Improving water content description of ice-rich permafrost soils

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ABSTRACT
The standard expression for soil gravimetric water content is on a dry basis (mass of water per unit mass of dry soil). In ice-rich soil, this method may produce extremely high values that are difficult to interpret. Alternatively, the wet-basis gravimetric water content (mass of water per unit mass of field-moist soil) may be used. Until now, this method has not been evaluated for use with ice-rich soils. We compare dry- and wet-basis gravimetric water contents, and find wet-basis to be a reliable and readily interpretable alternative to dry-basis for ice-rich mineral soils. However, it offers no clear advantage in organic soils or unfrozen mineral soils.

RÉSUMÉ
La teneur en eau des sols est habituellement rapportée de façon pondérale sur base sèche (quotient entre la masse d'eau et la masse de sol sec). Pour un sol riche en glace, cette méthode peut produire des valeurs extrêmement élevées qui sont difficiles à interpréter. Une autre façon de rapporter la teneur en eau pondérale est sur base humide (quotient entre la masse d'eau et la masse de sol humide tel qu'échantillonné). Jusqu'à maintenant, cette méthode n'avait pas été évaluée pour une utilisation avec des sols riches en glace. Nous avons comparé les teneurs en eau pondérales sur base sèche à celle sur base humide et avons conclu qu'une teneur pondérale sur base humide peut être une solution fiable et facile à interpréter pour les sols minéraux riches en glace. Toutefois, cette méthode ne présente aucun avantage clair pour les sols organiques ou les sols minéraux non gelés.

1 INTRODUCTION

Gravimetric water content determined on a dry-weight basis (W_d) is a standard and widely used expression for water content of soils (Reynolds and Topp 2008; Topp et al. 2008; ASTM D2216 2010). W_d values may be extremely high in ice-rich soils making interpretation and graphical representation difficult (e.g., Williams 1968; Mackay 1971; Kokelj and Burn 2003, 2005; Morse et al. 2009; O'Neill and Burn 2012). The scale required to display high W_d often masks important variation in W_d at lower values (e.g., Williams 1968, Fig. 2; Morse et al. 2009, Fig. 6; O'Neill and Burn 2012, Fig. 6). As a result, a logarithmic scale or broken axis is sometimes used. Volumetric water content (W_v) is restricted to values < 1 $cm^3\ cm^{-3}$ (Reynolds and Topp 2008), and is not subject to the same difficulties of interpretation and graphical representation as W_d. However, W_v requires the undisturbed volume of soil samples to be determined, which may be difficult in ice-rich soils, when it is not possible to obtain large intact samples, or time-consuming when many samples are required (e.g., Morse et al. 2009; Kanevskiy et al. 2014). We propose that gravimetric water content expressed on a wet-basis (W_w) may be a useful alternative to W_d in ice-rich soil. The purpose of this paper is to evaluate the potential of W_w as an alternative to W_d for permafrost-affected soils. We present an illustrative dataset to compare water contents expressed as W_w, W_d, and W_v.

2 BACKGROUND

2.1 Dry-basis gravimetric water content in ice-rich soils

The most commonly reported measure of water content in ice-rich soils is W_d, the mass of water per unit mass of oven-dried soil (Reynolds and Topp 2008):

$$W_d = m_w / m_{ds}, \quad [1]$$

where m_w is the mass of water (g) and m_{ds} is the mass of oven-dried soil (g). In unfrozen soils, water contents are constrained by available pore space. As W_d in these soils is typically less than 1 g g^{-1}, this is also commonly expressed as percent water content (Scott 2000). However, in soils containing excess ice, more water is present than in the saturated pore space of the thawed soil (French 2007), so any increase in water content must result in a reduced volumetric proportion of soil solids, and both m_w and m_{ds} change with the water content, i.e., as m_w increases, m_{ds} decreases. High values (> 3 g g^{-1}) are common in the literature (e.g., Mackay 1971; Kokelj and Burn 2003, 2005), and extremely high values (> 100 g g^{-1}) have also been reported (e.g., Morse et al. 2009; O'Neill and Burn 2012).

