Macroscale Variation in Peat Element Concentrations in Drained Boreal Peatland Forests

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Information on the variation in soil element concentrations at different spatial scales is needed for, e.g., designing efficient sampling strategies, upscaling the processes related to carbon cycling, and planning land use and management. In spite of intensive land use, such information concerning peat soils is still scarce. We analyzed the variation in peat mineral element concentrations in boreal peatland forests drained 50–60 years earlier. We wanted to quantify the proportions of variation deriving from differences between regions and peatland basins and from within-peatland heterogeneity, and to model the variation using relatively easily measurable site and soil characteristics. We utilized 878 peat samples representing the 0–20 cm layer and collected from 289 sites in 79 peatland basins. The sites represented three different drained peatland forest site types. The two strongest gradients in the element composition captured by principal component analysis were correlated with both the North-South gradient and the site type variation, and the East-West gradient. In general, most of the variation in the element concentrations was contributed by differences among peatland basins, and variation within the floristically determined sites. Most of the element concentrations were best modeled when either the bulk density or the ash content of the peat, or both, were used in addition to site type and geographical location. The explanatory power remained modest for most element concentrations. As for the P concentrations in soil, however, our models provide means for estimating a large part of the variation among drained pine mire sites.

Keywords drainage, peat soil, nutrient deficiencies, spatial variation, soil nutrients
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1 Introduction

Peat soils worldwide are important stores of carbon (C). While the peat C stores have been in focus because of their importance in greenhouse gas balance (Gorham 1991), clearly less is known about the variability of other elements at different scales. This information is needed for upscaling the processes related to C cycling (see Morris and Boerner 1998), the rates of which generally depend on the soil nutrient regime (Minkkinen et al. 2007), as well as for planning land use and management under the wise use concept. Together with an understanding of microscale, within-site variation in soil properties (Laiho et al. 2004), information on macroscale variation within and between larger geographical units, is essential for designing efficient sampling strategies for various purposes.

More than 10 million ha of peatlands have been drained for forestry in Northern Europe (Paavilainen and Päivänen 1995). In Finland they occupy 4.6 million ha of forest land and account for about a quarter (ca. 21 $M m^3 yr^{-1}$) of the current annual increment of the total growing stock (Tomppo 2005). The selection of peatland sites for drainage has usually been based on the evaluation of the floristic-ecological site types. Following drainage, when the influence of excess soil water is eliminated, the nutrient regime of the peat soil controls tree stand development. There is considerable variation in the soil nutrient characteristics within the floristic-ecological site types both in pristine (Westman 1981) and drained (Westman and Laiho 2003) peatlands. This has, however, not been acknowledged in the practical forest management planning.

Nutrient deficiencies severely limiting or even pre-empting tree growth have most often been observed on originally wet, treeless or sparsely treed site types with a thick peat layer (Kaunisto 1987, Kaunisto and Tukeva 1984). Partly because of severe nutritional problems, treeless site types have not been drained for forestry since the 1980's. The often sparsely forested, so-called composite site types that consist of both treeless and forested microforms, have, however, commonly been subject to drainage because of their good potential for wood production due to the high peat nitrogen (N) content (e.g. Westman and Laiho 2003). On treeless or sparsely stocked sites, scantiness of other nutrients relative to N may cause problems for tree growth (Kaunisto 1987, Pietiläinen et al. 2005). Potassium (K) deficiencies, especially, have been reported for such sites in the western parts of Finland (Kaunisto and Tukeva 1984, Kaunisto 1992, Saarinen 1997, Silver and Saarinen 2001, Rautjärvi et al. 2004). Low K stores may result from low biological retention due to the relatively small amounts of perennial plant organs on these sites. Catchment characteristics may however also have their influence. Phosphorus (P) deficiencies are also common in thick-peat, originally treeless or composite sites (Kaunisto and Tukeva 1984, Silfverberg and Hartman 1999, Silver and Saarinen 2001, Moilanen et al. 2005). Still, it is difficult to recognize, accurately and in time, the sites where a severe imbalance of nutrients is likely to develop.

Currently, we do not know whether there is such regional variation in the concentrations of some nutrients, such as K, that would not affect the vegetation-based site type classification outcome, but would affect tree growth. Although we have some knowledge of the average differences in soil nutrient pools among site types (Westman and Laiho 2003), we lack means for estimating the extent of variation within site types. Such models might facilitate recognizing the sites, where the tree stands are not likely to reach commercial maturity without successive fertilizations. More accurate knowledge on the inherent variation within peatland site types would be useful in planning more feasible guidelines for forest management. This would further help to allocate the resources more effectively, which is essential, e.g., in decreasing the environmental load of forestry.

Our aim was to examine and model the variation in element concentrations (P, K, Ca, Mg, Zn, Cu, B, Fe, Al) in drained peatland forests from the following points of view:

1) what are the *proportions of variation* deriving from various sources: differences between regions and peatland basins, and within-peatland heterogeneity,
2) can the variation be related to some relatively easily measurable *site* characteristics, such as site type, geographic location, peat thickness and distance from mineral soil site, and
3) can the variation be related to some relatively

easily measurable *soil* characteristics such as bulk density or ash content.

The study focused on old (40–60 years) drainage areas representing sparsely forested composite site types, which are considered vulnerable for tree nutrient deficiencies and imbalances.

2 Material and Methods

2.1 Study Sites

We used peat samples collected from drained peatlands throughout Finland by Minkkinen and Laine (1998a, b) for peat bulk density and carbon analyses. The sampling sites were clustered within five regions covering the macroclimatic gradient and the main zones of mire vegetation in the country (59°50´–67°15´N, 22°40´–31°20´E) (Fig. 1). The three southernmost regions were situated in the raised bog zone, where mires usually have an ombrotrophic centre surrounded by a minerotrophic lagg and marginal slope. The two northern regions lay in the zone of aapa mires, where the development of an ombrotrophic centre in the mire is inhibited, probably because of cold climate and repetitive flooding after snowmelt (Seppä 1996).

