Re-vegetation of block-cut and milled peatlands: an Estonian example

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SUMMARY

The re-vegetation of mined peatlands after abandonment is often a long-lasting process. The aim of this study was to clarify the factors influencing the re-vegetation of abandoned block-cut, milled and fertilised peat areas in Estonia by investigating and comparing their present vegetation. The analysis is based on 285 quadrat samples where plant species composition and cover were assessed, and the pH and electrical conductivity of bog water were measured. Whereas re-vegetation in the block-cut area was quite fast and progressive, in milled peat areas it was slow and irregular because of the absence of viable propagules and the unfavourable conditions for plant growth. The course of re-vegetation depends considerably upon the peat extraction method, the area and surface microtopography of the mined area, the pH and electrical conductivity of the bog water, and the density at which trees have established on the cutover surface. Plant species richness was most affected by the density of tree saplings, litter cover, former treatment and microtopography. A single application of fertiliser *ca* 25 years ago did not have a long-term effect on the total number of plant species, but did increase plant cover and the mean number of species *per* quadrat. On milled peatlands, neither the sowing of *Oxycoccus palustris* seeds nor the planting of *Rubus chamaemorus* had the desired effect unless growth conditions for the plants were improved.

KEY WORDS: environmental factors, microtopography, plant species composition, variance decomposition.

INTRODUCTION

In Europe, fuel peat was traditionally hand-cut from trenches in bog margins or extracted as block-cut peat using some form of machinery. Because these activities affected small areas and involved only surface (if any) drainage, the impacts on bog ecosystems were rather small and local, and these areas have re-vegetated spontaneously. The situation changed dramatically in the mid-twentieth century with the introduction of peat milling and (later) the vacuum mining technique, which required deep drainage and the removal of all living plants, together with the top peat layer, from extensive areas of peatland.

The climate and topography of Estonia are favourable for paludification. Consequently, peatlands cover around 22 % of the country's total area (Orru 1992) and there is a long tradition of peat mining for fuel. When manual and block-cut peat extraction methods were replaced by milling and vacuum mining in the 1950s, the number and especially the size of peat extraction areas increased rapidly, from only few hectares at the edges of the bog in most cases, to peat fields up to 1,500 ha in area covering most of the former bog. At present, about 20,000 ha of peatland are being mined and the area of abandoned cutaway peatland is 9,371 ha (Ramst & Orru 2009). Current legislation (Act on Sustainable Development, Earth's Crust Act, Mining Act *etc.*) requires that the areas left after mining must be restored, but no restoration has been carried out on the numerous peat fields that were abandoned during or shortly after the end of the Soviet period (in the early 1990s) and are still "without owners". Therefore, it is essential to understand the factors that enhance their re-vegetation.

On milled peatlands with almost-flat surface topography, the bog ecosystem—i.e. its vegetation, fauna, viable seed bank and the hydrological regime—has been totally destroyed. The water table is often more than one metre below the surface and, because the exposed peat layers have poor water-holding capacity, fluctuates extensively. Thus, the surface floods in wet weather and can dry out completely during dry periods (Price *et al.* 1998) giving moisture conditions which are unfavourable for plant growth. Milled peatlands are also exposed to wind erosion (Campbell *et al.* 2002) and frost heaving (Groeneveld & Rochefort 2002), which inhibits both plant growth and seed germination.

In natural bogs, the spread of many plant species is mostly vegetative, but this cannot happen in mined peatlands because living vegetation and propagules have been removed. The peat layers which are now exposed at the surface are thousands of years old and contain no viable diaspores (Salonen 1987). Thus, the only diaspores that may become available for the spontaneous re-vegetation of mined peatlands, and especially of milled peat fields, are those carried in by the wind. The seeds that arrive depend on the species present in the surroundings, as well as on their dispersal and immigration potential.

Techniques for the restoration of mined peatlands have been the subject of numerous scientific studies, and several peatland restoration guides have been published (Wheeler & Shaw 1995, Stoneman & Brooks 1997, Heikkilä *et al*. 2002, Quinty & Rochefort 2003, Paal 2007). Nevertheless, although abandoned mined peatlands have quite similar general features throughout their distribution area, they also have regional peculiarities depending on the local climatic conditions, vegetation *etc.* which need to be considered when undertaking restoration. Geobotanically, Estonia has variable climatic and hydrological conditions, and belongs to the hemiboreal (boreo-nemoral) vegetation zone. The western part of the country is slightly oceanic, while the eastern part is more continental (Moen 1999). Therefore, the mires here are in some ways similar to, and in other ways different from, mires in both western Europe and Russia.

The main aim of this study was to investigate the largely unmanaged re-vegetation of abandoned block-cut and milled peatlands in Estonia and, on this basis, to determine the main explanatory environmental factors. Consideration was also given to the potential effect of a single application of fertiliser to milled peat fields.

METHODS

Study sites

Viru Bog (235 ha, maximum thickness of peat layer 6–8 m; Orru 1992) is located within Lahemaa National Park in northern Estonia (Figure 1). An area of 37 ha in the northern part of the bog has been ditched, and peat was extracted using milling and vacuum mining techniques from 1966 to 1986. In the mid-1980s, *Rubus chamaemorus* was planted at the northern edge of the peat fields, adjacent to bog forest, in an attempt to promote re-vegetation. The area investigated here was a 4.2 ha portion of the peat fields (centre co-ordinates 59º 28' 31" N, 25º 39' 26" E) with an average residual peat depth of 2.5 m. The upper peat layer (0–1.05 m) is slightly decomposed (10–17 %) *Sphagnum* peat, and the lower part of the profile is well decomposed (27–30 %) *Eriophorum–Sphagnum* peat (Ramst *et al*. 2005). The surfaces of the peat fields between the ditches are flat with some seasonally flooded depressions and large patches of almost-bare peat. The mean annual temperature for the region is 4.6±1.1 °C (extreme monthly means -5.6 °C in February and +16.4 °C in July); the average annual precipitation is 668±95.9 mm, with 231±84.5 mm falling in the summer months (June–August); and the average length of the growing season is 178.4±14.5 days (meteorological data from Estonian Meteorological and Hydrological Institute).

Rabivere Bog (2686 ha, average thickness of peat layer 3.5 m; Orru 1992) is located on the North Estonian Plateau (Figure 1). The central and southern parts of the bog are almost undisturbed, but the northern part has been ditched and an area of 137 ha was used for block-cut peat extraction until 1950. Thereafter, peat extraction continued until 1982, using the milling and vacuum mining techniques, on a 24 ha area which partly overlapped the previously block-cut area. In 1985, 15 hectares on the eastern part of the milled peat extraction area was sown with *Oxycoccus palustris* seeds (20 kg ha^{-1}) and fertilised from aircraft with P_2O_5 (300–400 kg ha^{-1}) mixed with an unknown quantity of sawdust. The size of the area investigated in this study was 5.8 ha (centre co-ordinates 59º 8' 33" N, 24º 39' 51" E), comprising 3.8 ha of milled and 2.0 hectares of block-cut peatland. The average thickness of the residual peat layer on both areas was 2.1 m. The upper peat layer (0–0.7 m) is slightly decomposed (10–23 %) *Fuscum* and *Eriophorum–Sphagnum* peat, with well-decomposed (25–30 %) *Pinus–Eriophorum–*, *Lignum–Graminaceae–* and *Graminaceae–Sphagnum* peat below (Ramst *et al*. 2005). The surfaces of the milled peat fields between ditches are flat, whereas humps and depressions are characteristic on the block-cut area. The mean annual temperature for the region is 5.2±1.1 °C (extreme monthly means -6.5 °C in February and +16.5 °C in July); the average annual precipitation is 738±106 mm, of which 231±72 mm falls in summer months; and the average length of the growing season is 183.1±18.5 days (meteorological data from Estonian Meteorological and Hydrological Institute).