2.2 Volumetric water content in ice-rich soils

Another standard expression for water content is the volumetric water content (W_v), the volume of water per unit volume of undisturbed soil (Reynolds and Topp 2008):

$$W_v = m_w / V_t \rho_w \qquad [2]$$

for liquid water or:

$$W_v = m_w / V_t \rho_i, \qquad [3]$$

for ice, where V_t is the total sample volume (cm^3), ρ_w is the density of water (1.0 g cm^{-3}), and ρ_i is the density of ice (0.91 g cm^{-3}). W_v is a measure of the volumetric proportion of soil that is water or ice, and as such cannot be greater than 1 cm^3 cm^{-3}), eliminating the possibility of extremely high values that may make the use of W_d problematic. W_v then enables simpler interpretation and graphical representation.

In unfrozen soils, W_v may be determined by several well-established indirect methods, but these methods either do not perform well or are impractical in frozen soils. Time domain-reflectometry and ground-penetrating radar assess the dielectric permittivity of the soil, whereas capacitance and impedance methods assess the soil's function as a capacitor or resistor in an electrical circuit, respectively. These electromagnetic properties usually differ by more than an order of magnitude between liquid water and air or soil solids, and are used to infer W_v on this basis (Reynolds and Topp 2008; Topp et al. 2008). However, because these electromagnetic properties are not sufficiently dissimilar between ice and air or soil solids, commercially available methods based on electromagnetic properties cannot determine ice content in frozen soils (Patterson and Smith 1981). Neutron scattering detects the hydrogen concentration of the soil and relates it to the volumetric water content (Reynolds and Topp 2008). This method can discriminate ice (e.g., Williat 1979), but requires site-specific calibration, expensive equipment, and special training and licensing to work with the necessary radioactive materials.

By far the most common direct method to determine W_v is the thermogravimetric method (Reynolds and Topp 2008). In this method the weight of a sample of known undisturbed volume is measured before and after oven-drying. The mass of water is then related to the volumetric water content through its density, as in Eqs. 2 and 3. This method is possible in ice-rich soils, but it may be difficult to determine the volume of extracted permafrost samples in a field setting (Figure 1a). Furthermore, the thermogravimetric method requires destructive sampling of large samples which may preclude the use of samples for other analyses.

New methods of determining W_v specifically tailored to ice-rich soils have recently been developed. For example, computerized tomography (CT) scanning (Calmels and Allard 2008) employs medical equipment and software to determine W_v while leaving the extracted permafrost cores available for other analyses. However, this method requires expensive, specialized equipment and the cores must stay frozen during transport to a lab for imaging. Photogrammetric methods for determination of extra-pore ice volume have also been applied in conjunction with

