Are point measurements in a bog representative of their surrounding area?

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SUMMARY

Descriptions of abiotic properties in bogs are often based on point measurements. To assess whether these point measurements are representative of their surrounding area, depth to water table (DTW), soil moisture, pH, electrical conductivity (EC), the degree of peat humification and ash content were measured at 25 points in a 4 m × 4 m study site. The gravimetric moisture content of the peat samples varied little (coefficient of variation (CV): 2–4 %), while the volumetric moisture content (CV: 11 %) and DTW (CV: 48 %) were more variable. Pore water pH also varied little throughout the study site (CV: 1 %), but pore water EC was more variable (CV: 84 %). The degree of humification was generally within 1–2 points on the von Post scale. Ash content was fairly variable (CV: 61–100 %). Plant species composition varied across the study site in relation to microtopography and was, not surprisingly, most strongly influenced by DTW and near-surface soil moisture. Some point measurements in bogs (e.g. pH, gravimetric moisture content) are likely to be representative for an area of at least several square metres, while other variables (e.g. EC, volumetric moisture content, degree of humification, ash content) may need to be measured at more than one point to obtain a representative average.

KEY WORDS: measurement uncertainty, raised bog, small scale spatial variability

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INTRODUCTION

When studying bogs, it is common to assess the hydrochemistry, depth to water table, peat moisture content and ash content by taking point measurements along a transect at regular, random or ecologically-relevant intervals (e.g. Bubier 1991, Bragazza & Gerdol 1999, Langlois *et al*. 2015) or on a large (e.g. 10–20 m interval) sampling grid (e.g. Kellner & Halldin 2002, Tahvanainen & Tuomaala 2003, Lipatov *et al*. 2017). Due to financial and time constraints, replication is usually minimal and point measurements are assumed to be representative of the area surrounding the sampling site. However, peatland microtopography and varying peat properties affect hydrological properties (Van der Ploeg *et al.* 2012, Cunliffe *et al*. 2013, Graham *et al*. 2016) and can lead to biogeochemical hotspots and large differences in water chemistry (e.g. Frei *et al*. 2012) and microbial activity (Parvin *et al*. 2018). Hydrochemical characteristics of near-surface pore water can vary between hummocks and hollows due to differences in vegetation (specifically nutrient uptake by plants), redox reactions, biological activity (e.g. by microorganisms), rate of decomposition, cation and anion exchange, and vertical and horizontal variability in peat properties such as hydraulic conductivity and bulk density (Naucke *et al*. 1993, Schouwenaars & Vink 1992, Tahvanainen *et al*. 2002). Volumetric moisture content in peatlands is affected by differences in bulk density but also varies with microtopography, depth to water table and plant species composition (Schouwenaars & Gosen 2007). The degree of humification is closely related to the bulk density and saturated hydraulic conductivity of the peat (Lapen *et al*. 2005, Lewis *et al*. 2012, Rydin & Jeglum 2013) and, therefore, also varies spatially. Differences in peat composition (due to differences in plant species), accumulation and mineralisation can result in spatial differences in ash content (Lipatov *et al.* 2017).

Despite an appreciation of the existence of biogeochemical and hydrological hotspots and the inherent small-scale variation in peat properties, many studies in peatlands continue to rely on a single measurement to represent the surrounding area. In contrast, hillslope hydrological measurements have shown that groundwater responses can vary significantly over short distances (e.g. Tromp-van Meerveld & McDonnell 2006, Bachmair *et al*. 2012). Soil moisture measurements represent only a small area (~ 0.1–1 dm^3; Robinson *et al*. 2008) and, therefore, when the spatial variability of soil moisture in mineral soils is studied and manual measurements are taken with a soil moisture probe, often several measurements are taken around one location and

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averaged (e.g. Penna *et al*. 2013). Similarly, microtopography in peatlands can cause depth to water table and soil moisture measurements to vary substantially over a small area. Microtopographical variation is generally smaller for lawns and hollows than for hummocks (Almendiger *et al.* 1986) and, therefore, hollows may be the more suitable location for comparison of depth to water table measurements in bogs. Soil moisture measurements in bogs may be more representative of average conditions when measured in a variety of hummocks and hollows. It follows that replication may be required for studies of hydrological, hydrochemical and peat properties in peatlands and that it would be useful to know how much replication is required to obtain a representative sample (i.e. how spatially variable is the property across short distances?).

The objective of this study was to determine whether point measurements in a raised bog are representative of the general area around them and to determine which properties, if any, would require multiple measurements at a site to obtain a representative average value. Because depth to water table, peat and pore water chemistry, and peat properties in the rooting zone of peatlands can have a strong influence on plant communities, a related but secondary objective was to determine to what extent the spatial heterogeneity in plant species composition within a small area reflects the variability in abiotic factors. If the abiotic factors are spatially variable and reflect and cause small scale variation in plant species distribution, knowledge of the variability in vegetation could provide an indication of the degree of variation in abiotic factors and the potential representativeness of a point measurement.

METHODS

This study took place in the southwest corner of Burns Bog, a 3,000 ha raised bog located in Delta, British Columbia (BC), Canada (Figure 1). The *Sphagnum* peat soil in the study area would be classified as a Dystric Fibric Histosol in the

Figure 1. Photograph taken on 20 April 2012 of the 4 m × 4 m study site on Burns Bog located in Delta, British Columbia, Canada.

International Soil Classification System (FAO 2015) and was classified by AGRA Earth & Environmental Limited (1999) as a Typic Fibrisol using the Canadian System of Soil Classification (Agriculture and Agri-Food Canada 1998). The depth to water table measured in a shallow piezometer in the study site between 2010 and 2014 varied between 0 and 40 cm below the surface (unpublished data), which is within the normal range for an undisturbed bog (Wheeler *et al*. 1995, Price *et al*. 2003, Rydin & Jeglum 2013). The dominant plant species in the undisturbed area of Burns Bog include stunted *Pinus contorta* Douglas ex Louden var. *contorta*, *Rhododendron groenlandicum* (Oeder) K.A. Kron & W.S. Judd, *Cladina portentosa* subsp. *pacifica* (Dufour) Follmann, *Vaccinium uliginosum* L., *Andromeda polifolia* L., *Kalmia microphylla* var. *occidentalis* (Hook.) A. Heller (Small) Roy L. Taylor & MacBryde, *Rhynchospora alba* (L.) Vahl, and *Sphagnum* spp. (most commonly *Sphagnum capillifolium* (Ehrh.) Hedw. and *Sphagnum tenellum* (Brid.) Bory). This plant community, which is characteristic of the historical pre-disturbance conditions of Burns Bog, covers 26 % of the bog. The study site was chosen because it is located in this relatively undisturbed plant community. Much of the remainder of the bog is recovering from peat extraction that occurred in the 1930s–1980s, or has been disturbed by drainage ditches that are being blocked to restore the water table. There is one main hummock on the north side of the 4 m × 4 m study site, and several smaller hummocks near the edges (Figure 2a). There is a slight gradient in hummock height from the north side (somewhat hummocky) to the south side (less hummocky) of the study site.