The ditches in both milled areas are still open, but they are not maintained and are partly filled with wind-blown peat. The average depth of the ditches relative to the peat surface on cut-over peatland at Rabivere was 0.5–0.7 m, and on cut-over peatland at Viru it was 0.7–1.0 m. The average width of ditches was around 1 m in both areas. During fieldwork, the

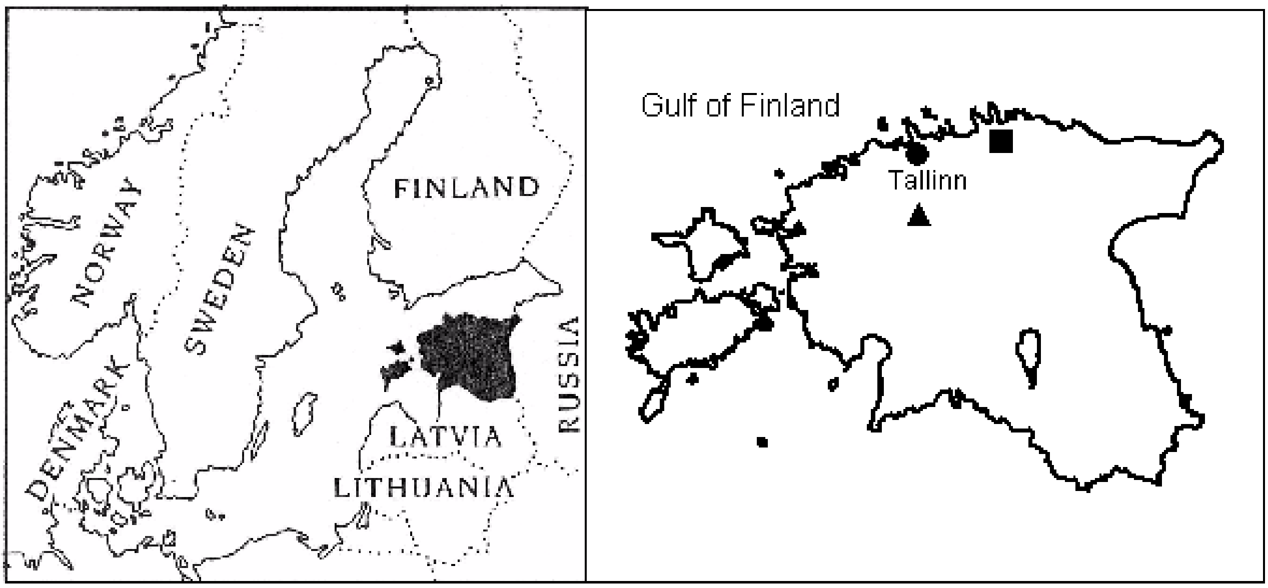

Figure 1. Locations of Estonia (shaded black) in northern Europe (left); and of the capital city Tallinn (●) and the two study sites (■ – Viru Bog; ▲ – Rabivere Bog) (right).

growth of plants was hindered because the summer water table was almost constantly more than one metre below the surface, but in spring and after heavy rainfall in summer, some lower-lying areas were flooded. The water table in the block-cut area was constantly closer to the peat surface and moisture conditions here were, therefore, more appropriate for mire plants.

Data sampling

At Viru Bog, nine contiguous peat fields, 220 m long and separated by ditches 20 m apart, were studied. Vegetation data were gathered on a total of 185 1×1 m sample quadrats within this area. In every peat field, five quadrats were placed in the centre of the field, five at the margins (0–5 m from a ditch), five in the drainage ditches and five at the edge of the road (20 quadrats in each of nine peat fields = 180). The remaining five quadrats were placed 5–10 metres from the edges of peat fields that abutted forest or bog.

Ten 200 × 20 m peat fields within the milled area of Rabivere Bog were studied. Five quadrats were located within each peat field so that two of them were in the centre of the field, two near the drainage ditches at the sides (0–5 m from the ditch), and one in the bottom of each drainage ditch (10 ditches). On the block-cut area, 50 quadrats were located randomly, half on humps and half in depressions.

The cover of plant species and litter was assessed for each 1×1 m quadrat. For a 10×10 m sample square centred on each quadrat, the density of pine and birch trees and their saplings was estimated visually as a decimal fraction of the maximum cover 1.0, and the maximum and average heights of trees and saplings of each species were recorded. Plant species nomenclature follows Leht (2007) for vascular plants and Ingerpuu *et al*. (1998) for bryophytes.

At each of the studied sites, pH was measured using a Schott Handylab pH 11 instrument, and electrical conductivity (µS cm^{-1}) was determined using a Microcomputer 900. The depth of the water table was measured in each sample quadrat using pipes which were perforated for 1 m of their lengths. Readings were obtained using a customised tape measure, and related to the level of the peat surface.

Data processing

The dataset was grouped according to peat extraction technique (Treatment): (i) the block-cut area on Rabivere Bog (BC); (ii) the fertilised milled area on Rabivere Bog (FM); and (iii) the unfertilised milled area on Viru Bog (UM). Each quadrat was allocated to one of the following microform/ microsite types: (i) ditch (Ditch); (ii) depression (Depr); (iii) flat area (Flat); (iv) ditch margin (DiMa; 0–50 cm from the ditches); (v) hump (Hump); and (vi) near road margins (RoMa; 0–7 m from the sides of peat fields adjacent to roads).

The relationship between vegetation data, tree layer characteristics and environmental variables was analysed using Canonical Correspondence Analysis (CCA; Ter Braak & Šmilauer 2002). Litter cover and the tree layer and saplings variables were treated as biotic environmental variables influencing the ground vegetation (Økland & Eilertsen 1994). In order to approximate better to normal distributions, these data were CCA log-transformed. Conditional effects and Monte Carlo permutation tests were used to estimate the importance of individual variables, and only significant variables were used for further analysis. Variation partitioning (Borcard *et al*. 1992) was performed in order to ascertain the fraction of data variation associated with different groups of variables (species, microforms, treatments, biotic and abiotic environmental variables = bog water chemistry data).

Differences in the environmental variables and species cover values according to treatments and microforms were evaluated using the Univariate ANOVA and the Tukey test (StatSoft Inc. 2004). The dependence of species richness on environmental variables was analysed using General Regression Model (GRM) analysis (StatSoft Inc. 2004). The characteristic species for the established data groups were estimated by Indicator Species Analysis (Dufrêne & Legrendre 1997), and the significance of each characteristic/indicator species was evaluated using the Monte Carlo permutation test (McCune & Mefford 1999). The similarity of species assemblages in sample quadrats grouped by 'Treatment' and 'Microform' factors was tested using Multi-Response Permutation Procedures (MRPP; McCune & Mefford 1999) taking into account the Bonferroni correction for multiple comparisons.

RESULTS

In general, the water table was highest and most stable in the block-cut area on Rabivere Bog, with average depth <40–60 cm even during the summer. In milled areas on both Viru Bog and Rabivere Bog, the summer water table was much lower (90–140 cm below the peat surface) and, therefore, inaccessible to plants. In the latter areas, the average water table was higher (55–70 cm below surface) after the September–October rainy period; and after heavy rainfall and/or snowmelt, some parts of the milled peat fields were flooded for several weeks. The measurements of water table depth were excluded from the data analyses because they were not comparable with the other datasets. Changing weather conditions caused the water table to fluctuate so widely within even a single day, that the inclusion of water table data in the analyses was likely to mask re-vegetation effects.