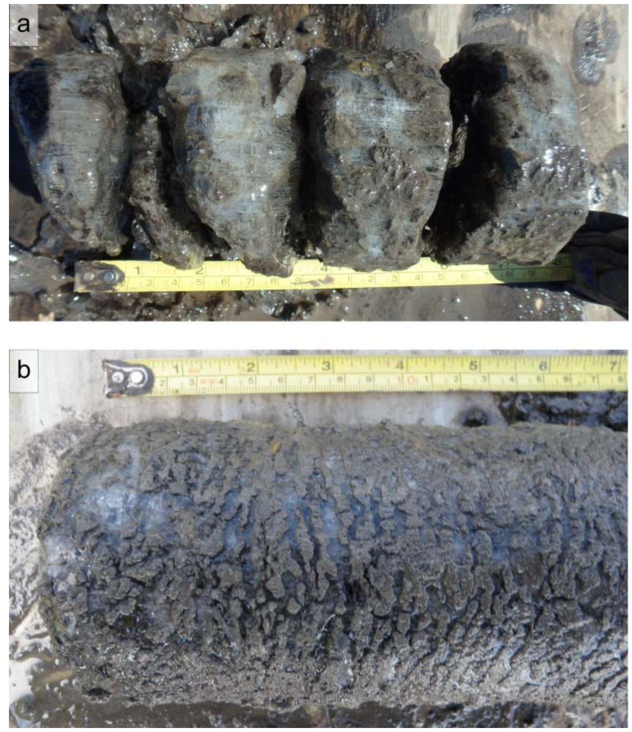

Figure 1. Examples of cores extracted from ice-rich permafrost: (a) a core that broke apart during extraction such that volume determination is difficult, and (b) an intact core.

thermogravimetric methods to produce W_v estimates (Kanevskiy et al. 2013, 2014). This requires photographs of intact cores or exposures (Figure 1b), which are often difficult to obtain for ice-rich soil. Furthermore, this method relies on estimates of the specific gravity of soil solids, which can have a considerable range of values in soils with significant amounts of organic matter (Hao et al. 2008).

2.3 Wet-basis gravimetric water content

Current methods used to determine and express water content in ice-rich soils have significant limitations for routine, inexpensive use in field studies. Wet-basis gravimetric water content (W_w) may be a useful alternative to W_d and W_v in ice-rich soils, but its performance has not been evaluated.

W_w is an adaptation of the standard expression for W_d (Eq. 1) where the mass of the field-moist soil is used in place of the dry soil:

$$W_w = m_w / (m_{ds} + m_w) = m_w / m_{ws}, \qquad [4]$$

where m_{ws} is the mass of field-moist soil (g). Similar to W_d (Eq. 1), for soils with excess ice, a change in m_w will lead to a change in m_{ws}. However, unlike the expression for W_d, these two variables converge at high water contents. For this reason, an incremental change in water content in a soil containing excess ice will produce a smaller change in W_w than in W_d. Moreover, as $m_w > m_{ws}$ is not possible, W_w is restricted to values between 0 and 1 g g^{1}, which

Table 1. The number of samples included for gravimetric water content determination, with the number of samples used for both gravimetric and volumetric water content determination (i.e., samples with known undisturbed volume) shown in parentheses. Note than 166 additional samples from the Yellowknife region were included for gravimetric water content determination, but data on the organic or mineral nature of the samples were not available.

Site	n				Reference
	Active Layer		Permafrost		
	Mineral	Organic	Mineral	Organic	
Mackenzie Delta (Forested)	133 (88)	4 (3)	79 (30)	0	This paper
Mackenzie Delta (Tundra)	100 (0)	34 (4)	423 (18)	10 (0)	Morse et al. 2009; this paper
Mackenzie Delta Region Uplands (Forested)	29 (29)	15 (13)	66 (38)	1 (1)	This paper
Mackenzie Delta Region Uplands (Tundra)	64 (58)	37 (40)	72 (34)	18 (18)	This paper
Peel Plateau	31 (31)	11 (11)	0	0	O'Neill et al 2015; this paper
Yellowknife Region	61 (0)	252 (0)	39 (0)	58 (0)	Wolfe et al. 2011; Gaanderse 2015
Mayo Region	0	0	0	103 (0)	Shugar 2003
Totals	418 (206)	353 (71)	679 (120)	190 (19)	
	1806 (416)				

may simplify the interpretation and graphical representation of W_w for ice-rich soils in comparison with W_d.