Twenty-five piezometers were installed in the study site in a square grid at 1-metre intervals in April 2012 (Figure 1): 12 piezometers were located in hummocks and 13 in hollows. The piezometers were 1.5 m long, 2.5 cm diameter Schedule 40 polyvinyl chloride pipe with a 40 cm slotted segment at the bottom; the remainder of the pipe was unslotted. For all of the piezometers used in this study, the top of the slotted segment was located near but fully below the water table for the purpose of collecting sufficient water for water quality analysis. See 'Limitations of the study' in the Discussion for an explanation of why the water level in the shallow piezometers is considered to represent the water table, even though piezometers instead of wells (fully slotted pipes) were used in this study.

The piezometers were purged once on 20 Apr 2012 and twice on 04 May 2012. The water table at this time was still near the wet season high water mark. The spring of 2012 was slightly drier (136 mm precipitation from 01 Apr to 31 May) than the long-term (1981–2010) average (154 mm from 01 Apr to 31 May) (data from Vancouver International Airport located 15 km away; source: Environment and Climate Change Canada (2018)). There were scattered showers on 04 May (1.4 mm) but there was no additional precipitation between purging and the measurements in the following days. Depth to water table (DTW) was measured in the piezometers to the nearest 0.5 cm with an electronic water level probe (Heron Instruments Little Dipper, Dundas, Ontario, Canada) on 09 May 2012. On 11 May, a WTW Multiline P4 water quality meter (College Station, Texas, USA) with a TetraCon 925 sensor was used to measure the electrical conductivity (EC_{field}) (accuracy: 0.5 % of measured value) and a WTW Multi 3430 water quality meter (College Station, Texas, USA) with a Sentix 41 sensor was used to measure pH (accuracy: 0.005 pH). The probes were inserted directly into the piezometers; pH and EC measurements were taken in the top 10–15 cm of the water column. The probes were calibrated prior to use and were rinsed with distilled water prior to insertion into the piezometers and after each measurement. Pore water EC was corrected for pH (EC_{corr}) using the following formula: $EC_{corr} = EC_{field} - EC_{H^+}$, where $EC_{H^+} = 3.49 \times 10^5 \times 10^{-pH}$, and 3.49×10^5 is the conversion factor for field measurements standardised to 25 °C by a handheld meter (Rydin & Jeglum 2013). Volumetric moisture content (VMC, $cm^3\ cm^{-3}$) was measured 5 cm east of each piezometer with a Moisture Point 917 single diode 30 cm TDR probe (Sidney, BC, Canada; accuracy 1 %) on 11 May 2012. The Moisture Point probe measurements were adjusted using the linear calibration equation ($r^2 = 0.97$) of Cheng (2011) for a large peat core from Burns Bog.

The surface microtopography in the site and the locations of the piezometers were surveyed in September 2012 with a Leica GS12 Netrover antenna and Leica C515 controller GPS unit with survey-grade accuracy (104 survey points). For greater precision, hummock height above the nearest hollow was also measured at each piezometer with a measuring tape; the boundary between hummocks and hollows was determined visually. Trampling of hummocks was minimised by walking only in the hollows on a folded tarpaulin.

Peat cores were collected at each piezometer location to determine von Post humification in the field. The von Post scale of humification rates the degree of decomposition of peat on a scale H1–H10, where H1 is the living layer of plant matter and H10 is completely decomposed peat (Rydin & Jeglum 2013). H1–H4 is generally considered to be fibric, i.e.

weakly decomposed with plant origin identifiable, H5–H6 is mesic, i.e. moderately decomposed with some plants identifiable, and H7–H10 is humic, i.e. strongly decomposed with plant remnants being unidentifiable (Agriculture and Agri-Food Canada 1998, Rydin & Jeglum 2013). The accuracy of the method is generally considered to be ±1 point on the von Post scale (personal communication with Dr

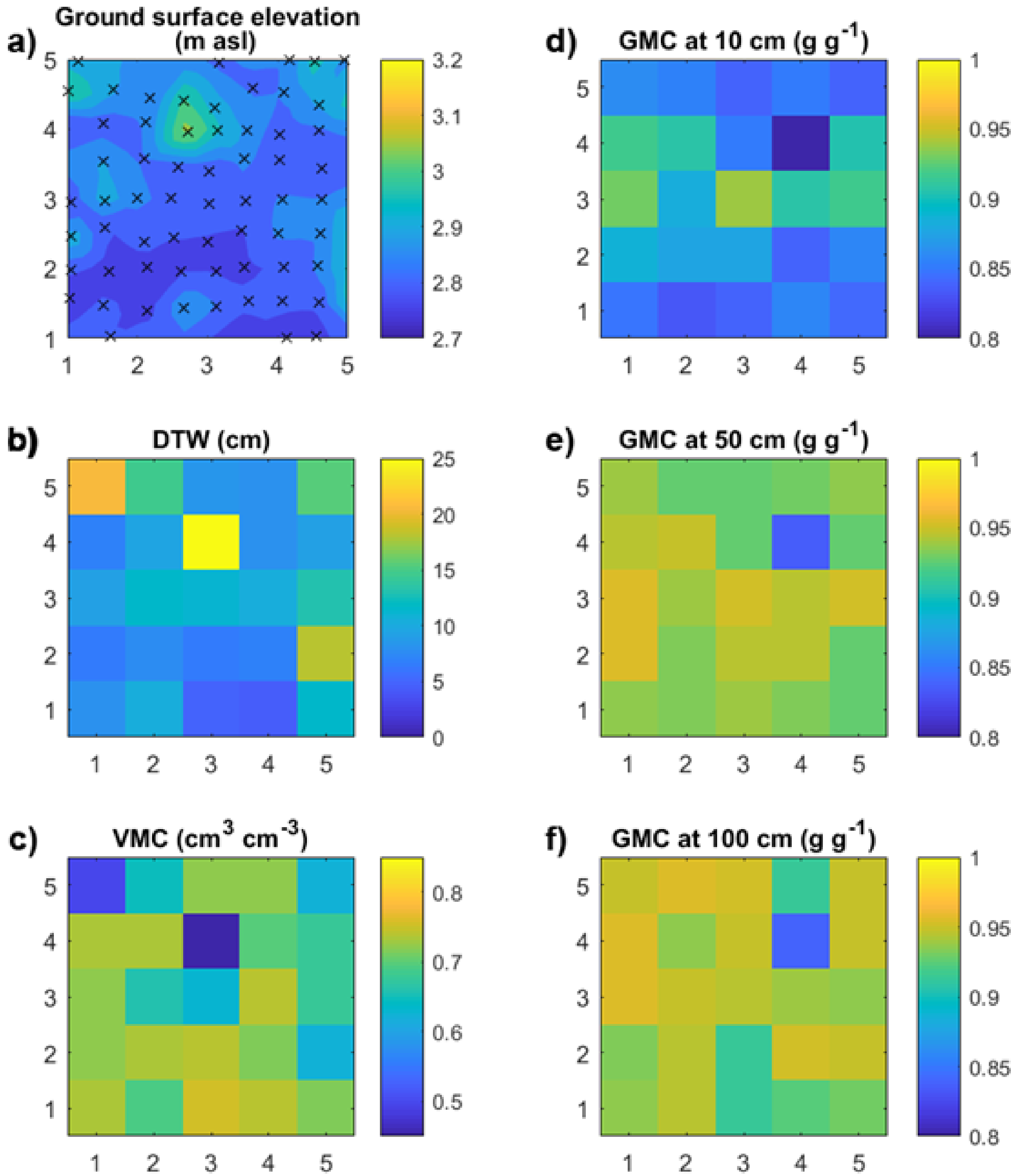

Figure 2: Spatial distribution of a) surface elevation in metres above sea level (crosses represent the survey points), b) depth to water table, c) volumetric moisture content (VMC) at 0–30 cm, and gravimetric moisture content (GMC) at d) 10 cm, e) 50 cm, and f) 100 cm depth. X and Y axes show distances in metres; location 1, 1 represents the southwest corner of the study site.