The material consisted of sites that represented the following drained peatland forest site types (Laine 1989): 1) *Vaccinium myrtillus* type II (henceforward Mtkg II), 2) *Vaccinium vitis-idaea* type II (Ptkg II), and 3) dwarf-shrub type (Vatkg). These mostly originate from the following pristine pine mire site types: 1) Herb-rich sedge birch pine fen (RhSR sensu Laine and Vasander 1996), 2) Tall sedge pine fen (VSR) and 3) Cottongrass tall sedge pine fen (TSR) or its northern counterpart Low-sedge *Sphagnum papillosum* pine fen (LkR). RhSR sites are mesotrophic, or intermediate fens, VSR sites are oligotrophic, or poor fens, and TSR and LkR sites are oligotrophic, very poor fens close to ombrotrophy. The chosen site types are the most common ones drained for forestry purposes in Finland, covering 30% of all peatlands drained during 1930–1978 (Keltikangas et al. 1986). The most common drained site type is VSR, which covers 11% of the total drained

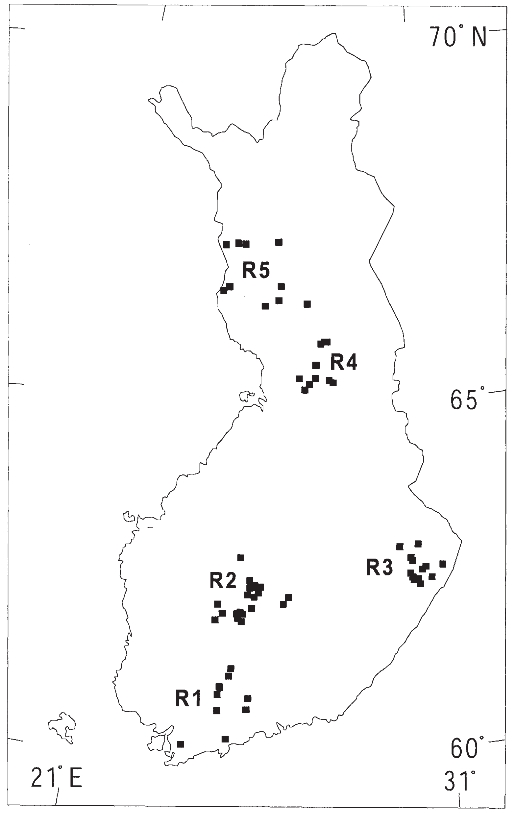

Fig. 1. Sampling locations. R1–R5 = codes given to regions within which the sampling was clustered.

area (Keltikangas et al. 1986). Since our sites were recognized based on the post-drainage site type, there may have been some variation in the pre-drainage site types within each class.

Typical for the pristine sites of all these site types is a mosaic-like pattern of tree-growing hummocks and treeless lawns. Scots pine (*Pinus sylvestris* L.) is the dominant tree species on all types while pubescent birch (*Betula pubescens* Ehrh.) is abundant only on RhSR sites. In pristine conditions, the trees usually remain stunted. Occurrence of mesotrophic herbs (e.g. *Potentilla palustris* (L.) Scop.) is restricted to RhSR sites. Mire dwarf shrubs (e.g. *Ledum palustre* L., *Vaccinium uliginosum* L. *Betula nana* L.) growing on hummocks are characteristic of all site types. Tall sedges (*Carex rostrata* Stokes, *Carex lasiocarpa* Ehrh.) dominate the lawn levels of RhSR and VSR sites but are found only infrequently on TSR and LkR sites. The bottom layer is covered by *Sphagnum* species (e.g. *Sphagnum fallax* (Klinggr.) Klinggr., *Sphagnum angustifolium* (Russ.) C. Jens.). Peat is formed mainly by remains of sedges with a mixture of *Sphagna* increasing along the gradient towards ombrotrophic conditions.

Drainage induces a secondary succession along which a gradual shift of mire vegetation towards more forest-like vegetation types takes place. In old drainage areas *Sphagna* as well as sedges and mire herbs are replaced by forest mosses (e.g. *Pleurozium shreberi* (Brid.) Mitt.) and dwarf shrubs (e.g. *Vaccinium myrtillus* L., *V. vitis-idaea* L.) (Laine et al. 1995). On TSR and LkR sites, mire dwarf shrubs may remain characteristic for a longer time, due to relatively sparse tree stand and consequent favourable light conditions. Biomass production is concentrated on the tree stand (Laiho et al. 2003), which is still dominated by Scots pine and/or pubescent birch.

2.2 Sampling and Chemical Analyses

The sites selected for the study had been drained mainly in the 1930's. On average, 54 years (range 35–61) had passed since drainage before sampling. Tree stand volume was estimated at each site using a relascope and ocular assessment of mean tree height. Volumetric peat samples (surface area 8 cm × 8 cm) were taken along ditch lines at 40 meter intervals about 7–8 meter from the ditch border (for a closer description of the site selection and sampling see Minkkinen and Laine 1998a). The living moss layer was removed from peat surface before sampling. Altogether, 878 peat cores collected from 289 sites in 79 peatland basins were included in this study (Fig. 2). Site means here a part of a peatland that represents a certain, floristically defined post-drainage site type.