Whereas W_d is a standard and widely used expression, it may be readily transformed to W_w for analytical purposes. W_d is related to W_w as follows:

$$W_d = W_w/(1 - W_w) \ . \qquad [5]$$

and similarly, W_w is related to W_d accordingly:

$$W_w = W_d/(1 + W_d) \ . \qquad [6]$$

We suggest that W_w is a useful expression to employ in ice-rich soils in place of W_d in cases where it is not practical to determine W_v. To explore this suggestion, we examined water contents from a large database (n = 1806) of water contents from permafrost-affected soils. The database included 416 samples with measured undisturbed volume. We examined the water contents determined by W_d, W_w, and W_v for ease of interpretation and representation. We also compared W_d and W_w to W_v, which we accept as a relatively easy-to-interpret measure because it is an expression of the water content not altered by the bulk density of the soil solids (see Eqs. 1–4). For this reason, nonlinear relations between W_d or W_w and W_v are less desirable than linear relations as an easily interpretable measure of water content.

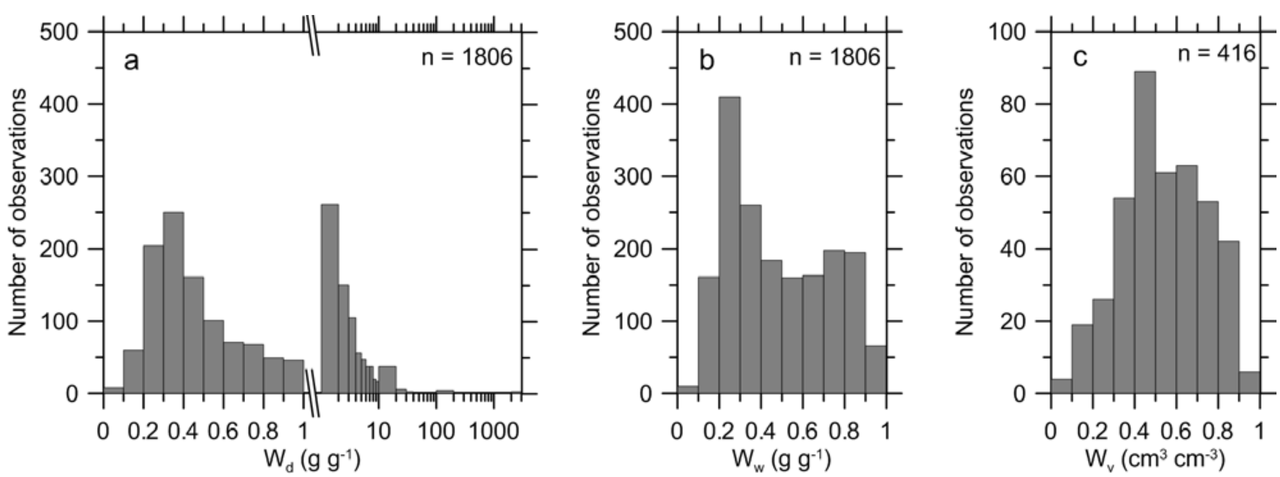

Figure 2. Histograms showing the distribution of water contents expressed as (a) dry-basis gravimetric water content (W_d, n = 1806), (b) wet-basis gravimetric water content (W_w, n = 1806), and (c) volumetric water content (W_v, n = 416). Note that W_w, W_v, and W_d < 1 g g^{-1} are shown on the same linear x-axis scale, while W_d > 1 g g^{-1} are shown on a logarithmic scale.