John Jeglum, Emeritus Professor in Forest Peatland Science, Swedish University of Agricultural Sciences, Umeå and Dr Håkan Rydin, Professor in Plant Ecology, Uppsala University, Sweden). Peat samples were collected from the cores at 10, 50, and 100 cm below the surface, enclosed in plastic wrap, sealed in plastic bags, and frozen until analysis. In the laboratory, the 5 cm long peat samples were weighed, dried at 105 °C for 24 hours and re-weighed to determine the gravimetric moisture content (GMC, g g^{-1}), then placed in a furnace at 550 °C for 24 hours and re-weighed to determine loss on ignition (ash content) (c.f. Dean 1974).

The vegetation around each piezometer was photographed from above in April and September 2012, with each photo covering an area of approximately 0.8 m × 1.0 m. Based on these photographs, percent cover was estimated to the nearest 5 % for each of the eight dominant plant species: *Pinus contorta* var. *contorta*, *Rhododendron groenlandicum*, *Cladina portentosa* subsp. *pacifica*, *Vaccinium uliginosum*, *Andromeda polifolia*, *Kalmia microphylla* var. *occidentalis*, *Rhynchospora alba*, and *Sphagnum* spp. The averages of the cover values for the September and April photographs were used in the analyses, except for the herbaceous (*Rhynchospora*) and deciduous (*Vaccinium*) species that may not have fully leafed out in April.

Spearman rank correlation (r_s) tests were used to assess the relationships between the abiotic variables and percent cover of the dominant plant species. Mann-Whitney U-tests were used to determine differences between hummocks and hollows for the abiotic variables and plant species cover; results are reported as significantly different for the abiotic variables only if the non-directional (‘two-tailed’) test was considered significant. A significance value of $p < 0.05$ was used for all analyses.

We determined the sample sizes required to obtain an average measured value within ± 5 and 10 % of the (true) mean with 95 % confidence for all variables except elevation and von Post humification, using the following formula:

$$m = \left(\frac{z_{\alpha/2}\sigma}{E}\right)^2 \qquad [1]$$

where m is the required sample size, $z_{\alpha/2}$ is the critical z value (z = 1.960 for the 95 % confidence interval used in this study), σ is the standard deviation, and E is the margin of error (i.e. 5 or 10 %). This formula gives the sample size for a normally distributed infinite population but, in reality, there are only a limited number of potential sampling sites within a small plot. Therefore, we applied the finite population correction to the calculated sample size:

$$n = \frac{m}{1+\frac{m-1}{N}} \qquad [2]$$

where n is the corrected sample size and N is the maximum sample size or finite population size. We assumed that the maximum (finite) sampling size was 1600 samples (i.e. each measurement requires a 10 cm × 10 cm area within the 4 m × 4 m plot), as it is impractical to install wells or take peat samples at shorter distances without one measurement influencing the other. In addition, we calculated the required sample size to obtain an average within a set limit from the (true) mean with 95 % confidence. The limits used were 2 cm for DTW, 0.02 cm^3 cm^{-3} for VMC, 0.02 g g^{-1} for GMC, 2 % for ash content, 0.05 for pH; and 5 µS cm^{-1} for EC_{field} and EC_{corr}. These limits were chosen based on field knowledge; using smaller limits, such as the accuracy of each measurement device, generally leads to unreasonably large sample sizes. Required sample sizes were calculated for the entire site, for hummocks only and for hollows only.

Because the sample size calculations (Equations 1 and 2) assume that the data are normally distributed, we tested the normality of the data using the Kolmogorov-Smirnov normality test. Even though not all data were normally distributed (particularly DTW, VMC and pH for the entire dataset; see p-values in Table 1), we still used the same sample size calculation for all variables for comparability of the results. The log of DTW for the entire site was normally distributed, so we also calculated sample size with the log-transformed DTW values; we used the average difference of the log of the mean DTW ± 2 cm (= 0.08 cm) for the set limit. None of the standard transformations resulted in a normal distribution of the data for VMC, GMC50, GMC100 and pH. Thus, the calculated sample sizes for these variables need to be interpreted with care.

RESULTS

Spatial variation across the study site

Topography and peat characteristics

The elevation range within the site (top of the highest measured point (hummock) to the lowest measured point (hollow)) was 46 cm (Figure 2a). The hummock heights, as determined with a measuring tape, ranged from 2 to 30 cm (mean: 12.7 cm; SD: 9.2 cm). The ground surface was more hummocky in the northern half and flatter in the southern half of the study site.

Table 1. Mean, median, standard deviation (SD), coefficient of variation (CV), the p-value for the Kolmogorov-Smirnov normality test for the measured abiotic variables, and the sample size (n_{95}) required to obtain an average value within 5 and 10 % of the true mean with 95 % confidence and to obtain average values within a set limit with 95 % confidence. The limits were: DTW: 2 cm (and 0.08 cm for Log10DTW); VMC: 0.02 cm^3 cm^{-3}; GMC: 0.02 g g^{-1}; AC: 2 %; pH: 0.05; and EC: 5 µS cm^{-1}. p-values < 0.05 indicate that the data vary significantly from the pattern expected if the data were drawn from a population with a normal distribution. DTW = depth to water table; VMC = volumetric moisture content at 0 – 30 cm below the surface; GMC = gravimetric moisture content at 10, 50 and 100 cm below the surface; AC = ash content at 10, 50 and 100 cm below the surface.

