Variation in Soil Nutrient Concentrations and Bulk Density within Peatland Forest Sites

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The within-site variability of soil characteristics on sites with different soil types remains poorly quantified, although this information is crucial for the success of research on soil properties, and especially for monitoring soil properties over time. We used coefficients of variation and multilevel variance component models to examine the within-site variation of soil (0–30 cm) mineral nutrient concentrations (P, K, Ca, Mg, Fe, mg g^{-1}; Mn, Zn, µg g^{-1}) and bulk density (kg m^{-3}) on boreal deep-peat sites. We then evaluated the reliability of the site-level estimates (sample means) obtained using different sampling intensities (numbers of samples per site). Our 11 sites represented a single original site type within the oligotrophic nutrient level. Two of the sites were undrained while the rest had been drained for forestry at different points in time. Overall, P concentrations showed the smallest and Mn concentrations the largest within-site variation. The sampling depth contributed more than 50% of the total variance in all other characteristics except the concentrations of P and Fe, and bulk density. The variance proportions of peatland basin, site (within basin), and sampling location (within site) varied by sampling depth for most soil characteristics. The estimates obtained when using a certain number of samples per site were always more reliable for the 0–30 cm layer's composite samples than for any single 10-cm layer at any depth sampled. On average, it was found that between 4 (P) and some 200 (Mn) samples per site would be needed for the estimates to have a theoretical 10% maximum deviation.

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1 Introduction

Peatlands are unique ecosystems in that their plant communities produce the substrate they grow on. The organic soil, peat, is deposited due to incomplete decomposition of dead plant material. The characteristics of the plant litter material directly affect the chemical composition of the resultant peat. The species composition of peatland plant communities is controlled to a large extent by variation in water level, or the volume of the aerated rooting zone, and the nutritional quality and acidity of the water supporting the ecosystem (Laine et al. 1995, Bridgham et al. 1996, Wheeler and Proctor 2000). Within a peatland site, the composition of the vegetation is patchy, and varies in terms of microtopography (Belyea 1996, Moore 1989).

Peat characteristics are modified by decomposition processes, nutrient uptake by the vegetation, and leaching/precipitation. Peat accumulation and decomposition processes may be highly variable on local scale (Belyea 1996, Ohlson and Økland 1998). Further, microforms (wet hollows, moist lawns, dry hummocks) have varying local hydrology, which in turn leads to local variation in the soil redox-conditions and, consequently, in nutrient mobility (Damman 1978). These factors together with the variation in vegetation presumably give rise to local variation in peat soil characteristics as well.

The majority of peatlands in Europe have been modified by man for agriculture and forestry, and this has altered natural processes in a way that may be reflected in soil properties. The extent of peat soil variability in both natural and modified ecosystems is still poorly understood, although this knowledge would be essential for all research concerning soil properties, e.g. in monitoring site properties over time (de Vries et al. 2003).

The aim in this study was to analyze the variation of soil nutrient concentrations on boreal deep-peat sites representing a single site type at the oligotrophic nutrient level. We wanted to assess 1) the variability in mineral nutrient concentrations (P, K, Ca, Mg, Fe, mg g^{-1}; Mn, Zn, μg g^{-1}) and bulk density (kg m^{-3}) within floristically defined peatland sites, i.e. between sampling points and peat layers, 2) the importance of different sources of variation (peatland basin, site, horizontal and vertical within-site variation) among elements, and 3) how reliable are the estimates obtained with different sampling intensities (numbers of samples per site).

2 Material and Methods

2.1 Sites

Peat sampling was done on 11 peatland sites, each represented by one sample plot, in central Finland (Table 1). Two of the sites were undrained (pristine). The undrained sites, and three other sites drained to improve forest growth 22, 30, and 55 years before sampling, were located within the zone of raised bogs in the southern boreal vegetation zone. The rest of the sites, drained 22 years earlier, were located in the zone of southern aapa mires in the mid-boreal vegetation zone. The sample plots were measured 30–40 m by 30–40 m, and extended from ditch to ditch on the drained sites. The ditch spacing of the drained sites was 30–40 m. Peat thickness was more than 1 m on the raised bog sites, and varied between 0.7–1.1 m on the aapa mire sites. The sites supported tree stands dominated by Scots pine (*Pinus sylvestris* L.). The initial sparse pre-drainage tree stands had been retained to form the basis for the production forest stands in the drained sites. Stand densities had increased after drainage due to natural regeneration and ingrowth.