3 DATA COLLECTION

Table 1 indicates the distribution of samples from the various sites included in the database. Samples were collected from three profiles in the forested portion of the Mackenzie River delta near Inuvik, NT (68.3°N, 133.8°W), and riverbank exposures were sampled at six other locations in the upper Mackenzie Delta south of treeline (Kokelj and Burn 2005). Additionally, 33 profiles were examined in the lower Mackenzie Delta north of treeline, predominantly from within and near the Kendall Island Bird Sanctuary (69.3°N, 135.0°W; Morse et al. 2009). The uplands adjacent to the Mackenzie Delta were also sampled, including six profiles south of treeline near Inuvik (68.4°N, 133.7°W) and 12 profiles north of treeline at Illisarvik, Richards Island, NT (69.5°N, 134.6°W) and Garry Island, NT (69.5°N, 135.7°W; Mackay 1992; Kokelj and Burn 2003; O'Neill and Burn 2012). Samples were collected from 30 locations near the Dempster Highway in the Peel Plateau west of Fort McPherson, NT (67.2°N, 135.6°W), 19 profiles near Yellowknife, NT (62.5°N, 114.1°W), and 7 profiles in a peatland near Mayo, YK (63.8°N, 135.2°W) (Burn 1991; Wolfe et al. 2011; Gaanderse 2015; O'Neill et al. 2015). Most profiles were sampled to a depth of 1–3 m from the soil surface, except on the Peel Plateau, where only the active layer was sampled, and at eight profiles from the Yellowknife region which extended beyond 3 m to a maximum of 7.25 m. Taken together, these locations include a considerable variation in site conditions, including peatlands, glaciolacustrine deposits, till, and alluvium. The dataset includes samples from discontinuous and continuous permafrost zones, as well as forested and tundra biomes. W_v was determined for a subset of samples in the database (Table 1, n = 416).

4 METHODS

Samples from different sites were not always collected by the same individuals and slightly variable sampling protocols were applied. For unfrozen samples where a measured volume of soil was extracted, volume was determined by using either a cylinder (~115 cm^3) or cube (~215 cm^3) of known volume for mineral samples and some organic samples, or by directly measuring the size of an extracted parcel of soil for other organic samples. Frozen samples were collected using Cold Regions Research and Engineering Laboratory (CRREL) core barrels with inside diameters of either 5.1 or 7.6 cm.

For some frozen samples the volume was determined by direct measurement of core segments following extraction. Samples were judged to be either mineral (< 50% organic matter by mass) or organic (> 50% organic matter) based on a field assessment of colour, density, and tactile feel. Samples were bagged in the field to avoid water loss during handling and transport and then weighed to determine their field-moist weight. Mineral samples were dried at 105 °C for 24–72 hours. Some samples estimated to be rich in organic matter were dried at a lower temperature (60–80 °C). W_d, W_w, and W_v were determined according to equations 1–4.

Active-layer thickness was usually determined for each profile by probing during late summer. In cases where active-layer thickness from probing was not available, samples were assumed to be from the active layer if they were thawed or from the permafrost if they were frozen at the time of sampling, which was usually late summer.

5 RESULTS

The dataset includes samples for a wide range of volumetric water contents between a minimum of 0.04 cm^3 cm^{-3} and a maximum of 0.97 cm^3 cm^{-3}. The distributions of W_d, W_w, and W_v shown in Figure 2

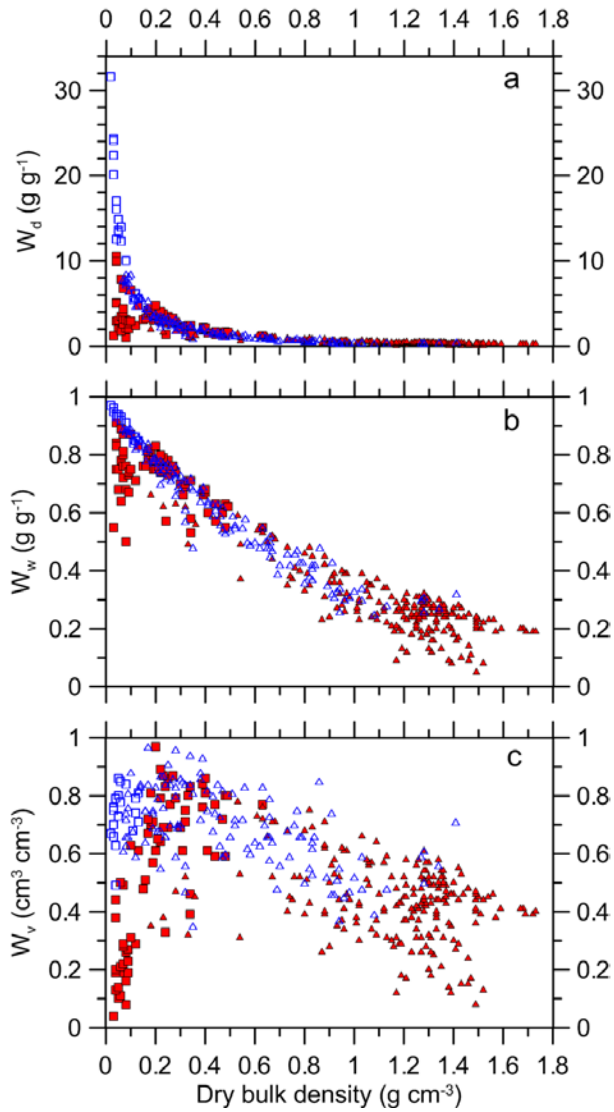

Figure 3. Scatterplots of water content measured as: (a) dry-basis gravimetric water content (W_d), (b) wet-basis gravimetric water content (W_w), and (c) volumetric water content (W_v) against dry bulk density. Triangles indicate mineral samples and squares indicate organic samples. Solid red markers denote active layer samples and open blue markers denote permafrost samples.

illustrate the difficulty involved in clearly representing W_d for ice-rich soils, as the unusual scale that must be employed to display the extreme positive skew of W_d without obscuring low W_d is difficult to interpret in comparison to that used for W_w and W_v. W_w and W_v are plotted on identical scales, as their maximum values are < 1 g g^{-1} and cm^3 cm^{-3}, respectively). There is a large proportion of high W_d, with 44% and 3% of W_d > 1 and > 10 g g^{-1}, respectively. W_d reaches extreme values, with three samples > 1000 g g^{-1}.

The dry bulk density of samples (n = 416) ranged from 0.02 to 1.73 g cm^{-3}, with mean and median densities of 0.76 and 0.80 g cm^{-3}, respectively (Figure 3). The distribution of dry bulk densities reflects the wide range of materials from very low density organic soil to dense mineral soil. The relation between W_d and dry bulk density is exponential when dry density is low, particularly for mineral permafrost samples and organic samples (Figure 3a). W_w also has a nonlinear relation with dry density, though to a much lesser degree than W_d (Figure 3b). When density is low (< 0.2 g cm^{-3}) even very dry samples (W_v < 0.2 g cm^{-3}) have relatively high W_d (> 1 g g^{-1}) and W_w (> 0.5 g g^{-1}), indicating that both W_d and W_w methods may be misleading for unsaturated, low-density soils.

Scatterplots of W_d and W_w against W_v are presented in Figure 4. The relation between W_d and W_v for mineral samples (Figure 4a) appears to be linear or nearly linear for all W_v below 0.6 cm^3 cm^{-3}. Above 0.6 cm^3 cm^{-3}, the relation becomes strongly nonlinear, though there is considerable spread in the data. The high values for W_d when W_v > 0.6 cm^3 cm^{-3} necessitate a large vertical scale. This makes it difficult to graphically evaluate W_d data for W_v < 0.6 cm^3 cm^{-3}; and an alternative scale for this relation is presented in Figure 5. The majority of W_d values for active layer samples appear to support a linear relation with W_v, whereas the majority of W_d values from permafrost samples do not.

Considerable scatter occurs in mineral W_w for W_v > 0.5 cm^3 cm^{-3} (Figure 4b), although less than in mineral W_d measurements (Figure 4a). For active layer mineral samples, most W_d values closely resemble a 1:1 relation with W_v (Figures 4a and 5), whereas W_w falls slightly farther from the 1:1 line with W_v (Figure 4b). For permafrost mineral samples W_w is closer to a 1:1 relation with W_v (Figure 4a) than is W_d (Figure 4b).

For active layer organic samples, the relations of both W_d and W_w with W_v appear to be linear but weak (Figures 4c and 4d). A considerable amount of the variation in W_d for active layer organic samples is likely more closely related to variation in dry soil mass than to W_v (c.f. Figures 3a and 3c). Linear relations between W_d and W_v for active layer organic samples are evident when narrow bulk density ranges are considered (data not shown), but they are not evident when the full range of samples is shown as in Figure 4c, indicating that comparisons using W_d in active layer organic soils are difficult unless bulk density is known. Because of the low dry bulk density of organic samples, m_{ws} is dominated by water and W_w is

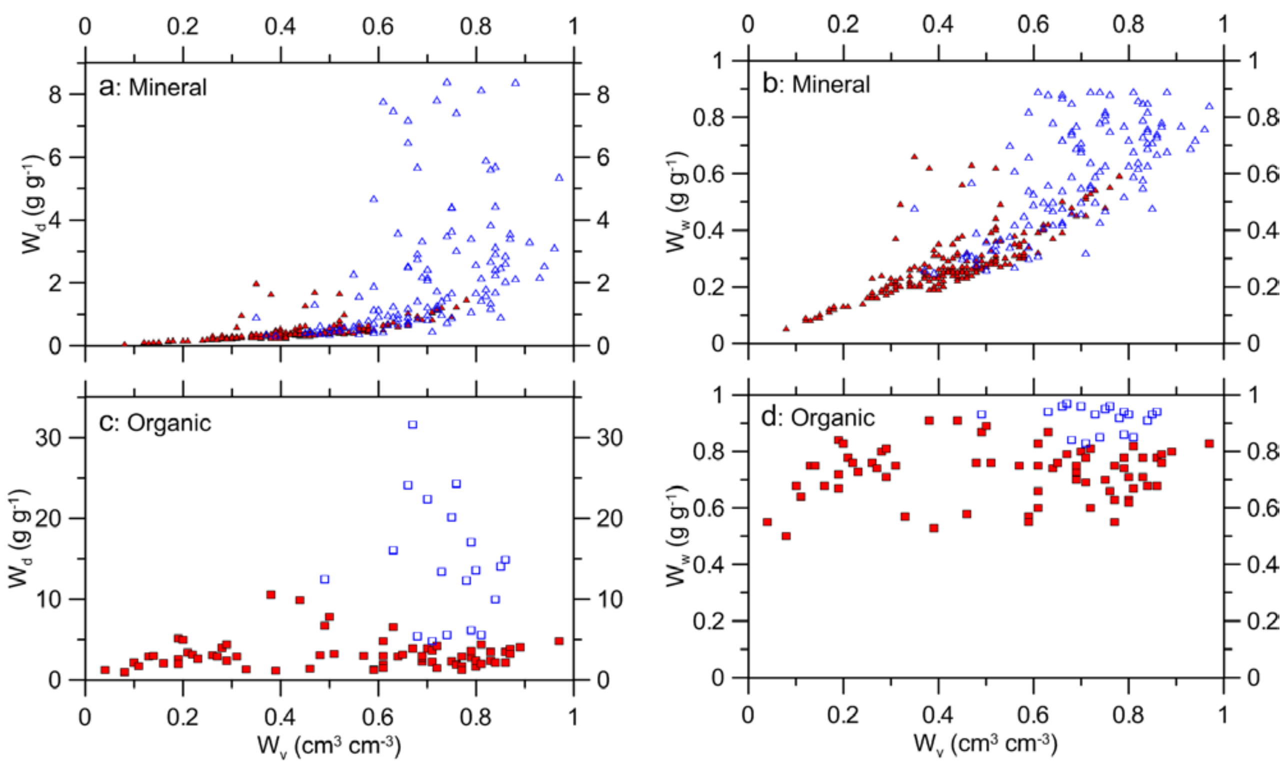

Figure 4. Scatterplots of the values of dry-basis gravimetric water content (W_d) in plots a and c and wet-basis gravimetric water content (W_w) in plots b and d for different values of volumetric water content (W_v). Plots a and b show water contents for mineral samples, while plots c and d show water contents for organic samples. For all plots, active layer

samples are depicted by solid red markers and permafrost samples are depicted by open blue markers. Note differences in vertical scale.

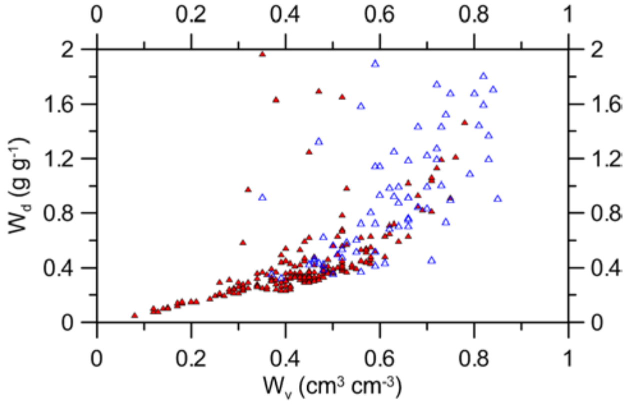

Figure 5. Scatterplot of dry-basis gravimetric water content (W_d) and volumetric water content (W_v). Active layer samples are shown as solid red triangles and permafrost samples are shown as open blue triangles. These are the same data depicted in Figure 4a, but only W_d values < 2 g g^{-1} are shown.

relatively high for all organic samples (Figure 4d), and no clear relation between W_w and W_v is apparent. When narrow dry bulk density ranges are considered relations are apparent, but are nonlinear (data not shown). There are too few samples in this database to reliably evaluate relations between W_d, W_w, and W_v in permafrost organic samples.

6 DISCUSSION

W_d is difficult to interpret in ice-rich soils. Values of W_d > 3 g g^{-1} are common in both the published literature (Mackay 1971; Kokelj and Burn 2003, 2005; Morse et al. 2009; O'Neill and Burn 2012) and in the dataset assembled for this paper. These high W_d values sometimes create difficulties in representation and interpretation of data (Figures 2a, 3a, 4a, and 4c). The extreme positive skew evident in W_d measurements from this database (Figure 2a) indicates that high W_d is common in ice-rich soils, and that there is a need for an easier way to express, display, and interpret gravimetric water content in ice-rich soils. W_w gives a distribution of values that is more interpretable (Figures 2b and 2c) with a lower degree of nonlinearity than W_d with respect to W_v (Figure 4) in ice-rich mineral soils.

W_w performs better than W_d as a metric of water content in ice-rich mineral soils, but not in organic soils and active layer mineral soils. For most active layer mineral soils W_d has a linear relation with W_v (Figure 5) that is closer to a 1:1 relation with W_v than is W_w (Figure 4b). Both W_d and W_w have poor relations with W_v in organic soils, much of which seems to be related to the variable dry bulk density in organic soils included in this database. This indicates that it is important to control for soil density when using gravimetric methods in organic soils, and W_v should be used whenever possible (Boelter 1968). As there is no apparent advantage to using W_w over W_d in organic soils (frozen or unfrozen) and W_d is the most widely used expression, there is no reason to recommend using W_w in these soil types unless it is necessary to maintain consistency with W_w used in the same analysis.

7 CONCLUSIONS

Based on analysis of the database in this paper, we recommend that W_w be used in ice-rich mineral soils where interpretation of water content is difficult because of high W_d values. This eliminates the problem of extremely sensitive, difficult to interpret water contents for ice-rich mineral soils. For consistency, W_w may be extended to the active layer mineral soils as well, because the difference between W_d and W_w for these soils is typically small.

At present, there is not enough information in this database to assess the performance of W_d and W_w as measures of water content in organic soils. However, expression of W_d in ice-rich organic soil presents similar difficulties to those encountered in ice-rich mineral soil, and further examination of this problem is warranted.

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