Measured variable	Mean	Median	SD	CV (%)	p-value normality test	n_{95} (5%)	n_{95} (10%)	n_{95} (set limit)
All locations in study site								
DTW (cm)	10.7*	9.0*	5.15	48	0.01	292	85	26
Log10 DTW	0.99	0.95	0.18	19	>0.2	52	14	20
VMC (cm^3 cm^{-3})	0.68*	0.72*	0.08	11	0.01	19	5	53
GMC10 (g g^{-1})	0.87	0.86	0.04	4	0.11	3	1	12
GMC50 (g g^{-1})	0.93	0.93	0.02	2	<0.001	1	1	5
GMC100 (g g^{-1})	0.94*	0.95*	0.02	3	0.01	1	1	6
AC10 (%)	4.3	4.0	2.92	68	0.19	497	162	8
AC50 (%)	0.9	0.8	0.86	100	0.10	784	310	1
AC100 (%)	0.6	0.7	0.39	61	0.15	420	131	1
pH	3.65	3.66	0.03	1	0.03	1	1	1
EC_{field} (µS cm^{-1})	84	84	7.5	9	>0.2	13	4	9
EC_{corr} (µS cm^{-1})	5.5	5.0	4.6	84	0.18	644**	231**	4
Hummocks only								
DTW (cm)	14.1*	12.3*	5.55	39	>0.2	208	58	29
Log10 DTW	1.12	1.09	0.16	14	>0.2	32	8	15
VMC (cm^3 cm^{-3})	0.64*	0.65*	0.08	13	0.01	27	7	67
GMC10 (g g^{-1})	0.88	0.86	0.04	4	0.08	3	1	13
GMC50 (g g^{-1})	0.94	0.93	0.01	1	>0.2	1	1	1
GMC100 (g g^{-1})	0.95*	0.94*	0.01	1	0.03	1	1	1
AC10 (%)	3.9	4.0	2.80	72	0.18	528	176	8
AC50 (%)	0.9	0.7	1.10	123	0.02	948	427	2
AC100 (%)	0.5	0.6	0.34	65	0.07	461	147	1
pH	3.65	3.65	0.03	1	>0.2	1	1	2
EC_{field} (µS cm^{-1})	84	86	8.84	10	>0.2	17	5	12
EC_{corr} (µS cm^{-1})	5.9	5.0	4.91	83	>0.2	637**	227**	4
Hollows only								
DTW (cm)	7.6*	8.0*	1.69	22	>0.2	74	19	3
Log10 DTW	0.87	0.90	0.10	12	>0.2	23	6	7
VMC (cm^3 cm^{-3})	0.73*	0.73*	0.02	2	>0.2	1	1	3
GMC10 (g g^{-1})	0.87	0.86	0.04	4	>0.2	3	1	12
GMC50 (g g^{-1})	0.93	0.94	0.03	3	<0.001	2	1	9
GMC100 (g g^{-1})	0.93*	0.94*	0.03	3	0.04	2	1	9
AC10 (%)	4.6	4.2	3.10	67	>0.2	487	158	10
AC50 (%)	0.8	1.0	0.62	74	>0.2	555	188	1
AC100 (%)	0.7	0.8	0.41	56	>0.2	368	111	1
pH	3.65	3.66	0.03	1	0.01	1	1	1
EC_{field} (µS cm^{-1})	83	84	6.40	8	0.16	9	3	7
EC_{corr} (µS cm^{-1})	5.1	5.0	4.42	87	>0.2	676**	247**	3

*Statistically significant ($p < 0.05$) difference between hummocks and hollows (two-tailed Student's t-test for the mean values and non-directional Mann-Whitney U-test for the median values).

**Sample size is not realistic because it is more accurate than the precision (1 µS cm^{-1}) of the instrument used to take the measurement. Five percent of the mean for EC_{corr} is 0.28 µS cm^{-1} and 10 % of the mean for EC_{corr} is 0.55 µS cm^{-1}.

At 10 cm depth, von Post humification was mostly H3 or H4 (Table 2). Samples from 50 cm depth were more variable, with the majority of samples being H3. At 100 cm depth, most of the samples were H2, but many of the samples from the flatter southern part of the study site were more decomposed (H3 to H5) (Table 2). There was no significant difference in the degree of humification between hummock and hollow sample locations for any depth.

All peat samples contained less than 10 % mineral material. Ash content was highest at 10 cm depth (mean: 4.3 %; SD: 2.9 %), and lower at 50 cm depth (mean: 0.9 %; SD: 0.9 %) and 100 cm depth (mean: 0.6 %; SD: 0.4 %) (Figure 3). Ash content was not significantly different between the hummocks and hollows for any depth.

Depth to water table and moisture content

DTW ranged from 5 to 27 cm below the surface (mean: 10.7 cm; SD: 5.2 cm; Figure 2b) and was (not surprisingly) positively correlated with surface elevation, i.e. the water table was significantly closer to the surface in hollows (Table 3). VMC at 0–30 cm depth ranged from 0.45 to 0.75 $cm^3\ cm^{-3}$ (mean: 0.68 $cm^3\ cm^{-3}$; SD: 0.08 $cm^3\ cm^{-3}$) (Figure 2c). Mean VMC was statistically significantly lower for the hummocks (mean: 0.64 $cm^3\ cm^{-3}$; SD: 0.08 $cm^3\ cm^{-3}$) than for the hollows (mean: 0.73 $cm^3\ cm^{-3}$; SD: 0.02 $cm^3\ cm^{-3}$). VMC was also negatively correlated with DTW and surface elevation (Table 3). GMC of the peat samples from 10, 50, and 100 cm below the surface averaged 0.87 $g\ g^{-1}$ (SD: 0.04 $g\ g^{-1}$), 0.93 $g\ g^{-1}$ (SD: 0.02 $g\ g^{-1}$) and 0.94 $g\ g^{-1}$ (SD: 0.02 $g\ g^{-1}$), respectively (Figures 2d–f). Only for the samples from 100 cm depth was there a significant difference in GMC between hummocks and hollows; GMC was significantly higher in the hollows. GMC was significantly (negatively) correlated with ash content of the peat samples for both the 10 cm and the 50 cm depths (Table 3).

Table 2. Number of samples out of a total of 25 for each von Post level of humification (H2–H6) measured in this study at 10, 50, and 100 cm below the surface.

Depth	H2	H3	H4	H5	H6
10 cm	1	6	18	-	-
50 cm	-	16	3	5	1
100 cm	17	4	2	2	-

Hydrochemistry

The average pH was 3.65 (range: 3.59–3.70; SD: 0.03) (Figure 4a). Field-measured EC ranged

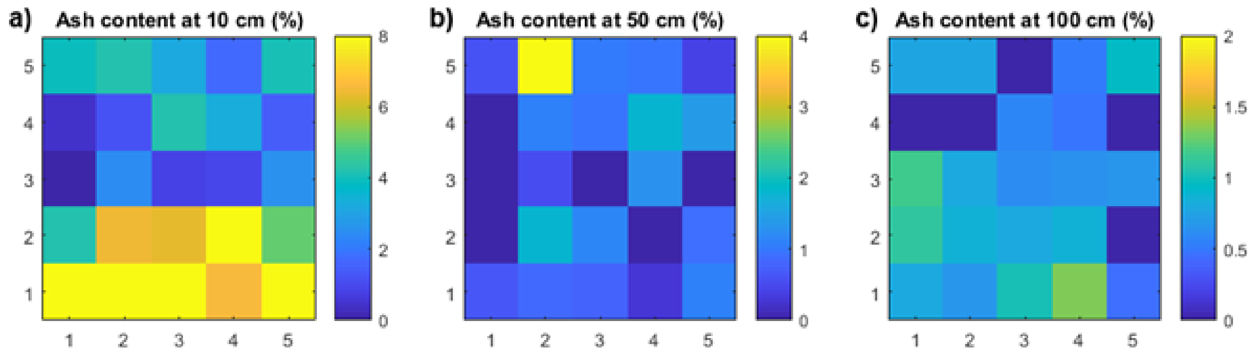

Figure 3. Spatial distribution of ash content (% of dry weight) at a) 10 cm, b) 50 cm, and c) 100 cm depth. X and Y axes show distance in metres; location 1, 1 represents the southwest corner of the study site.

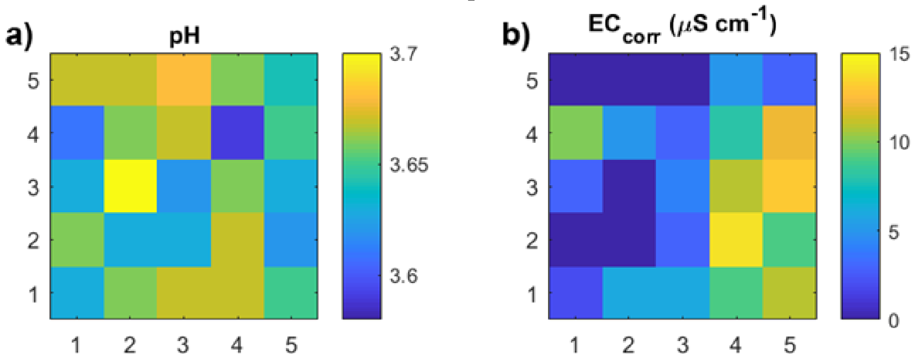

Figure 4. Spatial distribution of a) pH and b) EC_{corr} ($\mu S\ cm^{-1}$) in near-surface pore water. X and Y axes show distances in metres; location 1, 1 represents the southwest corner of the study site.