The sites were chosen to represent the same, floristically defined site type. In the Finnish classification of pristine peatlands, this site type is called tall-sedge pine fen (VSR; Laine and Vasander 1996) and following drainage for forestry these sites are classified as *Vaccinium vitis-idaea* type 2 (PtkgII; Laine 1989). This site type is the most common peatland site type in Finland, found both on the laggs of raised bogs and on the treed margins of aapa mires. Sites of this type have been commonly drained for forestry and they make up more than 10% (over 0.5 mill. ha) of the total drained area in Finland, i.e., more than any other site type (Keltikangas et al. 1986). These sites are nutritionally of especial interest, because they are potentially prone to deficiency of K (Kaunisto 1997, Saarinen 1997).

Table 1. The study sites.

Peatland basin	Location	Elevation m a.s.l.	Drainage age, years [a]	Tree stand	Tree stand volume, m^3ha^{-1}
Siikaneva	61°50'N, 24°12'E	160	0	unmanaged	6
Lakkasuo	61°47'N, 24°20'E	150	0	unmanaged	35
Lakkasuo	61°47'N, 24°20'E	150	30	unmanaged	102
Vaavunsuo	61°38'N, 24°07'E	140	22	unmanaged	76
Sauvasuo	61°51'N, 24°25'E	140	55	unmanaged	150
Rehula	63°53'N, 25°42'E	155	22	unmanaged	124
Rehula	63°53'N, 25°42'E	155	22	thinned [b]	70
Rehula	63°53'N, 25°42'E	155	22	unmanaged	155
Rehula	63°53'N, 25°42'E	155	22	thinned [b]	70
Rehula	63°53'N, 25°42'E	155	22	thinned [b]	85
Rehula	63°53'N, 25°42'E	155	22	unmanaged	160

[a] Time elapsed since ditching at the time of sampling; 0 = undrained
[b] Approx. 50% of basal area removed 8 years before sampling

In the pristine state, these sites are characterized by mosaic-like variation of lawns dominated by *Carex* spp sedges (*C. rostrata* Stokes, *C. lasiocarpa* Ehrh., and/or *C. chordorrhiza* L. fil.), and low hummocks with Scots pine. After ditching, the sedges disappear fairly soon, and the ground vegetation becomes characterized by dwarf shrubs, at first peatland species (*Betula nana* L., *Ledum palustre* L., *Vaccinium uliginosum* L.), and later on forest species (*Vaccinium myrtillus* L., *V. vitis-idaea* L.) (Laine et al. 1995).

2.2 Soil Sampling and Chemical Analyses

Twenty soil cores were taken from each sample plot. The sampling points were located on a systematic grid covering the entire plot. The minimum distances between sampling points varied between 5 to 8 m depending on plot size. The area of the corer used for sampling was 7×7 cm for the southern site drained 30 years earlier, and 8×8 cm for all other sites.

The layers sampled were 0–10 cm, 10–20 cm and 20–30 cm below the peat surface. The peat surface was here defined to be the limit below the green moss layer or litter layer (depending on microsite) where the first fine roots could be found. The top 30 cm of the peat represents the principal rooting zone in these peatlands (Laiho and Finér 1996).

The concentrations (total; mg g^{-1} or µg g^{-1}) of P, K, Ca, Mg, Fe, Mn and Zn in peat dry mass were determined using an ICP analyzer (ARL 3580) after nitric acid – perchloric acid digestion. The bulk densities (kg m^{-3}) of the peat samples were determined as dry mass per fresh volume.

2.3 Statistical Analyses

The question of whether simple distance-dependent but direction-independent spatial autocorrelation of nutrient concentrations existed within the sites was examined using the Mantel test for comparing the similarity matrices of nutrient concentrations to the distance matrix (e.g. Legendre and Legendre 1998). The aapa mire sites located next to each other in the same peatland basin were treated as one entity.

The coefficient of variation (CV; standard deviation divided by the sample mean) by site and peat layer was estimated for each variable measured. The mean CV's by peat layer were calculated to allow overall comparison of the variation in each variable in the material.