Nutrient concentrations were analyzed in the topmost 0–20 cm samples. The peat samples were dried to constant mass at 105 °C, weighed and milled through a 2-mm sieve. Organic matter content was determined by loss of ignition at 550 °C. In the first phase, 285 samples were analysed for P, K, Ca, Mg, Fe, Al, Zn, Cu and B concentrations using an ICP-analyser (Finnish Forest Research Institute, Parkano Laboratory) after 2M HCL extraction. We refer to these measurements as 'set 1'. For this study, the remaining 593 samples were analysed using an ICP-analyser (Finnish Forest Research Institute, Central Laboratory, Vantaa) after HNO_3-hydrogen peroxide digestion. These measurements will be referred to as 'set 2'. The concentrations of Na, Mn, Pb, S were analyzed as well, but are not examined in detail here.

2.3 Calculations and Data Analyses

The bulk density (D_b) of the samples was calculated by dividing the dry mass by the fresh volume. The mean temperature sum for 1960–1990 (corrected by altitude and areal proportion of lakes) was derived for each site from the SIPATI database (Alm and Lempinen, 1994).

Correlations among soil properties, and their overall correlations with site characteristics, were examined with ordination analyses. Principal component analysis (PCA) was first applied to explore the patterns in soil properties. Redundancy analysis (RDA) was then applied to evaluate the significance of the site characteristics in explaining the patterns. We also performed RDA using combination terms for site types and regions, to

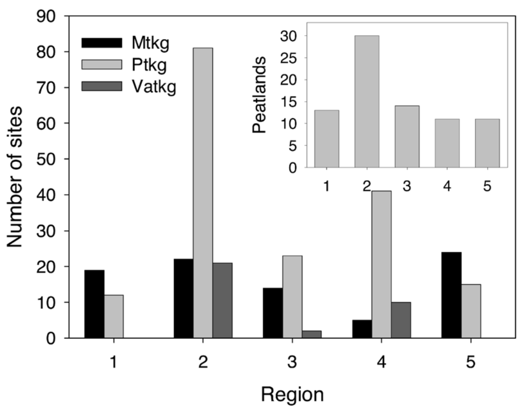

Fig. 2. Distributions of the sampled drained peatlands (smaller insert), and the sampled sites representing different floristic-ecological site types (larger graph), among regions.

see if patterns concerning site types diverged between regions. For these analyses, the values of soil properties (element concentrations, bulk density, ash concentration) were log-transformed because some of the distributions were skewed, and standardized to cope with the partly differing measurement units. The ordination analyses were performed using Canoco for Windows v. 4.5 (ter Braak and Šmilauer 2002).

For analyzing the variation in single soil properties, we applied multilevel modelling approach, with which the hierarchical data structure can be accounted for (e.g., Goldstein 1995).We identified four hierarchical levels, or levels of clustering, in the data: geographical region, peatland basin, site, and sampling point. Values of Fe, Mg, Zn and Cu were log(e) transformed to normalize their distributions. A few extreme outliers, which were abnormally high concentration values, were deleted based on examination of residuals.

First, we quantified the variation derived from the hierarchical levels by constructing simple variance component models, which had the following form:

$$y_{ijkl} = \alpha + \beta x_{ijkl} + f_l + v_{kl} + u_{jkl} + e_{ijkl} \quad (1)$$

where y_{ijkl} denotes the value of the response variable (element concentration) for sampling point i in site j in peatland k in region l, α denotes the mean intercept, x_{ijkl} is a binary variable accounting for the potential systematic differences between the two sets of chemical analyses (1 for set 1, 0 for set 2), f_l is the region-level residual (which is the same for all observations in region l), v_{kl} is the peatland-level residual (which is the same for all observations in peatland k in region l), u_{jkl} is the site-level residual, and e_{ijkl} is the sampling point-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, so that it is sufficient to estimate their variances, σ^2_f, σ^2_v, σ^2_u and σ^2_e. These variances are the random parameters of the model, while α and β are fixed parameters. The estimation was done by using MLwiN software (Rasbash et al. 2004), which estimates the fixed and random parameters simultaneously.

Next, we started adding explanatory variables to the fixed part of the model. This was done in four steps. First, dummy variables describing the site types were added, to see if there were, on average, significant differences between site types. Ptkg II was used as the baseline because it was the most commonly sampled site type. Second, geographic trends were evaluated by adding North and East coordinates. Third, general site or sampling point characteristics were added. The variables available were distance to the closest mineral soil site, peat depth, and tree stand volume at sampling point level, and average long-term temperature sum at site level. Last, easily measurable soil characteristics were added. The variables available were ash content and bulk density. The final models were estimated with the restricted iterative generalized least-square (RIGLS) method recommended for small samples.

We assumed that with inclusion of explanatory variables in the fixed part, f_l, v_{kl} and u_{jkl} would become insignificant, whereas e_{ijkl} would remain significant because of the inherent spatial heterogeneity of the soil. The distribution of the remaining variance among the hierarchical levels would indicate which level variables should be added to the model. Parameter standard error was used as a measure of parameter significance (value should be at least twice its s.e.). The value of –2*log-likelihood was used to compare the overall goodness-of-fit of the models of increasing complexity. Proportion of total variance explained was calculated by summing up the variance components of the models (including non-significant components), and comparing them with the initial total variances from Eq. 1.

To evaluate the model reliability and accuracy, systematic error (bias) and relative systematic error (bias_r) were calculated as follows:

$$\text{Bias} = \sum_{i=1}^{n} \left(y_i - \hat{y}_i \right) / n \quad (2)$$

$$\text{Bias}_r = \sum_{i=1}^{n} \left(\left(y_i - \hat{y}_i \right) / y_i \right) / n \quad (3)$$

where n is the number of observations, y_i the observed value of the nutrient concentration i, and $\hat{y}_i$ the predicted value of the nutrient concentration.