Table 3. Spearman rank correlation coefficients (r_s) between all measured variables. Statistically significant ($p < 0.05$) correlations are shown in bold text and are marked with an asterisk (*). All non-significant correlations are shown in plain text for completeness. Elev. = elevation; DTW = depth to water table; VMC = volumetric moisture content at 0–30 cm below the surface; GMC = gravimetric moisture content at 10, 50, and 100 cm below the surface; AC = ash content at 10, 50, and 100 cm below the surface; VP = von Post humification at 10, 50, and 100 cm below the surface; %S = percent cover of *Sphagnum* spp.; %RG = *Rhododendron groenlandicum*; %KM = *Kalmia microphylla* spp. *occidentalis*; %RA = *Rhynchospora alba*; %PC = *Pinus contorta* var. *contorta*; %VU = *Vaccinium uliginosum*; %CP = *Cladina portentosa* subsp. *pacifica*; %AP = *Andromeda polifolia*.

	Elev.	DTW	VMC	GMC10	GMC50	GMC100	AC10	AC50	AC100	VP10	VP50	VP100	pH	EC_{field}	EC_{corr}
Elev.															
DTW	**0.93***														
VMC	**-0.81***	**-0.81***													
GMC_{10}	0.08	0.04	0.11												
GMC_{50}	-0.24	-0.23	0.32	**0.66***											
GMC_{100}	0.36	**0.40***	**-0.44***	0.20	0.03										
AC_{10}	-0.28	-0.20	0.11	**-0.67***	-0.34	-0.33									
AC_{50}	0.13	0.09	0.11	-0.28	**-0.65***	-0.22	0.11								
AC_{100}	-0.37	-0.33	0.24	-0.04	0.39	-0.10	0.35	**-0.40***							
VP_{10}	-0.33	-0.28	0.37	0.33	0.30	-0.01	0.18	-0.17	0.15						
VP_{50}	**0.56***	**0.49***	**-0.69***	-0.21	**-0.40***	0.30	0.06	0.10	-0.22	-0.37					
VP_{100}	**-0.58***	**-0.51***	**0.41***	**-0.40***	-0.03	**-0.63***	**0.63***	-0.03	0.35	0.22	-0.34				
pH	0.14	0.06	-0.05	-0.28	-0.14	0.10	0.23	0.04	0.24	-0.04	-0.05	-0.00			
EC_{field}	-0.17	-0.12	0.07	0.18	0.03	-0.08	-0.11	-0.11	-0.28	0.12	0.25	0.00	**-0.76***		
EC_{corr}	-0.11	-0.11	0.11	0.05	-0.04	-0.17	0.01	-0.10	-0.30	0.18	0.23	0.03	-0.28	**0.79***	
%S	**-0.40***	-0.32	**0.46***	-0.03	0.17	**-0.53***	**0.40***	0.04	0.25	0.23	-0.18	**0.51***	-0.38	0.39	0.27
%RG	**0.61***	**0.55***	**-0.47***	0.29	-0.07	**0.46***	**-0.70***	0.05	**-0.49***	-0.35	0.36	**-0.69***	-0.02	-0.03	-0.03
%KM	0.01	-0.12	0.19	0.12	-0.02	0.18	**-0.44***	0.23	-0.19	0.07	-0.14	-0.24	0.04	-0.01	-0.06
%RA	**-0.70***	**-0.56***	**0.55***	-0.13	0.21	**-0.50***	**0.58***	-0.18	**0.56***	**0.44***	**-0.45***	**0.76***	-0.10	0.14	0.12
%PC	0.17	0.26	-0.29	0.16	-0.05	0.36	-0.06	0.03	-0.17	0.16	0.00	-0.21	-0.20	0.00	-0.17
%VU	0.31	0.29	-0.21	0.02	-0.08	**0.46***	-0.10	-0.00	-0.22	0.08	0.14	-0.28	0.25	-0.15	-0.03
%CP	0.27	0.34	-0.23	0.09	-0.09	0.32	-0.20	-0.16	-0.14	0.05	0.15	-0.24	0.15	-0.10	0.10
%AP	-0.03	0.05	-0.05	-0.03	0.05	0.27	0.21	-0.11	0.10	0.27	0.05	-0.05	0.21	-0.11	0.04

from 70 to 98 μS cm^{-1} (mean: 83.8 μS cm^{-1}; SD: 7.5 μS cm^{-1}), while EC_{corr} ranged from 0 to 14 μS cm^{-1} (mean: 5.5 μS cm^{-1}; SD: 4.6 μS cm^{-1}) (Figure 4b). EC_{field}, EC_{corr} and pH were not significantly different between hummocks and hollows. Their spatial distribution was also not significantly correlated with topography or any of the other measured variables (Table 3).

Required sample sizes

A large number of measurements would be needed for DTW to obtain an average within 5 % of the true mean with 95 % confidence: n = 292 for the field data and n = 52 for the log-transformed data (Table 1). Sample sizes would be smaller (n = 74 and 23, respectively) when only considering the hollows. To obtain an average DTW within 2 cm with 95 % confidence would require approximately 26 measurements across the site, but only three measurements would be required for just the hollows. The required sample size for the normally distributed log-transformed DTW data with a set limit of 0.08 cm was 20 for the study site, or seven for just the hollows. For ash content, it would require 420–784 measurements (depending on the depth) to obtain an average within 5 % of the true mean or 1–8 measurements to obtain an average within the 2 % set limit (Table 1). VMC would require a moderate number of measurements (n = 19 to obtain an average within 5 % of the true mean), but only one measurement would be required to represent the hollow sites (Table 1). Relatively small sample sizes would be required for GMC (n = 1–3). Electrical conductivity (EC_{field}) would require a moderate number of measurements: n = 13 to obtain a mean value within 5 % of the mean or n = 9 for a mean value within 5 μS cm^{-1} with 95 % confidence. To obtain an average EC_{corr} within 5 μS cm^{-1} of the mean with 95 % confidence requires a sample size of four (Table 1). The most consistent variable was pH, requiring only one measurement.

Vegetation

Plant species cover was significantly different between hummocks and hollows in a directional Mann-Whitney U-test for *Pinus contorta* var. *contorta*, *Rhododendron groenlandicum*, *Cladina portentosa* subsp. *pacifica*, *Rhynchospora alba*, and *Sphagnum* spp., and in a non-directional Mann-Whitney U-test for *Rhododendron groenlandicum*. There was no significant difference between hummocks and hollows for *Andromeda polifolia*, *Vaccinium uliginosum* or *Kalmia microphylla* var. *occidentalis*. Cover of *Rhododendron groenlandicum* was higher on the hummocky northern part of the study site, whereas *Sphagnum* spp. and *Rhynchospora alba* were more dominant on the flatter southern part of the study site (Figure 5). The abundance of the other plant species was not clearly related to topography for this study site (Figure 5).