The sources of variation in peat nutrient concentrations and bulk density were analyzed by constructing variance component models. We identified four hierarchical levels in the data: 1) Peatland basin, 2) Site within a peatland basin, 3) Sampling location within a site, and 4) Peat layer within a sampling location. A simple multilevel model (e.g. Goldstein 1995), with only a constant (mean intercept) fitted to the data for each independent variable, resulted in variance component

estimates for each hierarchical level. The model may be expressed as:

$$y_{ijkl} = a + f_l + v_{kl} + u_{jkl} + e_{ijkl} \qquad (1)$$

where y_{ijkl} denotes the value of the response variable (element concentration or peat bulk density) for sampling depth i at sampling location j on site k in peatland l, a denotes the mean intercept (constant), f_l is the peatland-level residual (which is the same for all observations in peatland l), v_{kl} is the site-level residual (which is the same for all observations on site k on peatland l), u_{jkl} is the sampling-location-level residual, and e_{ijkl} is the sampling-depth-level residual. The underlying assumption is that the so-called random variables f_l, v_{kl}, u_{jkl} and e_{ijkl} are uncorrelated and follow normal distributions with zero means, and thus it is sufficient to estimate their variances, σ^2_f, σ^2_v, σ^2_u and σ^2_e. The estimation was done using MLwiN software (Rasbash et al. 2000), which simultaneously estimates the fixed (only constant in model 1) and random parameters. We applied the restricted iterative generalized least square (RIGLS) method.

Because the peat layer 1) is not a random variable in a strict sense, and 2) had an overwhelming impact on the concentrations of some elements such as K, we report only the peat layer variance components from the results of Model 1. Then we proceed to examine the contributions of the other hierarchical levels by fitting Model 1 without term e_{ijkl} i) for the mean characteristics of all three layers ("0–30 cm composites"), and ii) for each layer separately (0–10 cm, 10–20 cm, and 20–30 cm). The significance of the variance components was evaluated based on the standard errors of the variance estimates. To be significant at the 0.05 level, the estimate should be at least twice its s.e. We applied the limit of estimate > s.e. for indicating a trend.

Further, as our data included sites with management treatments (drainage, thinning), we evaluated the impact of these measures on the peat characteristics by adding them as dummy variables to the fixed part of the models. The effect of drainage was also evaluated with continuous variables describing the drainage age of the site (years elapsed since ditching) and the distance of sampling location to the nearest

ditch, and a dummy variable receiving value 1 when the distance to the ditch was ≤ 5 m. The possible correlation of tree stand volume with peat characteristics was also tested. The significance of these variables was evaluated based on the parameter standard error. Further, the value of –2*log-likelihood was used to compare the models of increasing complexity.

Next, we evaluated the reliability of site-level soil characteristic estimates. The relation between sample size (within a site) and the maximum deviation of the sample mean from the population mean was analyzed making use of the central limit theorem (e.g., Ranta et al. 1989) according to which sample means follow asymptotically the normal distribution, with μ as expected value, and σ^2/n as variance. The theoretical maximum deviation of the sample mean from population mean with a probability $1 - \alpha$ can be expressed as

$$d = z_{1-\alpha/2}\, \sigma\, /\, \sqrt{n} \qquad (2)$$

where z is the $1 - \alpha/2$ fractile of the normal distribution. We chose $\alpha = 0.05$. The standard deviations σ for each site and peat characteristic were estimated from the samples as the average s.d. of 500 bootstrapped replications of the samples. The maximum deviations were transformed to percentages using the average mean of the bootstrapped samples as the estimate of μ. Mean percentage deviations with their 95% confidence limits for given sample sizes were then estimated for the entire material.

3 Results

3.1 Variation in Peat Characteristics

There was no significant direction-independent spatial autocorrelation over any site for any element in our material (Mantel-test correlation coefficients for all sites and elements were non-significant; not shown).

Overall, P concentrations showed the smallest and Mn concentrations the largest within-site variation in our material (Table 2). The coefficients of variation (CV) showed moderate variation among the peat layers sampled, with a

Table 2. Coefficients of variation (CV; mean of CVs calculated for the 11 sites) for each variable (nutrient concentrations and bulk density [D_B]) and peat layer sampled, and ranges (difference between the minimum and the maximum values) of the CVs among the study sites.