3 Results

3.1 Covariation of Soil Properties and Site Characteristics

PCA recognized two clear gradients in the soil properties (Fig. 3). The strongest pattern, captured by the first principal component (PC1), was shown as strong intercorrelations of the concentrations of P, Cu, Fe and Al; these were also correlated with bulk density and ash. On the other hand, the concentrations of base cations (Ca, Mg, K, Na) had strong intercorrelations, reflected by PC2.

The pattern reflected by PC1 was correlated with both the North-South gradient and the site type variation: concentrations of P and correlated elements increased towards North, and from Vatkg sites to Ptkg II and further Mtkg II sites (Fig. 3). Overall, the site types differed clearly from each other concerning the total variation in soil properties. A closer analysis revealed that Ptkg's in regions 4 and 5 were quite similar to

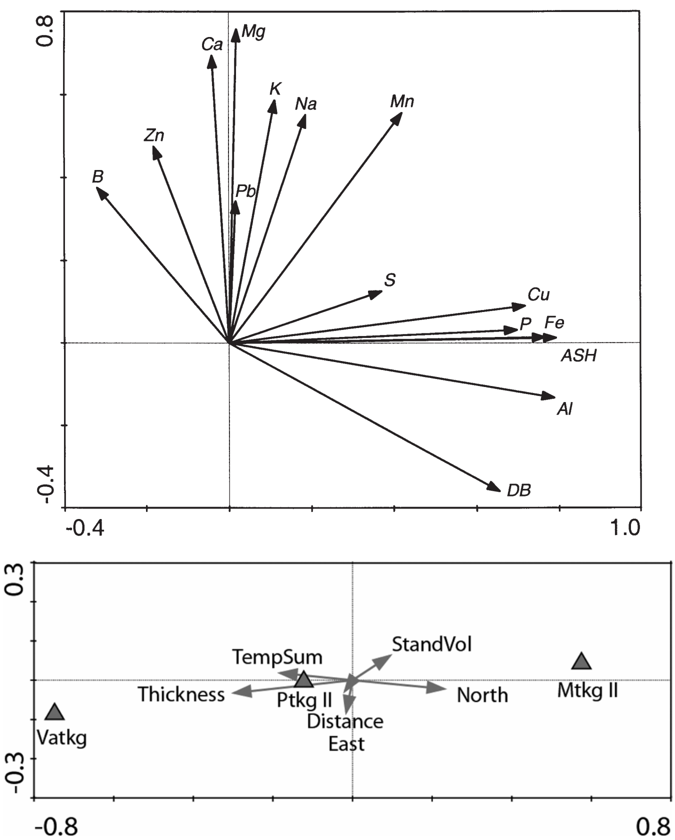

Fig. 3. Principal component analysis of the soil properties. Ordination of the soil properties (top), and the relations of the studied site characteristics therewith (below). The first principal component ("x-axis") explained 25.1%, and the second principal component ("y-axis") 17.8% of the variation in soil properties, respectively. Triangles depict centroids for binary variables: Mtkg II = *Vaccinium myrtillus* type 2, Ptkg II = *Vaccinium vitis-idaea* type 2, Vatkg = Dwarf-shrub type of drained peatland forest (*sensu* Laine 1989), while arrows depict continuous variables: East, North = longitude and latitude; Distance = distance to the closest mineral soil site; Thickness = thickness of the peat deposit; TempSum = long-term average of the air temperature sum with a 5 ºC threshold; StandVol = total volume of the tree stand.

Mtkg's, while Ptkg's in regions 2 and 3 were more similar to Vatkg's, especially those of region 4 (not shown). The pattern reflected by PC2 was related to the East-West gradient (Fig. 3).

The measured site characteristics (site type, sampling region, geographical location, temperature sum, peat thickness, stand volume) correlated significantly ($p<0.01$) with the pattern of variation in the soil properties; distance of sampling point from mineral soil site was the only exception. Altogether, they were able to explain only 24.3% of the total variation in the nutrient concentrations. Site type and geographic location together explained 15% of the variation.

3.2 Factors Explaining the Variation of Single Element Concentrations

In the variance component analyses (Eq. 1), the dummy-variable distinguishing the different sets of the chemical analyses had a significant coefficient for all elements except Ca (Table 1). This suggests a systematic difference between the analyses done with two different methods. Concentrations measured for set 1 were lower than those for set 2.

The variance component of the sampling region remained insignificant in all cases. Substantial regional differences were nevertheless indicated for Fe, especially, but also for P, Cu, Mg, B and Al (Table 1). Peatland basin was the major source of variation in Ca, Cu, Mg, Al and P concentrations. It further contributed around one third of the total variance for all other elements except Zn, for which the peatland basin explained only 14% of the total variation. For Ca concentrations the peatland basin was the largest source of the variation (59%). Site (within peatland) contributed 10%–20% of the total variance, except for B, for which the site effect was non-significant. Sampling point (within site) was the major source of variation for Zn, B and K, and contributed a substantial proportion of the total variance, 15%–34% for other element concentrations as well.

Significant differences among site types were found in most element concentrations; Ca and B were exceptional in this respect (Tables 2 and 3). Nutrient concentrations within Mtkg II sites generally differed from those on Ptkg II sites, while Ptkg II and Vatkg differed significantly from each other only regarding concentrations of P, Zn and Cu. The concentrations generally followed the order Mtkg II > Ptkg II > Vatkg. An opposite pattern was found for B, and for Zn, Ptkg II sites had the highest average concentrations.