The Spearman rank correlation results showed that percent cover of the eight dominant plant species was most strongly related to DTW (and surface elevation, which is linked to DTW), VMC in the upper 30 cm, and ash content at 10 cm depth (Table 3). Cover of *Rhododendron groenlandicum* was significantly (positively) correlated with DTW and negatively with ash content and VMC at 0–30 cm (Table 3). Cover of *Sphagnum* spp. and *Rhynchospora alba* were significantly (positively) correlated with VMC and ash content. Cover of *Rhynchospora alba* was also significantly (negatively) correlated with DTW. Cover of *Kalmia microphylla* spp. *occidentalis* was negatively correlated with ash content at 10 cm depth. The other dominant plant species were not significantly correlated with the measured abiotic variables in the rooting zone (i.e. 50 cm depth and above). There was no significant correlation between cover of any of the dominant plant species and pH, EC_{field} or EC_{corr} (Table 3).

DISCUSSION

Representativeness of point measurements

Soil moisture and depth to water table

VMC at 0–30 cm was higher for the hollows (mean: 0.73 cm^3 cm^{-3}) than for the hummocks (mean: 0.64 cm^3 cm^{-3}) because VMC was strongly correlated with DTW, which was greater in hummocks (mean: 14 cm) than in hollows (mean: 8 cm). VMC is also affected by bulk density; the higher variability in VMC than in GMC may be due to differences in bulk density. We did not measure the bulk density of the peat samples, but maximum and minimum values of bulk density for samples (n = 20) in the top 50 cm of the peat from the same plant community elsewhere in Burns Bog differed by up to 290 kg m^{-3} (unpublished data). GMC at 10 cm depth was not correlated with DTW and was similar for hummocks (0.88 g g^{-1}) and hollows (0.87 g g^{-1}). Cheng (2011) found for weekly/biweekly measurements that encompassed the summer and fall (autumn) of 2009, at a site in Burns Bog with the same plant community near the study site (< 400 m), that VMC was lower for hummocks than for hollows. Because there was a fairly high spatial variability in VMC due to the hummocky nature of the study site, VMC should be measured in a representative number of hummocks and hollows to obtain a reasonable average for the site. For example, 19 measurements would be

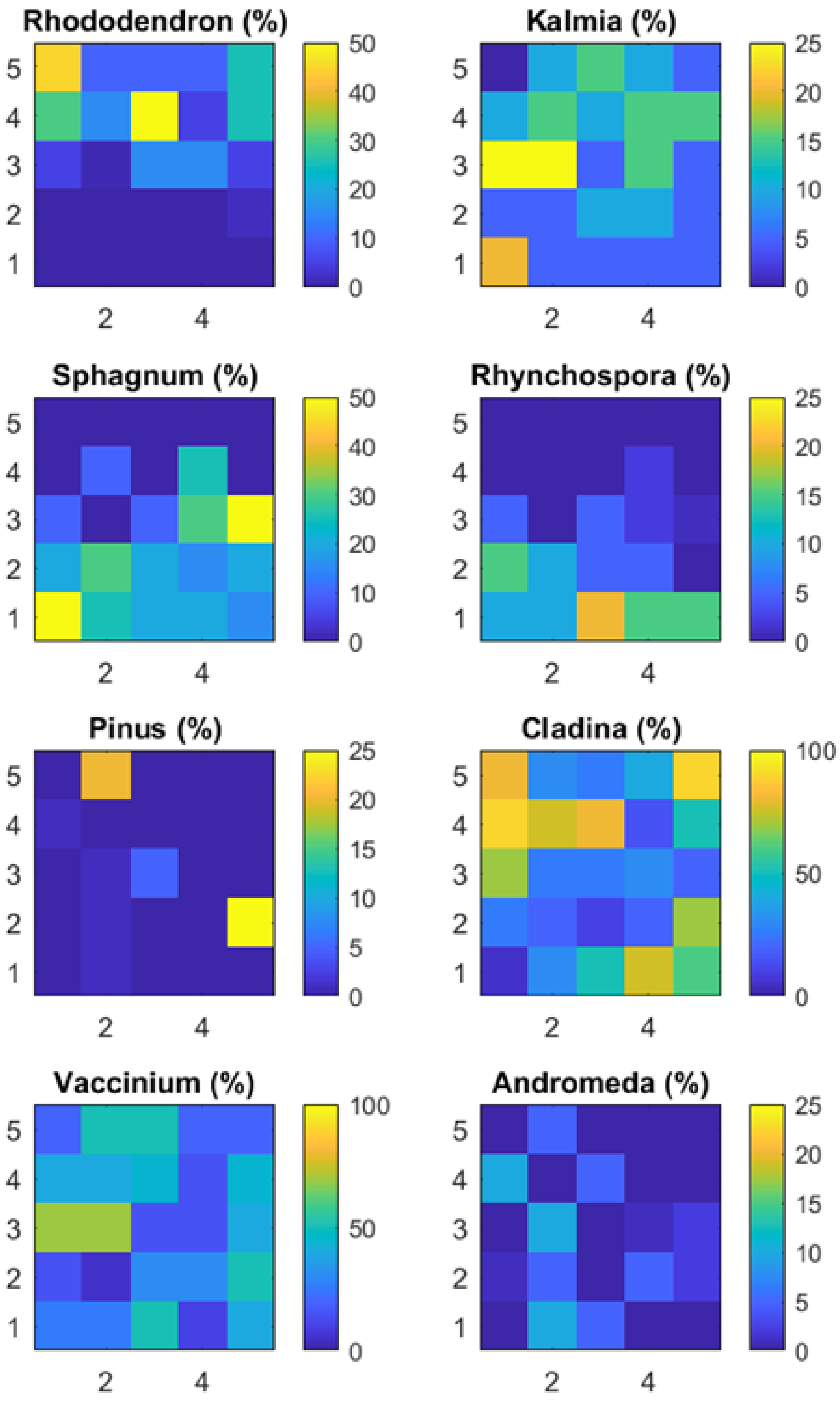

Figure 5. Spatial distribution of percent cover of *Rhododendron groenlandicum*, *Kalmia microphylla* subsp. *occidentalis*, *Sphagnum* spp., *Rhynchospora alba*, *Pinus contorta* var. *contorta*, *Cladina portentosa* subsp. *pacifica*, *Vaccinium uliginosum* and *Andromeda polifolia* in the study site. X and Y axes show distance in metres; location 1, 1 represents the southwest corner of the study site.

required to obtain an average value within 5 % of the true mean (or 53 measurements to know the average within 0.02 cm^3 cm^{-3}) with 95 % confidence (Table 1). However, these numbers need to be interpreted with care because VMC was not normally distributed. GMC is a more spatially-consistent variable; a sample size of 1–3 is sufficient to obtain a value within 5 % of the mean (Table 1). However, GMC may not be as useful for understanding peat moisture conditions; GMC at 10 cm depth was not correlated with DTW, and species cover was not correlated to GMC but was related to VMC. Another reason to prefer VMC measurements is that they are taken in the field, while samples for GMC are cored and transported to the laboratory and are, therefore, more prone to disturbance. Furthermore, it will likely take less time to take 19 VMC measurements than to obtain one GMC measurement.