	0–10 cm Mean	(Range)	10–20 cm Mean	(Range)	20–30 cm Mean	(Range)	0–30 cm composites Mean	(Range)
P	0.155	(0.134)	0.119	(0.049)	0.120	(0.095)	0.092	(0.061)
K	0.289	(0.406)	0.394	(0.380)	0.438	(1.431)	0.245	(0.300)
Ca	0.236	(0.319)	0.250	(0.372)	0.232	(0.316)	0.199	(0.267)
Mg	0.354	(0.581)	0.371	(0.450)	0.249	(0.455)	0.301	(0.453)
Fe	0.346	(0.700)	0.306	(0.305)	0.266	(0.201)	0.233	(0.229)
Mn	0.783	(0.955)	1.658	(4.072)	1.218	(2.398)	0.748	(0.973)
Zn	0.425	(0.726)	0.546	(0.737)	0.593	(2.207)	0.385	(0.403)
D_B	0.225	(0.221)	0.168	(0.232)	0.139	(0.214)	0.114	(0.158)

Table 3. Total variances (summed up from the variance component estimates) and variable means (model constants) from the variance component models (Model 1 for All data; Model 1 without e_{ijkl} for 0–30 cm composites and Data by layers). P, K, Ca, Mg, Fe: mg g^{-1}, Mn, Zn: µg g^{-1}, bulk density [D_B]: kg m^{-3} dry matter.

	All data [a] Variance [b]	0–10 cm Variance [c]	Mean	Data by layers 10–20 cm Variance [c]	Mean	20–30 cm Variance [c]	Mean	0–30 cm composites Variance [c]	Mean
P	0.158	0.174	0.826	0.185	0.868	0.107	0.765	0.138	0.817
K	0.050	0.041	0.473	0.012	0.196	0.005	0.094	0.011	0.256
Ca	1.693	2.025	3.193	1.010	2.643	1.742	3.004	1.170	2.929
Mg	0.088	0.161	0.579	0.057	0.335	0.017	0.295	0.042	0.399
Fe	11.53	14.03	5.20	10.76	3.855	8.51	3.418	9.212	4.089
Mn	10160	18115	118.4	4325	41.17	5245	39.82	4750	58.84
Zn	181.9	191.7	26.85	78.98	10.13	37.83	5.83	43.69	14.03
D_B	2276	1326	88.59	2870	109.54	2001	105.39	1627	99.95

[a] The entire data set including all layers sampled (0–10 cm, 10–20 cm, 20–30 cm)
[b] $f_l + v_{kl} + u_{jkl} + e_{ijkl}$
[c] $f_l + v_{kl} + u_{jkl}$

systematic decrease with increasing depth for Fe and bulk density, and an increase with increasing depth for K and Zn.

For 0–30 cm composites, the CV of Mn was significantly lower on the undrained sites (0.2) than on the drained (0.6–1). The CV's of Ca and Mg correlated positively with tree stand volume (Spearman r = 0.606 and 0.779, respectively). The CV of Ca further correlated negatively with the site's mean Ca concentration (r = –0.518).

The total variances of K, Mg, Fe and Zn showed a clear decreasing pattern with increasing sampling depth (Table 3). However, this was accompanied by decreasing mean concentrations, and thus the relative variation of K and Zn, but not of Mg and Fe, actually increased on average with increasing depth (Table 2).

The contribution of sampling depth (peat layer) was more than 50% of the total variance for all other elements except for P and Fe, and bulk density (Table 4). Sampling depth contributed as much as 90% of total variance of Zn and K concentrations.

For P and Ca concentrations, the variance proportions of the different hierarchical levels were relatively stable across the sampling depths (Fig. 1). The other properties showed more variation in this respect. For bulk density, for instance, there was considerable between- and within-site variation in the topmost peat layer, while in the two deeper layers, peatland basins contributed most of the variation (Fig. 1). For Fe and Mn concentrations, the proportion of between-basin variation increased with increasing sampling depth. For K concentrations, in contrast, the proportion of within-site variation increased with increasing

Table 4. Proportion of total variance, %, contributed by sampling depth for all data, and the proportions of total variances, %, contributed by other hierarchical levels for the 0–30 cm composites data (see Table 3). Values in parentheses show the ratio of the variance component estimate to its standard error.

	All data [a] Depth	Peatland basin	0–30 cm composites Site	Within-site
P	20 (16.9)	83 (1.5)	9 (1.6)	8 (9.9)
K	89 (17.0)	22 (0.8)	33 (1.7)	44 (10.0)
Ca	51 (13.9)	68 (1.5)	2 (1.0)	30 (9.9)
Mg	77 (17.0)	0	48 (2.2)	52 (9.8)
Fe	33 (13.9)	60 (1.3)	17 (1.6)	23 (9.9)
Mn	81 (13.9)	0	29 (2.1)	71 (9.9)
Zn	92 (17.0)	7 (0.4)	30 (1.7)	63 (9.9)
D_B	40 (16.9)	77 (1.4)	9 (1.6)	14 (9.8)