Significant overall North-South gradient was found for P, the concentration of which increased towards north (Tables 2 and 3). Significant overall East-West gradients were found for K, Fe and Al,

Table 1. Means, level difference between the two data sets (Anal. diff. = deviation of Set 1 values from Set 2 values; see Material and Methods), total variation, and variance components of soil element concentrations in the top 0–20 cm peat layer. The values were obtained from Eq. 1, with a constant for capturing the mean concentration and a dummy variable for capturing the difference as fixed variables, and region, peatland basin, site within peatland, and sampling point within site as random variables. ns = not significant. For Mg, Fe, Zn and Cu, back-transformed mean values are shown.

Element	n	Mean	(s.e.)	Anal. diff.	(s.e.)	Total variance	Variance, % Region	Peatland	Site	Locat.
P, mg g^{-1}	875	1.09	(0.1)	–0.047	(0.016)	0.167	25ns	35	15	25
K, mg g^{-1}	871	0.427	(0.018)	–0.110	(0.008)	0.027	3ns	34	16	47
Ca, mg g^{-1}	875	2.89	(0.32)	ns		3.88	8ns	59	12	21
lnMg, mg g^{-1}	875	0.499	(0.07)	–0.046	(0.023)	0.290	15ns	38	15	32
lnFe, mg g^{-1}	875	6.02	(1.38)	–0.208	(0.032)	1.17	41ns	36	8	15
Al, mg g^{-1}	874	3.21	(0.40)	–0.298	(0.100)	4.88	13ns	36	17	34
B, µg g^{-1}	875	2.7	(0.3)	–0.334	(0.090)	2.38	14ns	26	1ns	59
lnZn, µg g^{-1}	874	16.9	(1.1)	–0.213	(0.032)	0,31	5ns	14	17	64
lnCu, µg g^{-1}	875	6.7	(1.1)	–0.069	(0.023)	0.363	20ns	40	15	25

Table 2. Estimates of average concentrations for different regions and site types, based on site-level values [number of sites in brackets]. Standard deviations in parentheses. Set 1 values were adjusted with the deviation values shown in Table 1.

Region Site type [n]	P mg g^{-1}	K mg g^{-1}	Ca mg g^{-1}	Mg mg g^{-1}	Fe mg g^{-1}	Al mg g^{-1}	B µg g^{-1}	Zn µg g^{-1}	Cu µg g^{-1}
R1									
Mtkg II [18]	1.075 (.439)	0.559 (.444)	3.37 (1.38)	0.665 (.660)	30.13 (48.18)	4.82 (2.28)	3.8 (1.1)	17.7 (13.1)	11.5 (6.0)
Ptkg II [12]	0.867 (.231)	0.435 (.122)	3.73 (1.61)	0.511 (.163)	6.96 (8.81)	3.18 (2.38)	3.6 (1.4)	19.2 (9.3)	7.0 (2.2)
R2									
Mtkg II [22]	1.350 (.326)	0.506 (.145)	2.10 (0.67)	0.356 (.092)	4.68 (2.06)	4.46 (1.26)	1.5 (0.5)	11.1 (3.9)	7.5 (3.2)
Ptkg II [81]	1.017 (.242)	0.436 (.141)	2.11 (0.71)	0.377 (.089)	3.28 (1.18)	2.58 (1.43)	2.2 (0.8)	18.0 (6.0)	5.6 (1.9)
Vatkg [21]	0.812 (.166)	0.389 (.075)	1.90 (0.70)	0.368 (.097)	2.22 (0.62)	1.63 (1.01)	2.6 (0.9)	20.3 (6.0)	4.1 (0.9)
R3									
Mtkg II [14]	1.012 (.187)	0.374 (.055)	1.88 (0.72)	0.306 (.105)	10.03 (5.59)	3.48 (1.77)	2.4 (0.7)	15.6 (5.7)	20.2 (17.1)
Ptkg II [23]	0.756 (.154)	0.356 (.096)	2.82 (1.33)	0.373 (.146)	5.00 (5.42)	2.02 (1.25)	3.2 (0.9)	18.7 (7.9)	10.4 (9.6)
Vatkg [2]	0.745	0.395	1.77	0.404	2.36	1.63	2.0	25.9	4.6
R4									
Mtkg II [5]	1.570 (.244)	0.478 (.165)	4.57 (2.69)	1.044 (.559)	17.98 (8.24)	3.09 (1.47)	3.2 (0.8)	12.9 (2.8)	6.9 (2.5)
Ptkg II [41]	1.386 (.252)	0.413 (.094)	2.39 (1.02)	0.549 (.251)	9.53 (3.93)	3.55 (1.59)	2.2 (0.6)	11.6 (2.8)	5.2 (1.3)
Vatkg [10]	1.016 (.307)	0.411 (.094)	2.52 (0.65)	0.428 (.080)	6.15 (4.48)	2.46 (1.06)	2.7 (1.1)	17.8 (7.6)	4.5 (1.2)
R5									
Mtkg II [24]	1.517 (.494)	0.483 (.314)	2.18 (1.1)	0.496 (.256)	41.59 (31.50)	5.58 (2.86)	2.0 (1.0)	17.2 (9.6)	14.5 (7.1)
Ptkg II [15]	1.202 (.375)	0.502 (.500)	5.20 (6.0)	0.908 (.728)	26.48 (28.57)	4.09 (2.46)	2.8 (2.0)	14.1 (6.9)	10.7 (5.4)

Table 3. Fixed part parameters (standard errors in parentheses) for the models of soil element concentrations testing site type differences and geographical gradients. For site type differences, the *Vaccinium vitis-idaea* II type (Ptkg II) was used as the base line. Significant effects (parameter value at least double s.e.) are shown in bold face. a = constant; Analytical difference = deviation of Set 1 values from Set 2 values (see Material and Methods); Mtkg II = *Vaccinium myrtillus* II type; Vatkg = Dwarf shrub type, North = latitude (m); East = longitude (m).

Model	a	Analytical difference	Mtkg II	Vatkg	North	East	Variance explained, %	Relative bias, %
P2	1.029 (0.101)	–0.048 (0.015)	**0.220** (0.034)	**–0.128** (0.048)			8	+0.6
P3	–2.535 (2.365)	–0.048 (0.015)	**0.220** (0.034)	**–0.128** (0.048)	**0.735** (0.254)	–0.464 (0.502)	27	+1.6
K2	0.411 (0.018)	–0.110 (0.009)	**0.053** (0.016)	–0.003 (0.023)			<1	+24.8
K3	1.555 (0.524)	–0.110 (0.009)	**0.051** (0.016)	–0.002 (0.024)	–0.025 (0.057)	**–0.279** (0.118)	4	+18.6
Ca2	2.823 (0.307)		0.263 (0.158)	–0.258 (0.224)			0	+52.3
Ca3	–4.528 (1.551)		0.252 (0.158)	–0.254 (0.224)	2.417 (1.551)	–2.777 (3.110)	0	+55.3
lnMg2	–0.867 (0.105)	–0.046 (0.023)	**0.106** (0.049)	–0.038 (0.070)			<1	+21.1
lnMg3	–7.36 (4.71)	–0.046 (0.023)	**0.107** (0.049)	–0.041 (0.070)	0.864 (0.523)	0.118 (0.963)	0	+17.7
lnFe2	1.662 (0.306)	–0.208 (0.032)	**0.465** (0.070)	–0.187 (0.100)			12	+51.3
lnFe3	3.264 (8.488)	–0.208 (0.032)	**0.466** (0.070)	–0.186 (0.100)	1.733 (0.959)	**–3.980** (1.700)	25	+43.9
Al2	2.928 (0.347)	–0.298 (0.097)	**0.990** (0.206)	–0.412 (0.298)			12	+62.3
Al3	9.710 (8.722)	–0.296 (0.097)	**0.995** (0.205)	–0.415 (0.298)	1.292 (0.924)	**–4.587** (1.924)	19	+62.1
lnZn2	2.903 (0.107)	–0. 213 (0.032)	**–0.191** (0.079)	**–0.334** (0.092)			6	+16.7
lnZn3	6.536 (2.469)	–0.214 (0.032)	**–0.192** (0.079)	**–0.337** (0.092)	–0.549 (0.267)	–0.068 (0.531)	6	+16.4
B2	2.717 (0.290)	–0.334 (0.088)	–0.071 (0.126)	0.158 (0.181)			0	+51.8
B3	–3.460 (12.497)	–0.335 (0.088)	–0.073 (0.126)	0.158 (0.181)	–0.212 (1.408)	2.213 (2.486)	0	+50.0
lnCu2	1.833 (0.111)	–0.069 (0.023)	**0.260** (0.052)	**–0.160** (0.074)			16	+12.4
lnCu3	1.627 (4.700)	–0.069 (0.023)	**0.257** (0.052)	**–0.158** (0.075)	0.067 (0.519)	–0.075 (0.967)	6	+12.8

Table 4. Fixed part parameters (standard errors in parentheses) for the models of soil element concentrations testing site type differences, geographical gradients and peat properties. The models presented had the best performance in the data. For site type differences, the *Vaccinium vitis-idaea* II type (Ptkg II) was used as the base line. a = constant; Anal. diff. = deviation of Set 1 values from Set 2 values (see Material and methods); Mtkg II = *Vaccinium myrtillus* II type; Vatkg = Dwarf-shrub type; North = latitude (m); East=longitude (m); Dist. = lateral euclidic distance of the sample location to the closest mineral soil site (m); Peat thick. = thickness of the peat deposit (cm); Db = peat bulk density (g dry mass / cm^3 fresh volume); Ash = peat ash content (% of dry mass).

Model	a	Anal. diff.	Mtkg II	Vatkg	North	East	Temp. sum	Dist.	Peat thick.	Db	Ash	Variance explained, %	Relative bias, %
P4	–20.152	–0.044	0.213	–0.110	2.600	0.003		–0.001		–0.003		48	3.1
	(6.244)	(0.015)	(0.034)	(0.049)	(0.741)	(0.001)		(0.000)		(0.001)			
K4	0.611	–0.114	–0.046						–0.061	–0.002	0.006	16	17.4
	(0.030)	(0.008)	(0.015)						(0.015)	(0.000)	(0.001)		
Ca4	3.524		0.404							–0.007		0	59.1
	(0.386)		(0.155)							(0.001)			
lnMg4	1.450	–0.059	0.136				0.002			–0.004	0.014	0	42.5
	(0.078)	(0.022)	(0.047)				(0.000)			(0.000)	(0.002)		
lnFe4	–1.330	–0.199	0.309		1.715	–2.685		0.0007	–0.001		0.028	42	54.8
	(7.136)	(0.029)	(0.065)		(0.796)	(1.456)		(0.000)	(0.000)	(0.002)			
Al4	0.702	–0.0668	0.469							0.013	0.0611	28	28.2
	(0.355)	(0.106)	(0.175)							0.002)	(0.009)		
lnZn4	8.338	–0.235	–0.244	–0.139	–0.676					–0.0072	0.023	23	13.9
	(1.386)	(0.030)	(0.083)	(0.070)	(0.196)					(0.001)	(0.002)		
B4	4.319	–0.385								–0.017	0.042	3	54.1
	(0.388)	(0.083)								(0.002)	(0.006)		
lnCu4	–26.808	–0.066	0.204		3.312		0.005				0.010	20	20.6
	(9.901)	(0.023)	(0.051)		(1.169)		(0.002)				(0.002)		

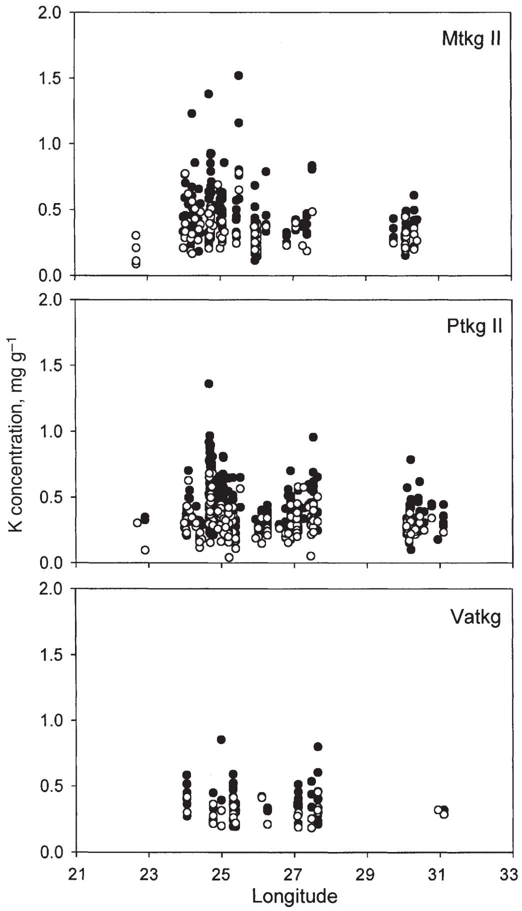

Fig. 4. Potassium concentrations relative to the longitude of the sampling point. Open circles represent data set 1 and filled circles set 2, based on different extraction methods (see Methods). Please note that since all of the sampling points do not represent independent observations in a statistical sense, the contents of the figure cannot be directly compared with the results of the model analysis.

the concentrations of which generally decreased towards east; however, the few observations from locations west of 24°60´E showed very low concentrations of K, especially for Mtkg II (Fig. 4). The variation in the concentration of P could be explained rather well with only site type and geographic location. For Fe and Al almost as much of the total variance could be explained but the bias remained high.

For most of the nutrient concentrations, the models based on site type and geographical location were significantly improved when either the bulk density or the ash content of the peat, or both, were added (Table 4). In addition, for K and Fe, the peat thickness and for P and Fe, the distance from the mineral soil significantly improved the explanatory power of the model. The average temperature sum of the growing season was significant in the models of Mg and Cu. For Cu this trend depended on the North-South coordinate: at a certain latitude there was more Cu in sites with a higher temperature sum.

Except for Ca, Mg, and B, whose variation could not really be explained, the simple peat characteristics, DB and/or ash content, clearly increased the explanatory power of the models. The explanatory power remained modest for most element concentrations; only for P and Fe, close to half of the variation could be explained by the "best" models. Further, the relative bias of the models remained generally high; P was the only exception with a relative bias of 3% only.

4 Discussion

4.1 Variation in the Element Concentrations

In general, most of the variation in the element concentrations was contributed by differences among peatland basins, and variation within the floristically determined sites. The contribution of the peatland-basin level underlines the ecohydrological uniqueness of each peatland complex: there are no two peatlands that would have identical catchment characteristics, water-inflow patterns, and peat deposition history. The chemical composition of the mineral soils in the catchment, as well as the speed at which water moves through the catchment before reaching the peatland basin, along with rainwater quality have a critical role in determining the basic chemical composition of the peatland soil water. Most of the peat "soil" is actually water (e.g., Päivänen 1973), so the composition of the water is an integral part of the composition of the peat soil.

The chemical composition of water and water level depth largely determine vegetation composition (Wheeler and Proctor 2000, Økland et al. 2001) and plant biomass production (Reinikainen et al. 1984) in peatlands, and consequently, the quantity and quality of organic matter inputs that eventually form the soil. Decomposition processes, which also are regulated by all the aforementioned factors, further modify the properties of the organic soil (e.g., Bragazza et al. 2007). The factors and processes mentioned above vary not only among peatland basins but also at different scales within the basins. The high proportion of variance contributed by spatial variation within a floristically defined site underlines the need for carefully considering the sampling schemes so that the number of subsamples required to reliably characterize a site is sufficient (see, e.g., Johnson et al. 1990, Hargreaves et al. 2003). Laiho et al. (2004) analyzed within-site variation in more detail and presented some guidelines for sampling at the site level. In the present study, the number of sample points per site remained relatively low, and the focus is more on the variation at larger scales. Vegetation-environment relationships are generally dependent on the scale of observation (Auestad et al. 2008).

The region-level variance component remained insignificant in all models. Most of the regional variation was explained by the fixed parameters, temperature sum and coordinates. In addition, the material was probably too small to deal with variance partitioning at four levels. The concentrations of Fe seemed to vary the most among the geographical regions. Fe is an interesting element since it to some extent reflects the level of minerotrophy (Laine et al. 2004) and peat N content (Hartman et al. 2001, Pietiläinen and Kaunisto 2003). Yet, the variation in its concentration also reflects the oxidation/reduction conditions (Damman 1978, Koretsky et al. 2007). The sites in the aapa mire region in the north are all minerotrophic; however, they may be more dependent on snowmelt waters than ground waters with generally high Fe concentrations. Thus, the regional variation may be more affected by the distribution of different minerals with varying Fe contents among regions.

Drainage is known to affect the concentrations of several nutrients (Kaunisto and Paavilainen 1988, Kaunisto and Moilanen 1998, Laiho et al. 1999), and thus some nutrient-based ecological features generally recognized in pristine peatlands have become obscured on our sites in old drainage areas. Most strikingly, concentrations of Ca, which is one of the major determinants of plant communities in pristine northern peatlands (e.g., Jeglum and He 1995), were not significantly different among the post-drainage site types studied. Even in the different-aged drained sites studied by Westman and Laiho (2003), the pools of Ca in the surface peat, which should reflect Ca concentrations, clearly distinguished the different site types. It has been suggested that a gradual decrease in Ca and/or Mg in drained peat soils may be caused by relatively high leaching rates, and that such decrease may already be observed in old drainage areas (Laiho et al. 1999, Westman and Laiho 2003), especially in Mtkg II sites (Westman and Laiho 2003). The material of Kaunisto and Paavilainen (1988), including some pine mires drained already 70–80 years earlier, showed even lower peat Ca concentrations than our study and in fact increasing concentrations from herb rich towards dwarf shrub site types. Our results further support the hypothesis of reduced Ca and Mg concentrations in old drainage areas, and call for attention.

Still, on average, the element concentrations in our material followed the presumed gradient in nutrient-richness, i.e. Mtkg II > Ptkg II > Vatkg, except for Zn and B. The concentrations of Zn and B were on average lower on Mtkg II than Ptkg II. For B, an inverse gradient relative to the presumed nutrient-richness was found. It seems that the faster-growing tree stands on the originally more nutrient rich site types have started to exhaust the scanty soil pools of these micronutrients. A similar trend in B concentrations in old drained pine mires was found by Kaunisto and Paavilainen (1988). In the models including additional explanatory variables, the parameter values of the site type dummy variables may differ from the average patterns; e.g., in the "best" model for K, Mtkg II has a negative parameter value. This indicates that one or all of the other factors included in the model affect the concentrations on Mtkg II sites less that on sites representing the other types, and the negative parameter downscales this/these effects.

Geographic location was reflected in the pattern of covariation of the studied elements more than in the concentrations of single elements: North-South and East-West gradients were significant in the RDA but only in few models for single elements. Concentrations of P increased towards north, supporting the findings of Sundström et al. (2000) and Westman and Laiho (2003). Higher concentrations within a single site type in the north than in the south may imply that larger total pools of mainly organically bound nutrients, such as P, are required in a colder climate to support a similar plant community, with the consequent identification into a certain site type (also Westman and Laiho 2003).

Surprisingly, the concentrations of K decreased on average from West to East, even though K deficiencies have mostly been reported in the West. Also, Moilanen (1992) observed an increase in pine needle K concentrations when moving from the western coastal plain eastwards to higher inland regions in northern Finland. He suggested 150 m a.s.l. to be a limit above which a severe K deficiency was rare. Accordingly, in our westernmost sites, which, unfortunately, were few, low concentrations were found. These sites were situated in an area that was sea bottom during the Litorina sea period (about 8500–4000 BP). Such sites are most common in the coastal areas along the Gulf of Bothnia. In this region, acid sulphate soils are found, with some peculiar properties that enhance leaching of several elements (Nordmyr et al. 2006). The problematic nature of these soils when in agricultural use has been recognized (e.g., Sunström & Åström 2006). Unfortunately, our material did not cover the coastal region. We suggest that it should be investigated whether or not acid sulphate soils, when underlying forestry-drained peat deposits, could lead to characteristically low soil K pools.

4.2 Prediction Capacity of the Models

The prediction capacity of the models remained poor for most element concentrations, and may not be sufficient for practical applications such as estimating the soil nutrient status on specific sites. We had hoped that the inclusion of easily measurable soil properties such as DB and ash content would improve the models considerably. They did indeed improve most of the models significantly but still for several elements the proportion of variance explained remained rather low and/or the bias was high. Yet, our analyses facilitate evaluation of some major factors in effect, and increase our understanding of the patterns and directions of variation. Since many of the soil properties measured were intercorrelated, simultaneous multivariate modelling of several concentrations might yield better results and should be tested.

The concentration of P could be best explained: almost half of the variation was covered by the "best" model, and the model bias was low. P, generally a limiting nutrient in drained peatland forests, was reflected in the site type, and also had the clearest geographic distribution pattern in our material. Concentrations of Ca, Mg, and B could not be explained with the available easily measurable variables. It is difficult to say, based on this material with old drainage areas only, whether this is caused by the inherent variation in bedrock and soil properties among catchments or by changes induced in their soil pools by drainage, and the consequently increased uptake by trees, especially in the case of B with low initial pools.

4.3 Data Sets Based on Different Extraction Methods

Different data sets cannot be combined without accounting for the systematic differences in element concentrations caused by differences in the analytical methods. This is unfortunate, since collection of large sample sets is laborious and expensive. Yet, in our material, it was possible to capture the differences seemingly reliably. The difference between the two data sets remained constant in all models of varying complexity. The data sets did not include common samples for calibration, but were uniform by site type and geographic distributions. Whether a similar method would work with more data sets probably depends on how much the data sets have in common: with clearly differing site type and geographic distributions it may not be feasible.

5 Conclusions

The patterns of variation in the element concentrations depended to a large extent on the element. Thus, when designing sampling schemes, the specific aims of the research: which element(s) and spatial patterns are targeted, should guide the decisions. For estimation of general nutrient levels for practical forestry, the floristic-ecological site type classification has a reasonable prediction power. Our models, even if bringing out some interesting patterns of covariation, did not show such explanatory power that they could be applied in, e.g., recognizing sites with low base cation pools. We suggest that a specific sampling should be carried out in the Litorina sea zone to assess our postulate of low K pools in this region. Concerning the P concentration in soil, which quite commonly limits tree growth in drained peatlands, our simple models provide means for estimating a large part of its variation among drained pine mire sites.

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