At the scale of treatment areas (factor 'Treatment'), all environmental variables differ significantly from the overall mean value in at least one area. Nevertheless, according to the Tukey test, bog water pH is rather similar in the block-cut and unfertilised milled areas (Table 1). Although the differences between all tree layer and saplings variables are also significant, the respective mean values are very low and of the same magnitude as standard deviations; therefore the ANOVA results have no fundamental importance in this case.

Table 1. Mean value (± standard deviation) of bog water and biotic variables in areas of different treatment, and significance of their differences by Univariate ANOVA and Tukey HSD test (marked with superscript letters). Notations: BC – block-cut area, FM – fertilised milled area, UM – unfertilised milled area, p – significance level by ANOVA.

Variable	Variable code	Treatment			p
		BC	FM	UM	
pH of bog water	pH	3.8±0.3^{a}	4.5±0.5^{b}	3.8±0.2^{a}	<0.001
electrical conductivity of bog water (µS cm^{-1})	EC	81.8±42.4^{a}	66.9±32.4^{b}	132.1±23.7^{c}	<0.001
litter cover (%)	Litter	12.5±10.7^{a}	7.7±7.1^{b}	3.5±8.0^{c}	<0.001
total density of trees and saplings	ToDe	0.5±0.2^{a}	0.3±0.2^{b}	<0.1±<0.1^{c}	<0.001
density of pine trees	PiDe	0.4±0.2^{a}	0.2±0.1^{b}	<0.1±<0.1^{c}	<0.001
density of birch trees	BeDe	<0.1±0.1^{a}	<0.1±<0.1^{a}	<0.1±<0.1^{b}	<0.023
average of height of trees	TrH	6.4±2.6^{a}	2.8±1.2^{b}	0.9±1.5^{c}	<0.001
maximum height of trees	TrHmax	9.5±2.8^{a}	5.1±1.1^{a}	1.5±2.5^{a}	<0.001
total density of saplings	SaDe	0.2±<0.1^{a}	<0.1±<0.1^{b}	<0.1±<0.1^{c}	<0.001
density of pine saplings	PiSaDe	<0.1±<0.1^{a,b}	<0.1±<0.1^{b}	<0.1±<0.1^{a}	<0.001
density of birch saplings	BeSaDe	<0.1±<0.1^{a}	0.1±0.1^{b}	<0.1±<0.1^{c}	<0.001
average height of saplings	SaH	0.7±0.4^{a}	0.8±0.3^{b}	0.3±0.3^{c}	<0.001

At the scale of microforms, all abiotic and most biotic environmental variables again prove to be significantly different. Bog water pH is usually highest in ditches or at their margins, and electrical conductivity is highest in road margins, flat areas, ditches and ditch margins (Table 2). Relatively low bog water electrical conductivity is specific for the fertilised milled area (Table 1).

Variation of the vegetation data across the whole dataset is defined primarily by the category variables, i.e. by microforms and treatments. According to the CCA, the variable ‘Ditch’ has the largest marginal effect, followed by ‘Block-cut area’ and ‘Depression’ (Table 3). Bog water pH also has significant importance.

The ordination diagram (Figure 2) demonstrates the distinction of vegetation in ditches from vegetation in other microhabitats. Also, the quadrats that sampled depressions in the block-cut area overlap only slightly with other quadrats. On the first ordination axis the quadrats in ditches are maximally opposed to quadrats situated on flat microsites or near road margins in the fertilised milled (FM) area. The second ordination axis corresponds to the gradient from depressions on the block-cut (BC) area towards flat microhabitats and road margins in the unfertilised milled (UM) area. The pH vector indicates decreased water acidity in ditches but also on road margins in the UM area.

The re-vegetation, evaluated on the basis of number of plant species and total plant coverage, was most successful on the BC area, where the moss layer alone covered *ca* 50 % of the ground. On the UM area, the total plant cover was only about 5 % and vegetation was often almost absent (mean cover 1–5 %) from the central parts of peat fields; although re-vegetation was better on parts adjacent to forest (mean cover up to 60 %) and near road margins (higher field layer and overall mean cover values). Re-vegetation was more successful in the FM area (Rabivere Bog) than in the UM area (Viru Bog).

Considering surface microforms/microsites, mean plant cover was highest in depressions and on humps in the block-cut area, second highest in ditches and near road margins on milled areas, and notably lower on flat areas and at ditch margins (Table 4). In the middle of the UM area, vegetation cover was 60–100 % in some ditches but could be only 5–20 % in the very next ditch; whereas in the FM area, the vegetation cover in ditches was usually 40–90 %. The vegetation of ditches differed substantially from that of other microforms; they were densely covered by *Eriophorum vaginatum* accompanied by *Carex rostrata*, *Warnstorfia fluitans* and five species of *Sphagnum*.

Table 2. Mean values (± standard deviation) of environmental variables in landscape microforms and significance of their differences as determined by Univariate ANOVA and the Tukey HSD test (p is the significance level returned by ANOVA). For key to variable codes, see Table 1.

Variable code	microform/microsite type and (Code)						p
	ditch	ditch margin	flat	depression	hump	road margin	
	(Ditch)	(DiMa)	(Flat)	(Depr)	(Hump)	(RoMa)	
pH	4.2 ± 0.6^{a}	4.0 ± 0.4^{b}	3.9 ± 0.3^{b}	3.8 ± 0.2^{b}	3.8 ± 0.5^{b}	3.8 ± 0.1^{b}	<0.001
EC	$112.7\pm30.4^{a,b}$	109.0 ± 42.0^{a}	$121.3\pm42.2^{a,b}$	83.4 ± 54.1^{c}	81.8 ± 16.8^{c}	133.2 ± 21.8^{b}	<0.001
Lit	1.5 ± 5.0^{a}	4.0 ± 6.3^{a}	4.6 ± 9.8^{a}	$10.1\pm6.7^{b,c}$	13.7 ± 6.7^{c}	9.6 ± 13.0^{b}	<0.001
ToDe	0.1 ± 0.1^{a}	0.1 ± 0.2^{a}	0.1 ± 0.2^{a}	0.4 ± 0.2^{b}	0.5 ± 0.2^{b}	$<0.1\pm<0.1^{a}$	<0.001
PiDe	0.1 ± 0.1^{a}	0.1 ± 0.1^{a}	0.1 ± 0.1^{a}	0.4 ± 0.2^{b}	0.4 ± 0.2^{b}	0.1 ± 0.1^{a}	<0.001
BeDe	$<0.1\pm<0.1^{a}$	$<0.1\pm0.1^{a}$	$<0.1\pm0.1^{a}$	$0.1\pm0.1^{a,b}$	0.1 ± 0.1^{b}	$<0.1\pm<0.1^{a}$	0.023
TrH	1.1 ± 1.7^{a}	1.2 ± 1.5^{a}	1.4 ± 2.0^{a}	6.1 ± 2.0^{b}	6.9 ± 3.3^{b}	1.4 ± 1.5^{a}	<0.001
TrHmax	1.9 ± 2.9^{a}	2.3 ± 2.6^{a}	2.3 ± 2.9^{a}	9.6 ± 2.7^{b}	9.4 ± 3.0^{b}	2.8 ± 2.4^{a}	<0.001
SaDe	$<0.1\pm0.1^{a}$	$<0.1\pm<0.1^{a}$	$<0.1\pm<0.1^{a}$	0.2 ± 0.1^{b}	0.2 ± 0.1^{b}	$<0.1\pm<0.1^{a}$	<0.001
PiSaDe	$<0.1\pm<0.1^{a}$	$<0.1\pm<0.1^{a}$	$<0.1\pm0.1^{a}$	$<0.1\pm<0.1^{a}$	$<0.1\pm<0.1^{a}$	$<0.1\pm<0.2^{a}$	0.334
BeSaDe	$<0.1\pm<0.1^{a}$	$<0.1\pm<0.1^{a}$	$<0.1\pm<0.1^{a}$	$0.1\pm<0.1^{b}$	0.1 ± 0.1^{b}	$<0.1\pm<0.1^{a}$	<0.001
SaH	0.3 ± 0.4^{a}	$0.4\pm0.3^{a,b}$	$0.4\pm0.4^{a,b}$	0.7 ± 0.4^{C}	$0.7\pm0.4^{b,c}$	$0.5\pm0.3^{a,b,c}$	<0.001