[a] The entire data set including all layers sampled (0–10 cm, 10–20 cm, 20–30 cm)
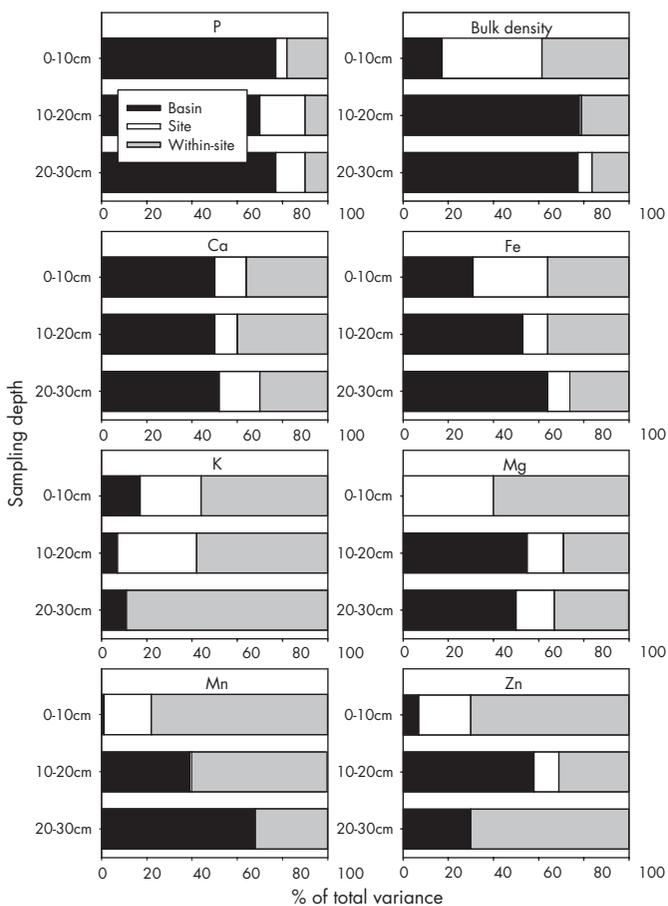
Fig. 1. Proportions of total variance, %, contributed by different hierarchical levels (peatland basin, site, and within-site variation) at different sampling depths.

Table 5. Significant correlations of tree stand volume, drainage, and thinning with nutrient concentrations and bulk density (D_B) of the 0–30 cm composites. '+' denotes positive and '–' negative correlation. Correlations were derived from multilevel models including fixed effects (see section 2.3). For Fe and Mn concentrations, none of the effects was significant. Parentheses show where estimates were indicative, but not significant at the 0.05 level. Distance to ditch is a sampling-location-level variable; other effect variables are site-level variables.

Effect	Variable					
	P	K	Ca	Mg	Zn	D_B
Tree stand volume	+	+	+	(+)	–	+
Drainage age	–	–	–	–		(–)
Thinning	+	(+)	+		–	+
Distance to ditch	–					

sampling depth.

The variance patterns for the 0–30 cm composites varied among the elements. Variation among peatland basins contributed as much as 80% of the total estimated variance in bulk density and the P concentration (Table 4). For Fe and Ca concentrations, between-basin variation contributed 60–70% of the total variance. For Mg, Mn, Zn and K concentrations, in contrast, the between-basin variation was clearly non-significant in our material. Of the elements studied, Mg, K, Zn and Mn varied most strongly among the sites, but even for these elements, the within-site variation contributed the biggest proportion of the total variance for the 0–30 cm composites (Table 4).

Concentrations of P, K, Ca and Mg were lower on the drained sites than on the undrained (Table 5). There was positive correlation between the concentrations of P, K and Ca, as well as bulk density and tree stand volume of the site. Bulk density and the concentrations of P and Ca were higher in sites where tree stands had been thinned.

3.2 Sample Size and Reliability of Site-level Estimates

Bulk density and the concentration of P were the peat characteristics requiring the least intensive sampling for reliable estimates of site mean values to be obtained (Fig. 2). On average, 4–5 samples per site gave a theoretical 10% maximum deviation of the mean when examining the 0–30 cm composites. To reach similar reliability with the estimates in 95% of the sites, 5–6 samples would be needed. The estimates of Mn concentrations were the most variable: 200 samples per site would be needed to achieve 10% maximum deviation from the mean.

The estimates obtained with a certain number of samples per site were always more reliable (i.e. had the smaller theoretical maximum deviation) for the 0–30 cm composites than for any single 10-cm layer at any depth sampled (Figs 2–3). For most variables, the differences in estimate reliability among sampling depths were minor (P and Mg as examples, Fig. 3). However, the unreliability of the Mn mean concentration estimates was even more pronounced in the two lower sampling depths than in the topmost 10 cm sampled. In the case of K, and Zn, reliability was at its lowest in the deepest layer sampled (Fig. 4).

4 Discussion

4.1 Variation in Peat Characteristics

Our sites represented a single initial mire site type, and one nutrient level class. Both undrained and drained sites were included. The site type we studied is in its natural state characterized by a mosaic-like variation of low hummocks and wetter lawns. Local variation in hydrology and vegetation composition and, consequently, soil
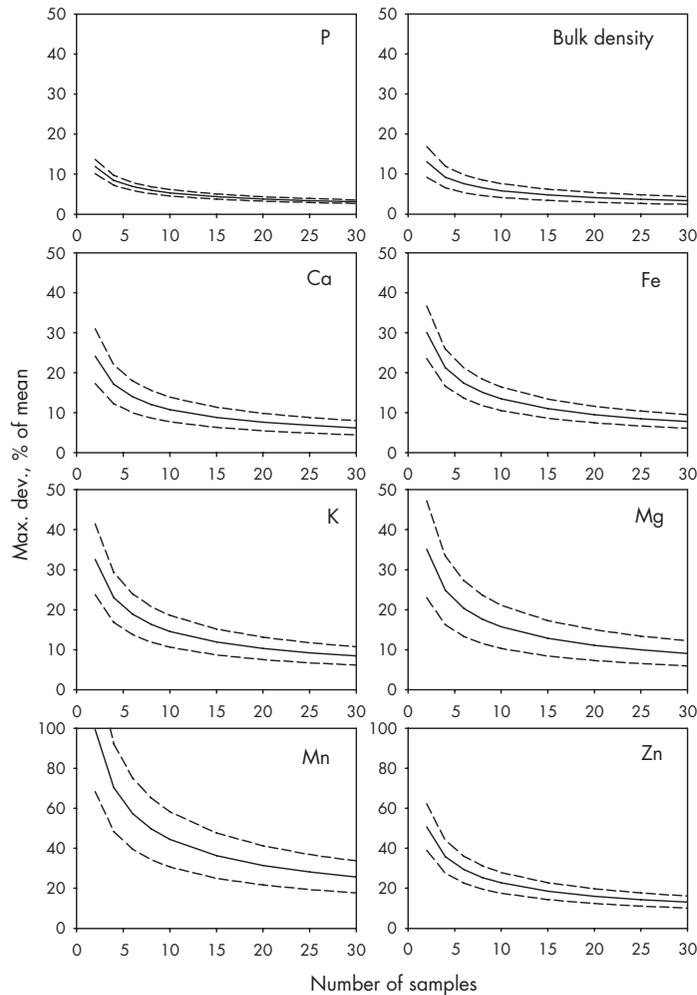
Fig. 2. Theoretical maximum deviations of sample means from population means in the 0–30 cm peat layer relative to the number of samples taken per site. Solid line = mean of all 11 sites, dashed lines = 95% confidence limits.

redox potential and litter quality (Belyea 1996, Moore 1989) are presumably crucial factors in determining the extent of within-site variation in soil characteristics on the undrained sites.

Drainage has often been found to cause an increase in peat bulk density (Minkkinen and Laine 1998, Silins and Rothwell 1998). Drainage also changes the patterns of total nutrient uptake by the vegetation (Laiho et al. 2003) and element leaching (Sallantaus 1992), thus leading to decreases in the soil base cation concentra-

tions (Laiho et al. 1999). These impacts were also detected in our material. For most soil characteristics, however, the extent of within-site variation was similar on our undrained and drained sites.

Of all the elements studied, Mn showed the highest within-site variation, and its variability was even higher on the drained than on the undrained sites. The mobility of Mn varies strongly according to its valence, which, in turn, depends on whether the conditions in the soil are reducing or oxidizing. The extreme horizontal within-site
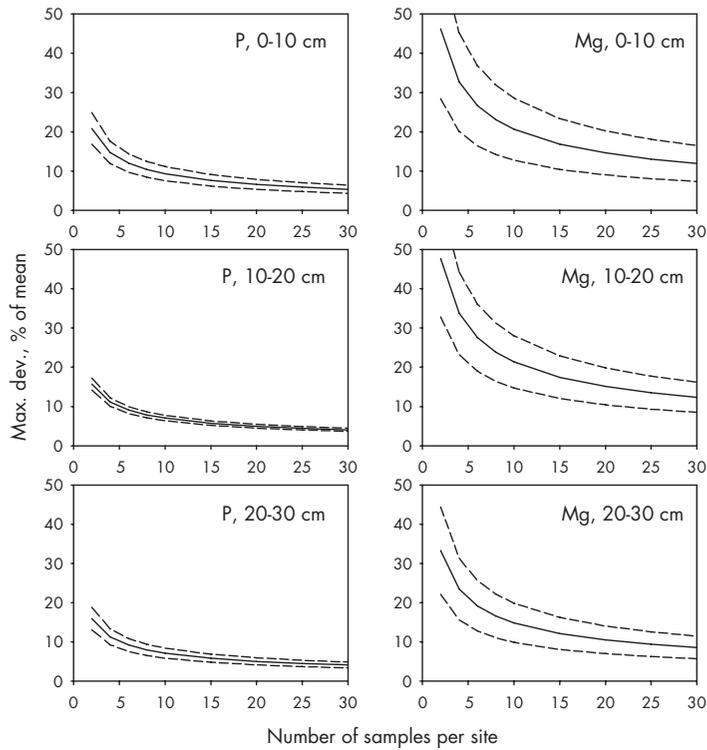
Fig. 3. Theoretical maximum deviations of total P and Mg concentration estimates (sample means) from population means in different peat layers (sampling depths) relative to the number of samples taken per site. Solid line = mean of all 11 sites, dashed lines = 95% confidence limits.
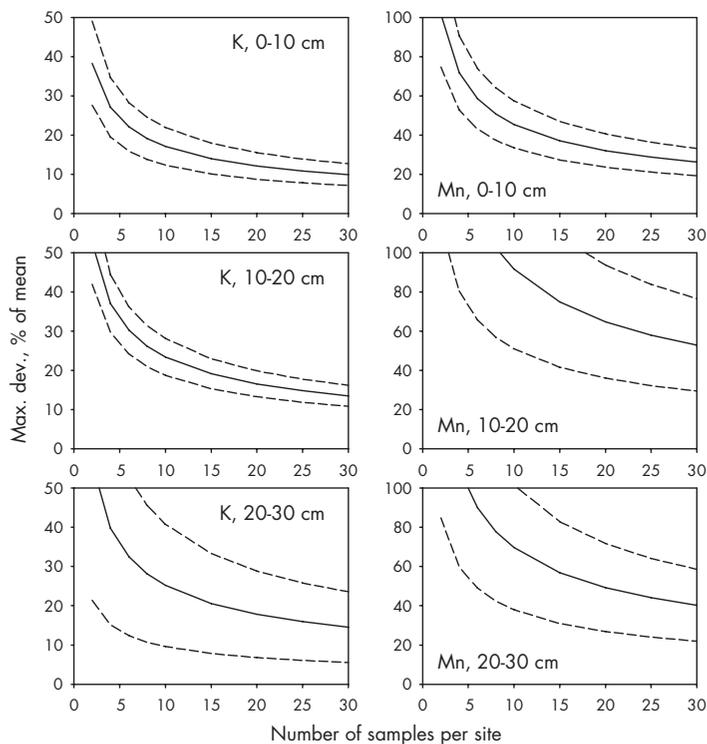
Fig. 4. Theoretical maximum deviations of total K and Mn concentration estimates (sample means) from population means in different peat layers (sampling depths) relative to the number of samples taken per site. Solid line = mean of all 11 sites, dashed lines = 95% confidence limits. Note the difference in y-axis scales between K and Mn.

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variation in Mn concentrations especially below 10 cm may thus reflect spatial and temporal variation in soil redox. Despite the generally lower water-levels and greater aerobic limit depths (Boggie 1977, Silins and Rothwell 1999), the aerobic limit depth varies greatly on drained sites, being clearly above the water level especially during the summer months, when oxygen consumption is at its highest (Lähde 1969, 1971).

Ca and Mg concentrations showed increasing within-site variation with increasing tree stand volumes. There are several possible reasons for this. Increasing nutrient uptake (Laiho et al. 2003) may vary locally if root distribution is uneven. Nutrient input in throughfall and stemflow varies with tree distribution, which was uneven on all our sites. A Scots pine canopy acts as a source of Ca and Mg, but also of Mn and K (Helmisaari and Mälkönen 1989). Increasing tree stand biomass leads to increasing soil acidity as well, due to cation uptake and the acidity of the throughfall. Buffering of soil leachate acidity may be a more important factor for changes in peat soil Ca and Mg concentration than uptake by trees (Laiho et al. 1999).

The distinctive vertical distribution of K, with the concentration dropping drastically with increasing depth, has been regularly observed (e.g. Holmen 1964, Damman 1978, Laiho et al. 1999). It is explained by biological cycling (Jobbágy and Jackson 2001) of this element that is in short supply on most deep-peat sites (Westman and Laiho 2003). On our sites, Zn concentrations followed a similar pattern. Because K in peat is largely soluble (Starr and Westman 1978) and moves readily with water, we were somewhat surprised to see that the within-site variation of K concentrations was not more clearly higher than that of more abundant elements. The majority of plant roots that are involved in the biological retention of K are to be found in the topmost peat, and their biomass drops clearly as one moves from the 0–10 layer to the 20–30 cm layer (Heikurainen 1955, Paavilainen 1966, Laiho and Finér 1996, Saarinen 1996). The increased relative variability of K and Zn in the 20–30 cm layer may suggest that vegetation and/or microbes are able to maintain spatially rather even distribution in the upper peat layers, while in the deeper layers K distribution becomes more patchy and

potentially more affected by water movements. The observation that variability in the K concentration did not correlate with tree stand volume supports the conclusion that tree uptake is not the major factor affecting the variability of Ca and Mg either, as tree uptake would be likely to affect K concentrations more than those of Ca and Mg, the latter two not being as much in demand.

Our sampling was designed for quantifying within-site variation in peat characteristics. Our data are not sufficient for examining the extent or causes of variation between or within peatland basins. Further, as only two peatland basins in our material contained several sample sites, distinguishing between the effects of these two levels of data is uncertain. This manifests as nonsignificant variance estimates (variance-estimate: standard-error ratio < 2). Consequently, our results concerning variation between and within peatland basins should be interpreted with due caution.

In previous studies, peat thickness, climate (temperature sum) and drainage have been identified as factors systematically affecting at least some peat characteristics (Laiho and Laine 1995, Sundström et al. 2000, Westman and Laiho 2003). Local variation in underlying mineral soil properties as well as in minerogenic water inputs are likely factors inducing random variation at all levels. The great variability among peatland basins in Ca and Fe concentrations may also reflect ecohydrological differences between aapa mire and raised bog sites. The concentrations of these elements were clearly higher on the aapa mire sites than on the more southern sites (see also Starr and Westman 1978).

4.2 Implications for Sampling Designs

On the drained sites, P concentrations were, on average, slightly lower close (≤ 5 m) to the ditches, while the other peat characteristics measured were not significantly affected by the distance to the nearest ditch. The drainage effect and, consequently, changes in decomposition and nutrient cycling processes, may be more pronounced close to drainage ditches than in the middle of the strip (Seppälä 1972, Silins and Rothwell 1999). Thus, it is safest to have sam-

pling, designed to represent a drained site, cover the entire strip between ditches.

On our sites, sampling location distances ≥ 5 m from each other produced spatially independent observations in the statistical sense, or spatially non-correlated replicates, on the scale of the site. Our material did not allow for analysis of a finer-scale spatial structure, which probably exists. Ohlson and Økland (1998) found a spatial structure in peat nitrogen concentration at scales below 1 m. Our results suggest that when the sampling location distances are at least 5 m, soil samples may be used for estimation of the site mean (also as a composite sample) without the need to account for a spatial structure.

As to the elements that show clear variation with sampling depth, especially K and Zn, it is crucial to determine with care the base-line (zero-line) for sampling. Small deviations in sampling depth among sites would lead to disparate estimates.

To achieve accurate site-level estimates, a considerable number of replicates is needed for most peat characteristics. This is especially crucial for sampling designs in monitoring studies. If we could assume that 1) the magnitude of variation remains constant over time, and 2) there are no correlations between the estimates obtained with two consecutive samplings, we could use the within-site variation to estimate the magnitude of change that may be detected with a certain sample size in two consecutive samplings (see Johnson et al. 1990, Hargreaves et al. 2003). On our peatland sites, the mean difference detectable with 20 samples per site for the 0–30 cm peat layer in 95% of the cases would vary from 6–8% for P concentration and bulk density, and 14–22% for base cations and Fe, up to 60% for Mn. Thus, to overrule the uncertainty caused by within-site variation, the change between two consecutive samplings would have to be considerable for most soil characteristics, and the smaller the number of samples per site, the greater the change would have to be.

Acknowledgments

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