The coefficient of variation of DTW was less for hollows (CV: 22 %) than for hummocks (CV: 39 %), indicating that the DTW in hollows is less variable than for hummocks or the entire site. Hollows are, therefore, the preferred location for DTW measurements when comparing sites along a transect or in different bogs. Measuring DTW in a hummock would be less reliable because the DTW is strongly influenced by the hummock height and, therefore, not representative of the surrounding ground surface. A single point measurement in a typical shallow hollow or lawn will suffice as a general representation of the DTW in the non-hummocky area surrounding the measurement location but of course is not representative for the average DTW for the area, particularly not for the hummocks. Indeed, it has been shown that the water table in bogs is not necessarily flat, but can mirror the surface topography, even at small scales (Wilson 2012). However, impractically large sample sizes would be required to obtain a representative average DTW for a site with 95 % confidence if measurements are taken at random locations. For example, we estimated that one would need to take 292 measurements to obtain an average value within 5 % of the mean, or 26 measurements to obtain an average within 2 cm of the mean (Table 1). One could reduce this number by taking surface topography into account. Measuring the water level relative to a common datum, rather than the local ground surface, would result in more consistent results and allow for fewer measurements.

Hydrochemistry

The pore water pH measurements were the most consistent of the abiotic variables measured at the study site (SD: 0.03; CV: 1 %, Table 1). In a similar study in a moderately rich fen, Tahvanainen & Tuomaala (2003) measured pH just below the water table in ten wells on a 38 m long transect. They also found very little variation in pH along the transect, with a range of 0.3 pH units for unaerated samples, and noted that pH was consistent regardless of the hummock-hollow sequence on the transect. The pH range for our small study grid, which also contained both hollows and hummocks, was even smaller (0.1 pH units). We found no difference in pH between hummocks and hollows (mean for both: 3.65), although our study site was located in an area with relatively little topographic variation and only small (< 30 cm, mean 13 cm) hummocks. Gerdol *et al*. (2011) also found no significant differences in groundwater pH between hummocks and hollows. One can therefore expect a single measurement of pH of near-surface pore water to be representative of the surrounding area. However, Bragazza *et al*. (1998) found that groundwater pH was lower in hummocks (mean: 4.17) than hollows (mean: 4.36), which was attributed to the greater cation exchange capacity of the hummock *Sphagna* (Bragazza & Gerdol 1999).

EC_{corr} (SD: 4.6 µS cm^{-1}; CV: 84 %) varied more than pH but had a small range (0–14 µS cm^{-1}). The estimated sample size to obtain an average EC_{corr} within 5 µS cm^{-1} of the mean is n = 4 but it is important to note that EC_{corr} is based on pH. For EC_{field}, a larger sample size was estimated: 13 measurements to obtain an average value within 5 % of the true mean or nine measurements to obtain an average within 5 µS cm^{-1} of the mean. There was no significant difference in EC_{field} or EC_{corr} between hummocks and hollows, which suggests that there was also little spatial variation in major cation and anion concentrations. Gerdol *et al*. (2011) found no significant differences in Ca^{2+} or Mg^{2+} concentrations between hummocks and hollows across a ~200 m wide bog in the south-eastern Alps in Italy. Bragazza & Gerdol (1999), on the other hand, found that cation concentrations (Ca^{2+}, Mg^{2+}) were higher in surface water in a hummock than a hollow, although the difference was generally not significant. The opposite was found for groundwater sampled from piezometers, where Ca^{2+} and Mg^{2+} concentrations were slightly higher in hollows during both the wet and dry season (Bragazza & Gerdol 1999). Bragazza *et al*. (1998) also observed significant differences in Na^+, K^+, and Mg^{2+} concentrations between hummocks and hollows, with higher Na^+ and K^+ concentrations and lower Mg^{2+} concentrations in hummocks.

When considering the representativeness of point measurements, it is also important to consider the temporal variability of the hydrochemical measurements. Bragazza *et al*. (1998) found that cation concentrations were more temporally variable in hummocks than hollows, and that pH, EC, and cation concentrations differed significantly between sampling dates. In contrast, EC_{corr} and pH did not differ significantly over a 1.5 year monitoring period in Burns Bog and Blaney Bog (30 km from Burns Bog) (Howie & van Meerveld 2012). Wieder (1985), Vitt *et al*. (1995) and Avagyan *et al*. (2014) observed that pH was relatively constant during the growing season in bogs in the United States of America, in Canada, and in Russia, respectively. Vitt *et al*. (1995) also found little temporal change in EC_{corr} in a raised bog in central Alberta. This suggests that a one-time measurement for pH and EC may provide a reasonable representation of the hydrochemical characteristics of the site; however, this may not hold true for sampling of cations or nutrients.

Peat properties

The degree of peat decomposition in bogs is generally assumed to increase with depth (Schouten 2002, Rydin & Jeglum 2013). For example, Levrel *et al*. (2009) observed consistently increasing humification from H1–H2 at the surface to H7 at 1 m below the surface in bogs of James Bay, Quebec. We found the opposite pattern, whereby humification was highest at the surface and decreased with depth; H4 was the dominant degree of decomposition at 10 cm, H3 at 50 cm depth, and H2 at 100 cm depth. This is possibly due to drainage in the area that resulted in a lower water table in the past decades (Schouten 2002), although the nearest ditch is > 200 m from the study site. It should be noted, though, that von Post measurements are subjective and depend on one's experience with this methodology. Furthermore, the average difference in von Post values observed between the three depths is similar to the typically considered accuracy for these measurements (±1).

Approximately two thirds of the von Post values for each sample depth were the same. The percentage of samples that were within ±1 point of the median value on the von Post scale was 96 % for 10 cm depth, 76 % for 50 cm depth and 84 % for 100 cm depth. A single von Post measurement for a given depth can, therefore, be expected to be representative of the surrounding peat at least 75 % of the time. However, Hobbs (1986) recommended that a large number of von Post tests be carried out because peat is usually not uniformly decomposed. We agree with this recommendation for cases in which an accurate estimate of humification is required.

Ash content of bog peat is usually less than 5 % (Brooks & Stoneman 1997); 66 of the 75 peat samples (88 %) were within this range. The remaining samples (all at 10 cm depth) had an ash content of 5–10 %. Lipatov *et al*. (2017) similarly found higher ash content (7 %) in the top 10 cm than at 50 and 100 cm below the surface (2–3 %) for a bog on Russia's east coast. The higher mineral content and higher level of humification at the bog surface suggests that increased decomposition of the surface peat (due to oxidation in more aerated conditions as a result of drainage) resulted in denser, more 'concentrated' peat. Alternatively, atmospheric deposition of pollutants and dust, caused by human activities (e.g. nearby industry, roads and farms) or a fire, may have increased the mineral content of the surface peat.

Ash content varied considerably across the study site, with coefficients of variation of 68, 100, and 61 % at 10, 50, and 100 cm below the soil surface, respectively. Lipatov *et al*. (2017) also found large spatial variation for ash content at 0–7 cm (CV: 52 %) and 7–23 cm (CV: 23 %) below the surface. As noted earlier, differences in peat composition (i.e. source plant species), hummock and hollow formations, and accumulation and mineralisation, can result in small scale heterogeneity of peat properties including ash content (Lipatov *et al*. 2017). Given the relatively high standard deviations and coefficients of variation for ash content at the three depths, we recommend collection of multiple samples to obtain a representative average value for ash content. To know the ash content within 2 % with 95 % certainty requires a few samples (1–8, depending on the sampling depth; Table 1). Larger sample sizes may help to reduce the uncertainty in the average ash content values but, for most studies, the required sample size to know ash content within 10 % of the mean is unrealistically large (Table 1). Since ash content was not significantly different between hummocks and hollows for any depth, it may not be necessary to collect separate measurements for each but this may be different in other study sites.

Vegetation

Vegetation in bogs tends to be patchy and heterogeneous. For example, Bragazza *et al*. (1998) found that hummocks and hollows were "floristically well-differentiated" from each other. A single small (e.g. 1 m^2) vegetation plot will not accurately represent the variability of the site and, therefore, larger or multiple vegetation plots are recommended (Brooks & Stoneman 1997). A standard international plot size for bog vegetation inventories has not been established, but 4 m^2 appears to be the minimum plot size used in most bog studies (Chytrý & Otýpková 2003). Chytrý & Otýpková (2003) recommend either a 16 m^2 or 50 m^2 plot size for bog vegetation, based on an extensive review of vegetation plot sizes in Europe. However, a small vegetation plot such as the one used in this study (0.8 m × 1.0 m) can be used to compare vegetation response to abiotic factors within a small study area. For example, Anderson *et al*. (2010) used 20 cm × 20 cm quadrats to sample plant community composition in relation to microtopographical gradients. Indeed, any plot size can be useful for studying vegetation patterns, as long as a sufficient number of plots are surveyed and comparisons are only made between plots of similar size (Chytrý & Otýpková 2003).

Correlation between plant species cover and abiotic factors

Plant species composition varied across the study site in relation to microtopography. Cover of some species (*Pinus contorta* var. *contorta*, *Rhododendron groenlandicum*, *Cladina portentosa* subsp. *pacifica*, *Rhynchospora alba* and *Sphagnum* spp.) was significantly different between hummocks and hollows. The significant correlations between species cover and DTW and VMC were expected since plant species distribution in peatlands is closely linked to DTW (and, therefore, to soil moisture) (Jeglum 1971, Ivanov 1981). The unexpected correlation between plant species cover and ash content at 10 cm depth may be due to an associated effect with peat chemistry (e.g. pH and concentrations of major cations) because peatland vegetation is also strongly linked with soil chemistry (Bridgham *et al*. 1996). However, pH was relatively constant across the small study site and pH and EC_{corr} were not well correlated with ash content, although it should be noted that we took samples from near-surface pore water (~20 cm below the surface), not the peat, and this is, therefore, not a direct comparison. Water content at 10 cm depth was significantly (negatively) correlated to ash content at 10 cm depth (Table 3); it is therefore more likely that the plants did not respond to the higher mineral content of the peat, but rather to the lower water content. It is also possible that some plants (e.g. *Sphagnum* leaves and branches) are better at retaining ash from atmospheric deposition than more openly-branched plants such as *Rhododendron groenlandicum*, which may have resulted in the higher ash content at 10 cm depth on the southern side of the study site where *Sphagnum* was more abundant.

Interestingly, there was no statistically significant correlation between plant species cover and pH and EC_{corr}, despite a general assumption among peatland scientists that pore water chemistry (particularly pH) influences plant species composition (Malmer 1986, Rydin & Jeglum 2013). Graham *et al*. (2016) showed that plant assemblages in a northern Alberta peatland complex were not closely related to near-surface base cation concentrations, but pore water pH was an important factor, as well as shade, DTW, and dissolved organic nitrogen. Vitt & Chee (1990) observed that vascular plants of fens in Alberta responded to varying nutrient concentrations in surface water, whereas bryophytes were more affected by acidity and EC than by nutrients. Cooper & Andrus (1994) found that pH and base cation concentrations varied little between different plant communities in fens in Wyoming but plant species composition was strongly related to DTW and groundwater discharge. The small range in EC_{corr} and pH in our 4 m × 4 m study site may explain the lack of correlation with vegetation cover; other studies analysed hydrochemical patterns over larger areas, with larger variability in EC and pH, and perhaps therefore found a stronger link between species cover and EC and pH than at our study site.

Because cover of some species was significantly correlated with the hydrological variables, it may be possible to use species cover information to design a robust sampling scheme. For example, if plant species composition is fairly homogenous across the study area (e.g. *Sphagnum* carpet or lawn), a single point measurement is likely to represent the average soil moisture (Table 1). On the other hand, in locations where the ground surface is hummocky and plant species composition is heterogeneous, sampling in both hummocks and hollows is required to obtain a representative average value for the site.

Limitations of the study

This study took place at a single site within a single bog. There were no across site or intersite comparisons. The values for sample sizes given here are only representative for the study site in Burns Bog and may be different for other sites. Therefore, further research on the representativeness of point measurements and the required sample sizes is needed. Also, not all data were normally distributed and, therefore, the estimated sample sizes for VMC and pH are uncertain. However, the results of this study do highlight the need to consider the representativeness of point measurements when comparing sites on a transect or measurements from different bogs.

We used shallow piezometers instead of wells for the DTW measurements. Water level measurements over eight years at five shallow piezometers (113 measurements in total) in the same undisturbed plant community in Burns Bog were on average 1.2 cm (SD: 0.8 cm) different from the water level measured on the bog surface during inundated conditions (unpublished data collected by City of Delta). Therefore, the differences between the measured water level in the piezometers and the actual water table in our study are assumed to be small (< 1–2 cm) and likely similar among the piezometers in the study site. However, we acknowledge that this small potential error could affect the correlations between DTW and plant species composition.

Sphagnum was not identified to the species level in this study. The two main *Sphagnum* species in the study site were *Sphagnum capillifolium* and *Sphagnum tenellum* (Howie 2013). *S. capillifolium* is typically found on the top of hummocks, while *S. tenellum* is more of a lawn species (Laine *et al.* 2011). We expect that if the percent cover of these and other *Sphagnum* species had been identified for each measurement point, there would have been different *Sphagnum* species assemblages for the hummocks, lawns, and hollows. Total *Sphagnum* cover was significantly greater for the hollows.

CONCLUSIONS

Detailed measurements at Burns Bog suggest that pH and gravimetric moisture content are spatially uniform enough to assume that a single point measurement represents an area within at least 4 m of the sampling location. A more robust average value for electrical conductivity can be obtained when four groundwater samples are taken. Volumetric moisture content at 0–30 cm below the soil surface was related to topography and should, therefore, be measured in a representative number of hummocks (n > 25) and hollows (n = 1) to obtain a representative average value for the site. The degree of humification at a given depth below the surface appears to be somewhat spatially stable; one can expect a point measurement to represent the average degree of humification (±1 point on the von Post scale) for approximately three quarters of the time. Ash content ranges were small for each depth (< 10 % at 10 cm, < 5 % at 50 cm, and < 1.5 % at 100 cm depth), but had large coefficients of variation; an unreasonably large number of samples (n > 100) would be required to determine the average ash content with certainty, although < 10 samples would be needed to determine the ash content within 2 %. These sample sizes are likely specific to Burns Bog and the plant community that was studied. Research on the representativeness of point measurements and the required sample sizes is needed for other bogs. While values may differ in other bogs, the results of this study show that point measurements are not necessarily representative for a larger area and that small scale spatial variability needs to be considered when comparing measurement sites on a transect or in different bogs.

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