Table 3. Conditional and marginal effects of the environmental variables and their inter-set correlations with Axes 1 and 2 derived by CCA. Notation: λ_1 : amount of variance explained by the variable; λ_A : amount of variance explained by each variable when it was included in the analysis model; p : significance level of the F-statistic; p_{Bonf} : critical p value for significance level 0.05 after Bonferroni correction. For meanings of variable codes, see Tables 1 and 2.

Variable code	Marginal effect	Conditional effect			Inter-set correlation	
	λ_1	λ_A	p	p_{Bonf}	Axis 1	Axis 2
Ditch	0.45	0.45	0.002	0.050	0.740	-0.011
BC	0.23	0.23	0.002	0.025	-0.125	-0.574
Depr	0.21	0.15	0.002	0.017	0.015	-0.426
pH	0.22	0.12	0.004	0.012	0.340	0.357
EC	0.07	0.07	0.064	0.010	-0.097	-0.016
FM	0.17	0.06	0.048	0.008	0.152	0.437
Flat	0.15	0.04	0.312	0.007	-0.171	-0.001
RoMa	0.10	0.03	0.790	0.006	-0.299	0.146
DiMa	0.15	0.01	0.880	0.006	-0.165	0.011
Hump	0.14	-	-	-	-0.126	-0.015
UM	-	-	-	-	-0.085	-0.056

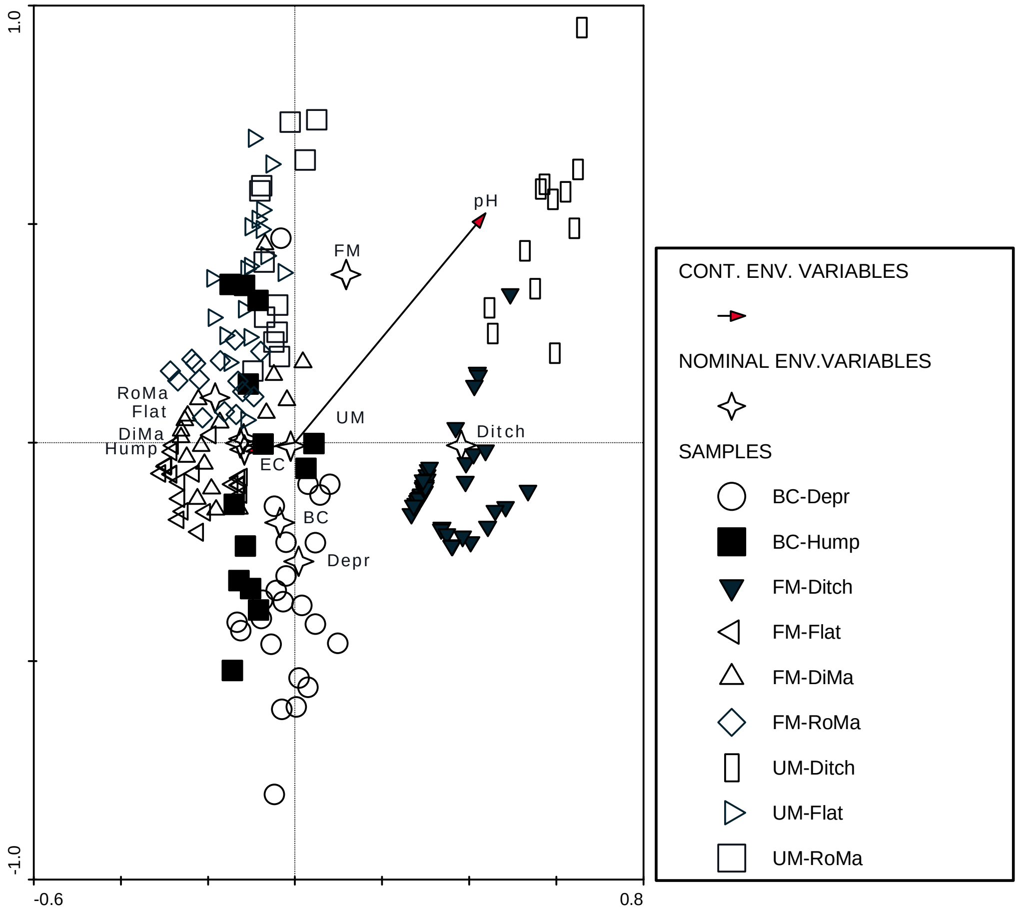

Figure 2. Canonical Correspondence Analysis biplot of environmental variables and sample quadrats by Axis 1 (eigenvalue 0.463) and Axis 2 (eigenvalue 0.274). Key: BC-Depr: depressions in block-cut area; BC-Hump: humps in block-cut area; FM-Ditch: ditches in fertilised milled area; FM-Flat: flat microforms in fertilised milled area; FM-DiMa: ditch margins in fertilised milled area; FM-RoMa: road margins in fertilised milled area; UM-Ditch: ditches in unfertilised milled area; UM-Flat: flat microforms in unfertilised milled area; UM-RoMa: road margins in unfertilised milled area. Other variable codes as in Tables 1 and 2.

Table 4. Plant species composition and cover (mean ± standard deviation) in the microform/microsite types of the different treatment areas. Asterisks (*) identify the significant (p<0.05) indicator species. Treatment and microform/microsite codes as in Table 1, Table 2 and Figure 2.

treatment code	UM	FM	BC	UM	FM	UM	FM	BC	UM
microform/microsite code	Ditch	Ditch	Depr	DiMa	DiMa	Flat	Flat	Hump	RoMa
number of species	7	13	30	15	16	18	18	21	11
total cover	86.2±28.6	63.9±35.3	99.6±33.4	40.6±32.5	42.1±26.7	48.4±34.5	45.7±23.0	81.8±27.6	80.4±25.1
Cover of trees and saplings	–	0.3±0.8	1.3±2.3	1.6±4.3	<0.1±0.1	1.9±4.9	<0.1±0.1	0.7±1.7	1.3±4.1
Betula nana	–	–	1.1±2.2*	–	–	–	<0.1±0.1	0.7±1.7	–
Betula pendula	–	–	<0.1±0.1	<0.1±0.1	<0.1±<0.1	<0.1±0.3	<0.1±0.1	<0.1±<0.1	0.1±0.3
Betula pubescens	–	–	<0.1±0.2	<0.1±0.1	–	0.3±2.2	<0.1±0.2	–	–
Picea abies	–	–	–	–	<0.1±0.1	–	<0.1±<0.1	<0.1±<0.1	–
Pinus sylvestris	–	–	0.1±0.2	1.6±4.3	<0.1±<0.1	1.3±4.4	0.1±0.2	0.1±0.1	1.3±4.1
Salix spp.	–	0.4±0.8*	<0.1±0.2	–	–	–	–	–	–
Field layer mean cover	83.0±32.9	21.5±16.7	38.9±20.4	31.8±31.0	25.1±19.7	35.4±36.8	32.0±20.7	37.2±18.1	60.4±34.7
Agrostis capillaris	–	–	–	–	–	0.2±0.8	–	–	–
Andromeda polifolia	–	–	1.9±3.1*	0.4±2.4	–	–	–	0.5±0.8	–
Calluna vulgaris	0.3±1.0	1.2±3.3	16.8±14.4	16.8±27.3	22.8±19.8	17.3±31.4	28.4±21.7	14.3±12.6	43.6±42.2*
Carex rostrata	–	7.6±16.0*	<0.1±<0.1	–	–	–	–	–	–
Drosera anglica	–	–	<0.1±<0.1	–	–	–	–	–	–
Drosera rotundifolia	–	–	0.6±1.2*	–	–	–	–	–	–
Empetrum nigrum	4.7±18.1	–	1.6±4.1	3.5±12.9	–	1.7±9.8	–	1.4±2.6	1.4±9.5
Epilobium angustifolium	–		–		–	0.3±1.2	–	–	–
Eriophorum vaginatum	78.7±32.7*	10.4±10.1	1.7±2.8	8.3±20.3	0.8±1.6	13.9±26.4	2.1±5.0	1.2±2.3	14.8±24.4
Ledum palustre	–	–	1.2±3.4	0.9±5.4	0.3±1.5	0.2±1.1	0.9±2.0	3.4±5.5*	0.2±1.2
Oxycoccus palustris	0.2±1.2	3.4±10.5	8.4±16.9*	1.1±5.7	0.2±0.3	–	0.3±0.8	1.1±3.8	–

treatment code microform/microsite code	UM Ditch	FM Ditch	BC Depr	UM DiMa	FM DiMa	UM Flat	FM Flat	BC Hump	UM RoMa
Rhynchospora alba	–	–	0.1±0.6	–	–	–	–	–	–
Rubus chamaemorus	–	–	3.2±6.0	<0.1±0.3	–	0.1±0.4	0.2±0.8	5.6±5.6*	–
Typha latifolia	0.1±0.6	0.2±0.6	–	–	–	–	–	–	–
Trichophorum alpinum	–	–	0.5±2.8	–	–	–	–	–	–
Vaccinium uliginosum	–	–	2.1±6.1	0.8±3.8	0.6±1.9	<0.1±0.3	<0.1±0.1	5.8±12.7*	0.4±2.4
Vaccinium myrtillus	–	–	–	–	–	–	–	1.5±6.4	–
Vaccinium vitis-ideae	–	–	0.7±2.4	–	–	<0.1±0.1	–	2.5±8.6*	–
Moss layer mean cover	3.2±15.9	42.1±38.2	59.3±34.2	7.2±16.3	16.9±21.9	11.1±22.3	13.6±13.5	43.8±26.4	18.7±34.5
Aulacomnium palustre	–	–	<0.1±<0.1	–	–	–	–	–	–
Dicranum polysetum	–	–	0.9±2.7	1.0±3.5	0.1±0.4	1.1±3.6	–	3.9±6.5*	<0.1±0.3
Pleurozium schreberi	–	–	8.9±15.2	0.5±3.0	2.8±6.6	0.6±4.6	2.5±8.1	15.6±21.8*	–
Polytrichum strictum	–	0.3±0.6	<0.1±0.2	4.3±15.2	4.7±8.3	5.5±18.2	3.1±6.8	<0.1±<0.1	11.1±27.2
Sphagnum angustifolium	–	0.3±0.9*	–	–	–	–	–	–	
Sphagnum balticum	–	0.4±0.9*	–	–	0.1±0.6	–	–	–	0.3±1.8
Sphagnum capillifolium	–	3.4±11.2	21.3±26.3*	–	–	<0.1±0.3	0.1±0.5	5.7±11.2	–
Sphagnum cuspidatum	–	3.2±7.2*	0.2±1.1	–	–	–	–	–	–
Sphagnum fuscum	–	–	10.7±20.5*	–	–	0.2±1.4	0.6±2.4	6.8±15.8	–
Sphagnum magellanicum	–	–	10.4±22.5*	–	–	–	–	0.2±0.9	–
Sphagnum squarrosum	2.2±14.6	7.5±22.5*	0.7±2.8	–	4.4±20.5	–	–	–	–
Warnstorfia fluitans	1.1±7.3	29.3±41.9*	–	–	–	–	–	–	–
Cladonia spp.	–	–	0.3±0.6	1.5±4.8	5.0±4.9	4.4±13.8	6.7±7.3*	1.6±2.8	7.3±16.6
Cladina spp.	–	–	4.5±9.7	–	<0.1±0.1	0.3±1.4	0.6±2.2	11.6±14.7*	–
Hypogymnia physodes	–	–	–	–	0.2±0.9*	–	<0.1±0.1	–	–

The common dominant species on flat microforms, ditch and road margins were *Calluna vulgaris*, *Polytrichum strictum* and *Cladonia* spp.; in addition, *E. vaginatum* was abundant on flat microforms and road margins (Table 4). Flat microforms on the UM area do not have any significant characteristic species, but for similar microforms on the FM area the presence of *Cladonia* spp. appears to be a reliable indicator even though its mean cover differs little from that on the UM area. For road margins, *C. vulgaris* is a significant indicator species due to its relatively high cover. Ditch margins in the UM area do not have any significant indicator species and are distinguished mainly by the higher cover of *E. vaginatum*, whereas *Sphagnum squarrosum* and *Cladonia* spp. are represented more abundantly within analogous microsites in the FM area (Table 4). Depressions and humps on the BC area have been mostly vegetated by typical bog species (Kask 1982); the main indicator species for depressions are *Oxycoccus palustris*, *Sphagnum capillifolium*, *S. fuscum* and *S. magellanicum*, while for humps, species such as *Ledum palustre*, *Rubus chamaemorus*, *Vaccinium uliginosum*, *Pleurozium schreberi* and *Cladina* spp. are characteristic.

According to the MRPP test, species composition differs significantly between the three treatment areas considered (Table 5). The same can be said about microforms; except that species composition is essentially similar for flat microforms, ditches and road margins so that vegetation differences between these microsite types are apparent only on the basis of species abundance.

The total number of plant species was highest (32) in the block-cut (BC) area on Rabivere Bog, whereas in milled areas it was almost similar – 24 and 23 species for Rabivere Bog (FM) and Viru Bog (UM) respectively. The mean number of plant species per quadrat was highest (9±4) on the BC area, and noticeably higher on the FM area (5±1) than on the UM area (2±1). At the scale of microforms, the number of species was highest in depressions, followed by flat microsites and humps.

According to the GRM analysis, species richness in abandoned peat extraction areas is also strongly influenced by the factors ‘Treatment’ and ‘Microform’ (Table 6). Besides these category factors, average height of saplings, density of *Pinus sylvestris* trees and saplings, and bog water pH have considerable positive effect, whereas the influence of litter cover is negative. The CCA biplot (Figure 3) provides a synthetic view of the mutual relationship between species and environmental variables which confirms that the main factors determining the vegetation pattern on abandoned

Table 5. Results of a pair-wise comparison of species composition between different treatments and microforms using the Multi-Response Permutation Procedures (MRPP) test. Taking into account the Bonferroni correction for multiple comparisons, the critical significance level 0.05 corresponds to p-value 0.017 for the comparison of data for different treatments, and to p-value 0.0033 for the comparison of data for various microforms. Notations: A: value of A-criterion; p: its significance level.

Data compared	A	p
Treatments		
UM *versus* FM	0.071	<0.0001
FM *versus* BC	0.049	<0.0001
BC *versus* UM	0.079	<0.0001
Microforms		
Ditch *versus* Depression	0.256	<0.0001
Ditch *versus* Ditch margin	0.192	<0.0001
Ditch *versus* Flat	0.143	<0.0001
Ditch *versus* Hump	0.252	<0.0001
Ditch *versus* Road margin	0.203	<0.0001
Depression *versus* Ditch margin	0.073	<0.0001
Depression *versus* Flat	0.078	<0.0001
Depression *versus* Hump	0.039	<0.0004
Depression *versus* Road margin	0.128	<0.0001
Ditch margin *versus* Flat	0.004	0.1173
Ditch margin *versus* Hump	0.063	<0.0001
Ditch margin *versus* Road margin	0.021	0.0009
Flat *versus* Hump	0.068	<0.0001
Flat *versus* Road margin	0.013	0.0156
Hump *versus* Road margin	0.127	<0.0001

Table 6. Significance of factors affecting species richness in 1×1 m sample quadrats, according to the stepwise forward General Regression Analysis. Notations: F: value of the F-criterion for variable removing; p: significance level; lgSaH: log-transformed average height of saplings; lgPiToDe: log-transformed density of *Pinus sylvestris* trees and samplings; other notations as in Table 1.

Variable	F	p	Influence direction
Treatment	27.903	<0.001	
Microform	6.633	<0.001	
lgSaH	7.794	0.006	+
lgPiToDe	8.546	0.004	+
Litter	9.852	0.002	-
pH	5.549	0.019	+

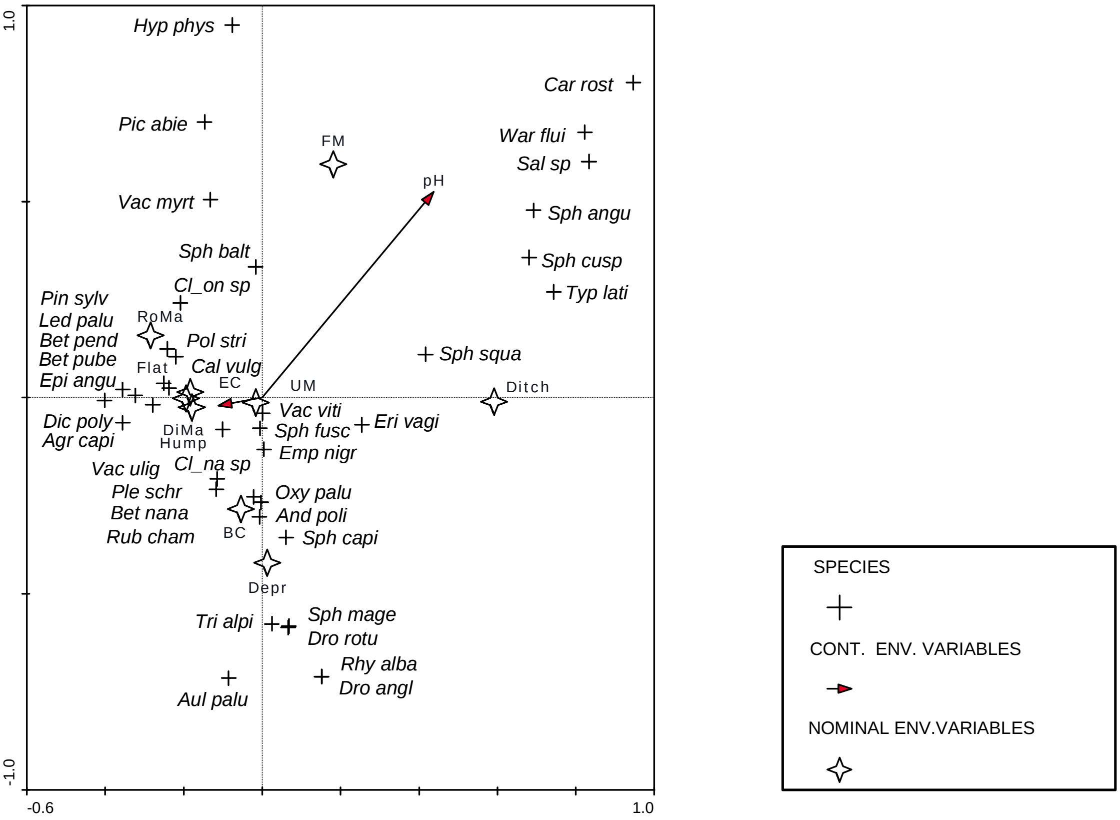

Figure 3. Canonical Correspondence Analysis biplot of environmental variables and species (Axis 1 and Axis 2). Species names are abbreviated to the first three letters of the genus and the first four letters of the specific epithet; the full names are given in Table 4. Environmental and microform/microsite codes as in Tables 1 and 2.

milled peat fields are surface microtopography (microforms) and the peat extraction technique (treatment). According to the scores on the first ordination axis, the species assemblage of ditches is clearly distinct from assemblages occurring on other microforms. The highest positive score on the second axis corresponds to the lichen *Hypogymnia physodes* growing on spruce (*Picea abies*) stems and branches, mainly in the FM area; this is opposed by species recorded primarily in depressions on the BC area. At the same time, an increase of bog water pH is obvious in the FM area and in ditches.

Table 7 shows the fractions of the total variation in species data that are explained by different variables. It appears that the effect of the 'Microform' variables (6.7 %) is much larger than that of the 'Treatment' variables (2.5 %). A considerable part (4.7 %) of the variation is explained by interaction between the two sets of environmental variables (shared variance). Comparing the effects of biotic environmental variables and environmental chemistry variables shows that the effect of tree layer and saplings (7.8 %) is almost three times the effect of bog water pH and electrical conductivity (2.7 %), and that in this case the fraction of shared variance (1.2 %) is very small. Although the individual percentage contributions of the different sets of environmental variables considered in this analysis seem unremarkable, the Monte Carlo permutation test generally confirms their significance.

DISCUSSION

Our results show that, of the factors tested, the main ones influencing the unmanaged re-vegetation of mined peatlands are their surface microforms and former treatment (block-cut or milled), but the total density of established trees and saplings also has some effect. The importance of microtopography in enhancing local habitat variety has been pointed out also by Rochefort & Campeau (1997). The positive effect of tree layer and saplings is explained by the better moisture conditions *via* shading and reducing wind erosion and frost heaving (Lachance & Lavoie

Table 7. Decomposition of species data variance by CCA and partial CCA. Key: Env. Chemistry: bog water chemistry variables (pH, conductivity); Env. Biotic: log-transformed biotic environmental variables (total density of trees, average height of tree layer, total density of saplings, density of *Betula* spp. saplings, average height of saplings); $p_{axis\ 1}$: significance level of the first canonical axis; p_{all} : significance level of all canonical axes.

Environmental variables	Covariables	Variance explained (%)	Shared variance (%)	Overall explained variance (%)	Unex-plained variance (%)	Monte Carlo permutation test	
						$p_{axis\ 1}$	p_{all}
Data: Species – Microforms – Treatments							
Microforms		11.3				0.002	0.002
Treatments		7.3				0.002	0.002
Microforms	Treatments	6.7				0.002	0.002
Treatments	Microforms	2.5				0.002	0.002
			4.7	13.9	86.1		
Data: Species – Env. chemistry – Env. biotic							
Env. chemistry		3.9				0.002	0.002
Env. biotic		9.0				0.002	0.002
Env. chemistry	Env. biotic	2.7				0.008	0.002
Env. biotic	Env. chemistry	7.8				0.002	0.002
			1.2	11.7	88.3		

2004). Because the litter on the areas studied contains large quantities of *P. sylvestris* needles, it forms a dense acidic and nutrient-poor layer locally under the trees, which will further impede propagule germination and re-vegetation.

Regardless of the study region, the areas left after block-cut peat extraction are more favourable than milled peat fields for spontaneous re-vegetation (Poulin *et al.* 2005). This is because they have shallower—if any—drains, and smaller areas so that plants can invade more readily from the surroundings as well as from the strips of vegetation left between the mining trenches. The Rabivere Bog block-cut area has been exclusively re-colonised by common plant species for Estonian bogs (Kask 1982), namely *Drosera anglica*, *D. rotundifolia*, *Rhynchospora alba*, *Trichophorum alpinum* and *S. magellanicum.* The number and cover of *Sphagnum* species are particularly indicative of successful vegetation recovery; the organic matter accumulated in peatlands consists mostly of *Sphagnum* mosses, and good *Sphagnum* cover is the main target of bog restoration (Rochefort 2000, Quinty & Rochefort 2003). The cover and diversity of higher plants (<30 species) on the block-cut area is favoured by microtopographical heterogeneity, which creates suitable growth conditions for various plant species. The block-cut areas have also had longer to re-vegetate because they were abandoned ~60 years ago, compared with *ca* 30 years ago for milled areas. There is no unambiguous explanation for the higher bog water pH in the Rabivere Bog block-cut area as compared to the milled areas. However, because the values were within the range limits for Estonian bogs (Masing 1984), the effect on vegetation recovery is likely to be small.

Re-vegetation on milled peat fields is much slower. It usually begins in the ditches and on their banks, but also occurs around the edges of milled peatlands, especially if they are close to forests and roads. These areas re-vegetate mainly with vascular plants like *Pinus sylvestris, Betula* spp., *Calluna vulgaris* and *Eriophorum vaginatum*; and with cryptogams such as *Polytrichum strictum* and *Cladonia* spp. Better re-vegetation of peat fields adjacent to a calcareous gravel maintenance road has also been documented in Viru Bog. Here, the number of plant species was relatively low, but their total cover was much greater than in the central parts of the peat fields. To some extent, this can be explained by the outwash of minerals from the gravel into the peat, as shown by the increased electrical conductivity of the bog water, and by the relative ease with which plants can spread from the roadside. The spread of plants is hindered by a ditch running parallel with the road, and they will spread more easily and farther along ditches running perpendicular to the road (Triisberg 2006).

Re-vegetation is faster in ditches whose bottoms are formed from peat dust blown in from adjacent peat fields, which rise and sink synchronously with the fluctuating water table. Therefore, the water level in ditches is not usually more than 10–20 cm below the surface regardless of the range of water table fluctuation in the adjacent peat fields. This creates relatively stable moisture conditions for plants so that they achieve greater cover. Of the microforms studied here, ditches had the smallest number of plant species due to their small area and relatively uniform growth conditions, but the species composition was quite similar to that in natural bogs. The predominant species, *E. vaginatum*, *W. fluitans* and *Sphagnum* mosses, find here suitable conditions for growth and vegetative expansion, and their propagules can be dispersed by water movement. Thus, they can spread more efficiently than by wind dispersal alone. An example is provided by *C. rostrata*, which had relatively high cover in ditches at Rabivere Bog because, once established, this species can spread well vegetatively (Salonen 1992). Additionally, the plants in ditches are favoured by water movement carrying more nutrients and oxygen (Campeau *et al*. 2004).

The flat central parts of milled peat fields remain plantless for decades because of their large areas, which delay the arrival of propagules and provide unfavourable conditions for their germination and survival. At the same time, a greater number of different propagules can be carried by the wind onto a large area, resulting in a greater average number of species. However, in these hostile conditions, only some propagules can germinate and few plants can persist, resulting in much lower plant cover. The most important pioneer species colonising the milled peat fields are *E. vaginatum* and *P. strictum.* These species promote the retention of moisture in the peat and reduce frost heaving, thus creating an appropriate microclimate for the growth of *Sphagnum* mosses and other species (Tuittila *et al*. 2000, Groeneveld & Rochefort 2002). On the milled areas studied the vegetation consisted mainly of pioneer species, together with *P. sylvestris, Betula* spp., *C. vulgaris* and *Cladonia* spp. *E. vaginatum* can often cover quite extensive parts of peat fields, but due to the ongoing drainage and lack of nutrients, it eventually dries out and may vanish after 10–20 years. This could explain the higher cover of *E. vaginatum* in ditches at Viru Bog than at Rabivere Bog, which was abandoned a little earlier.

Of the 39 plant species recorded, only 14 were growing on all three studied areas. Apart from two typical forest species, *Betula pendula* and *Dicranum polysetum*, all other species are common in natural bogs. The reason lies in the dispersal of propagules, which originate mostly from adjacent areas of intact bog. At Viru Bog, the total number of plant species was highest on peat fields situated alongside the natural bog, and this number decreased towards the centre of the milled area (Triisberg 2006).

The abiotic factors that commonly influence the re-vegetation of extracted peatlands are the depth of the water table and the consequent moisture conditions on the peat surface, the pH and electrical conductivity of the bog water, and peat density (Girard *et al*. 2002). According to our results, the pH of bog water was closest to that in natural bogs in the block-cut and unfertilised milled areas, which would favour the re-establishment of bog plant species in these locations. However, the re-vegetation of the areas we studied has taken place very differently, indicating that other environmental factors are involved. In all of the areas considered, there is a superficial layer of residual *Sphagnum* bog peat ~1 m thick. Due to the irregularities of the mineral bottom, more mineral- and nutrient-rich water can be accessible to the roots of plants in some places, favouring their growth. The upward movement of groundwater (Ilomets *et al*. 2004), combined with calcareous dust blown in from the local roads, may be responsible for the higher conductivity of the water in Viru Bog.

Comparing the results from the milled peat fields at Rabivere Bog and Viru Bog enables us to draw some general conclusions concerning the effect on re-vegetation of a single application of fertiliser combined with sowing. These sites were abandoned at almost the same time, and have comparable surface peat characteristics and environmental conditions, except that fertiliser was applied only at Rabivere Bog. Although there is almost no difference in the total number of plant species (23 *vs* 24), the mean number of species in sample quadrats on the fertilised area was almost twice as great and the first plant associations were forming, whereas at the unfertilised Viru Bog the vegetation cover was more fragmented and random. Surprisingly, there were more (6 *vs* 3) species in the tree layer (only) of the fertilised area, although the number of species in the field and moss layers was only slightly higher at Viru Bog. Fertilisation had a positive effect on tree and sapling density except in the case of birch. Three tree species (*Betula nana*, *Picea abies* and *Salix* sp.) that were found only in the fertilised area on Rabivere Bog are common to different types of peatlands. Most unexpected was finding *B. nana*, which is known to have a very small capacity for dispersal and a relict distribution pattern, and grows on some bogs as a remnant from post-Ice Age periods (Aston 1984). Amongst microforms, the only essential difference in species numbers was detected in ditches. Thirteen species in the ditches of

Rabivere Bog (fertilised) *versus* seven species in the ditches of Viru Bog (unfertilised) may reflect fertiliser outwash from the peat fields.

Generally, the milled peatlands were sparsely re-vegetated due to the occasional nature of colonisation by plant species. The re-vegetation was more successful—and approaching the plant cover typical for natural raised bogs or bog forests—on the block-cut areas and in the ditches, where the environmental conditions are more favourable and stable, and plants spread vegetatively as well as by seed.

After fertilisation and sowing of *Oxycoccus palustris* seeds on Rabivere Bog at the end of the 1980s, this species had high cover and yield (Ramst *et al*. 2005), but the positive effect was short-lived and within a few years the added nutrients were washed out. *Oxycoccus* has now disappeared, or occurs only at low cover and yield in some patches. However, the number of plant species is higher in ditches at Rabivere Bog, which indicates that there is still some long-term positive effect of fertilisation combined with better moisture conditions. The same has happened at Viru Bog, where planted *Rubus chamaemorus* has almost disappeared.

On the basis of our results, some recommendations can be provided to make the restoration of extracted peatlands more successful:

- When only block-cut peat will be mined, the top peat layer—with plants and viable propagules—should be replaced on the mined areas instead of being removed from the site altogether.
- If possible, some bog fragments should be left within the larger milled peat areas. These can serve as refugia from which bog plant species can spread to neighbouring milled areas.
- To support the natural re-vegetation of cutover peatlands, one should close the ditches and try to create some microtopographical heterogeneity during the final stages of peat mining.
- The sowing and planting of bog plants, accompanied by a single application of fertiliser, will lead to faster re-vegetation of milled peatlands, but only for a short period. For better results, this treatment should be combined with improving growth conditions for the plants.

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REFERENCES

Aston, D. (1984) *Betula nana* L., a note of its status in the United Kingdom. *Proceedings of the Royal Society of Edinburgh*, 85B, 43–47.

Borcard, D., Legendre, P. & Drapeau, P. (1992) Partialling out the spatial component of ecological variation. *Ecology*, 73, 1045–1055.

Campbell, D.R., Lavoie, C. & Rochefort, L. (2002) Wind erosion and surface stability in abandoned milled peatlands. *Canadian Journal of Soil Science*, 82, 85–95.

Campeau, S., Rochefort, L. & Price, J.S. (2004) On the use of shallow basins to restore cutover peatlands: Plant establishment. *Restoration Ecology*, 12(4), 471–482**.**

Dufrêne, M. & Legrendre, P. (1997) Species assemblages and indicator species: the need for a flexible asymmetrical approach. *Ecological Monographs*, 67, 345–366.

Girard, M., Lavoie, C. & Thériault, M. (2002) The regeneration of a highly disturbed ecosystem: a mined peatland in southern Québec. *Ecosystems*, 5, 274–288.

Groeneveld, E.V.G. & Rochefort, L. (2002) Nursing plants in peatland restoration: on their potential use to alleviate frost heaving problems. *Suo*, 53(3–4), 73–85.

Heikkilä, H., Lindholm, T. & Jakkola, S. (2002) Soiden ennallistamisopas (A guide for the restoration of peatland habitats). *Metsähallituksen luonnonsuojelulkaisuja*, Sarja B 66, 124 pp. (in Finnish).

Ilomets, M., Pajula, R. & Karofeld, E. (2004) Temporal changes in pore water chemistry in the peat deposit of a raised bog. In: Päivanen, J. (ed.) *Wise Use of Peatlands*, Proceedings of the 12th International Peat Congress, Volume 1, International Peat Society, Tampere, 38–41.

Ingerpuu, N., Kalda, A., Kannukene, L., Krall, H., Leis, M. & Vellak, K. (1998) *Eesti sammalde määraja* (*The Key-Book of Estonian Bryophytes*). Eesti Loodusfoto, Tartu, 239 pp. (in Estonian).

Kask, M. (1982) A list of vascular plants of Estonian peatlands. In: Masing, V. (ed.), *Peatland Ecosystems*, Academy of Sciences of the Estonian S.S.R., Tallinn, Valgus, 39–49.

Lachance, D. & Lavoie, C. (2004) Vegetation of *Sphagnum* bogs in highly disturbed landscapes: relative influence of abiotic and anthropogenic factors. *Applied Vegetation Science*, 7, 183–192.

Leht, M. (ed.) (2007) *Eesti taimede määraja* (*The Key-Book of Estonian Plants*). Eesti Loodusfoto, Tartu, 398 pp. (in Estonian).

McCune, B. & Mefford, M.J. (1999) *PC–ORD. Multivariate analysis of ecological data, version 4*. MjM Software Design, Gleneden Beach, Oregon, USA.

Masing, V. (1984) Estonian bogs: plant cover, succession and classification. In: Moore, P.D. (ed.) *European Mires*, Academic Press, London, 120–148.

Moen, A. (1999) *National Atlas of Norway. Vegetation.* Norwegian Mapping Authority, Høenfoss, 200 pp.

Økland, R.H. & Eilertsen, O. (1994) Canonical Correspondence Analysis with variation partitioning: some comments and an application. *Journal of Vegetation Science*, 5, 117–126.

Orru, M. (1992) *Eesti turbavarud* (Estonian Peat Resources). Eesti Geoloogiakeskus, Tallinn.

Paal, J. (ed.) (2007) *Jääksoode korrastamise käsiraamat* (*Handbook on the Reclamation of Cut-over Peat Fields*). Tartu. Online at: http://www.envir.ee/orb.aw/class=file/action=preview/id=797949/J%E4%E4ksoode+korrastamise+k%E4siraamat.pdf (last accessed 09 Dec 2010).

Poulin, M., Rochefort, L., Quinty, F. & Lavoie, C. (2005) Spontaneous revegetation of mined peatlands in eastern Canada. *Canadian Journal of Botany*, 83, 539–557.

Price, J.S., Rochefort, L. & Quinty, F. (1998) Energy and moisture considerations on cutover peatlands: surface microtopography, mulch cover and *Sphagnum* regeneration. *Ecological Engineering*, 10, 293–312.

Quinty, F. & Rochefort, L. (2003) *Peatland Restoration Guide*, second edition. Canadian *Sphagnum* Peat Moss Association and New Brunswick Department of Natural Resources and Energy, Québec, 120 pp.

Ramst, R. & Orru, M. (2009) Eesti mahajäetud turbatootmisalade taastaimestumine (The regeneration of Estonian abandoned milled peatlands). *Eesti Põlevloodusvarad ja –jäätmed*, 1, 6–7 (in Estonian).

Ramst, R., Orru, M. & Halliste, L. (2005) *Eesti mahajäetud turbatootmisalade revisjon. 1. etapp: Harju, Rapla ja Lääne maakond* (*The revision of Estonian abandoned milled peatlands. 1st stage: Harju, Rapla and Lääne districts*). Eesti Geoloogiakeskus, Tallinn, 132 pp. (in Estonian).

Rochefort, L. (2000) *Sphagnum* – a keystone in habitat restoration. *The Bryologist*, 103, 503–508.

Rochefort, L. & Campeau, S. (1997) Rehabilitation work on post-harvested bogs in south eastern Canada. In: Parkyn, L., Stoneman, R.E. & