4\%$ VMC for the CS616 and CS625 and $R^2 > 0.77$ and s.e. $< 10.4\%$ VMC for the CS615. Given the lack of suitability of the default mineral calibrations for these organic soils, and the fact that (to our knowledge) the only other published WCR probe-specific calibration is for live feather moss with the CS615 (Overduin *et al*. 2005), the algorithms presented in Tables 2 and 3 represent a good starting point with improved accuracy over the default equation. Although the soil-specific algorithms provide the best calibrations, the general equation was significant but comparable only with the duff layers.

Validation analysis of HydroSense calibration algorithms

A validation of the CS620 HydroSense probe algorithms (Fig. 5) was conducted using the *in situ* probe measurements and the circular harvested soil samples as described in the methods. This assessment allows the evaluation of the organic soil calibration algorithms for operational use.

The assessment showed overall good agreement between the CS620 algorithm-predicted and field-derived % VMC (Fig. 5). Most of the soil-profile types had six or more validation samples, with the exception of live sphagnum and burned aspen, which had only two each and are not presented. The plots of Fig. 5 show the algorithm-predicted soil moisture that is based on *in situ* probe period (*y* axis) *v.* the actual % VMC measured from harvested validation samples collected coincident with each *in situ* probe measurement (*x* axis). Fig. 5 shows 6- and 12-cm probe depth moisture plotted together, along with the number of validation samples for each soil-profile type (*n*) and the root mean square error (RMSE) in % VMC.

It is noticeable that the validation field samples are sometimes clustered at the lowest end of the probe periods. This is due to the dry conditions when many of the samples were harvested. Live feather moss shows good results, as do the new and middle regenerating moss types. The recently burned mineral soil and older regenerating moss types have better correspondence of 6-cm probe calibrations to field-measured moisture than for 12-cm calibrations, with the 12-cm calibrations overpredicting actual moisture in both instances. In a few cases, the predicted VMC falls below the one-to-one line with field-derived VMC; thus, soil moisture was greater than predicted by the laboratory-derived probe calibration. For the wetter *in situ* points, some of the soil water was lost at harvest.

Overall, the RMSE for all samples, except burned aspen, are less than 12.6% VMC, with a low RMSE of 3.9% VMC, and most between 5 and 6% VMC (Fig. 5). Some of the variability in the plots may be due to lack of temperature calibration as the probe periods here were measured *in situ* and the algorithms were developed in the laboratory with samples at room temperature. None of the field samples had ice content at the time of sampling.

Summary and conclusions

In the research presented here, we have established that commercial WCR probes can be calibrated to the low-bulk-density organic soils of moss- and non-moss-dominated ecosystems in boreal Alaska for retrieval of volumetric water content with improved accuracy over the default algorithms for both surface-down and horizontal probe sampling techniques.

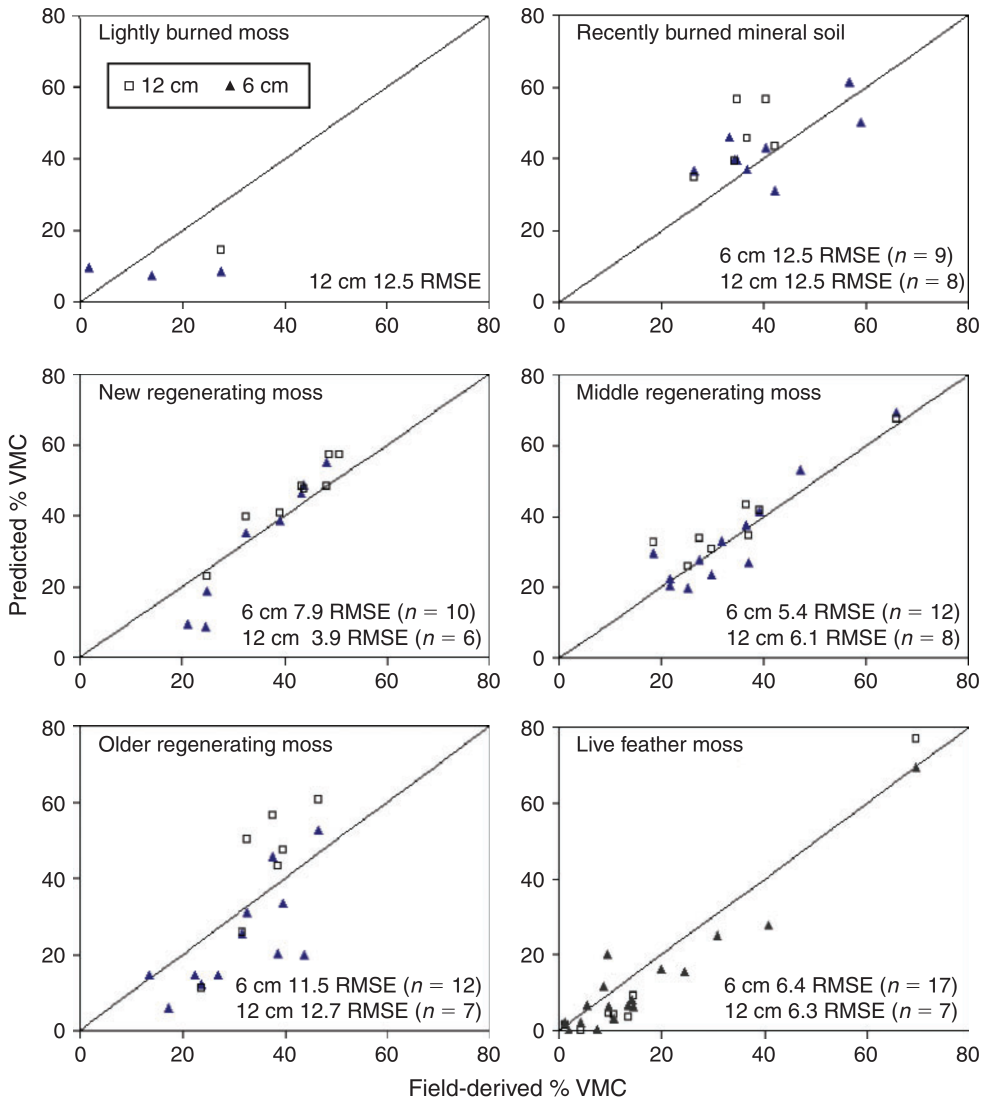

Fig. 5. Validation plots of surface-down 6- and 12-cm depth field-derived (gravimetric) volumetric soil moisture (VMC) (from small cylindrical samples) *v.* predicted soil moisture (from our laboratory-derived calibration algorithms) for lightly burned moss, recently burned mineral soil, new regenerating moss, middle regenerating moss, older regenerating moss and live feather moss soil-profile types. A one-to-one line running through zero is plotted to assist in the visual comparison of these plots. Listed on each plot are the root mean square error (RMSE) in % VMC and number of samples (*n*), for 6- and 12-cm depths.

For surface-down sampling of the HydroSense (CS620), we defined eight soil-profile types that are commonly found in Alaska and can be used by other researchers to relate to their own soil-profile types under investigation. When applying these algorithms to a new soil under investigation, it is recommended to use the soil type and probe-depth-specific algorithm presented in Table 1 whenever possible. If there is uncertainty in the particular soil-profile type, Tables 4 and 5 should be used to determine the error associated with applying the incorrect algorithm from a similar soil-profile type or from the general algorithm. The general organic soil algorithms developed for the CS620 (Table 1, lines 14–15) are fairly robust and can be used for all non-live-moss soil-profile types, whereas the algorithm for live feather moss (Table 1, lines 1–2) should be utilised for that soil type and the algorithm for live sphagnum may be used for itself and lightly burned moss (Table 1, line 12 or 13). In areas dominated by mineral soil, including severe-burn areas, the default calibration for mineral soil should be employed. However, note that fine-textured soils or soils of high electrical conductivity result in errors with the default CSI calibration. This is shown in the plots of Fig. 4 for the horizon-sampling CS616 and CS615 probes. Thus, even with mineral soils, validation samples are suggested to determine if a particular soil type fits the calibration being employed.

Although the 6- and 12-cm general organic soil models were determined comparable, we found sampling depth (6 *v.* 12 cm) to affect HydroSense probe calibration when using a specific soil-profile type calibration. Thus, it is important to match the correct probe calibration depth with *in situ* sampling depth. Further, a soil-specific calibration for a depth different from 6 or 12 cm would need a new calibration developed, or the 6-cm general algorithm can be employed, as it is fairly robust (Table 4, lines 44–49).

For the horizontal sampling probes (CS615, CS616 and CS625), soil-horizon-specific calibration algorithms were developed with strong statistics (Tables 2–3). The general organic soil algorithms developed for these probes were significant only for duff, and non-significant for other soil horizons (Table 6, line 25; Table 7, lines 10–11). Thus, the horizon-specific algorithms should be used whenever possible (Tables 2 and 3). It is evident from Fig. 4 that the general organic soil algorithm is much better than the default mineral-soil calibration algorithm for predicting soil moisture within any organic soil horizon. In soils of high organic soil content, using the default CSI mineral-soil calibration can lead to errors in excess of 20% VMC. In the absence of a known profile, the more generalised calibration equations developed for organic soils may be utilised, but care should be taken. Refer to Tables 4–7 for comparisons of equations and to determine the error associated with using a specific equation for the wrong soil type or horizon. Note that the role of temperature has been established for WCR measurements in general, and it is suggested that soil temperature be measured in unison with moisture probing in the field to allow for correction.

Finally, it is recommended that some samples from a new site be collected for validation of the calibration algorithm chosen, whether soil-specific or the default mineral algorithms. The method described here for harvesting point-validation samples coincident with an *in situ* probe measurement is a quick way to get a validation check of the algorithm chosen for specific sites being monitored.

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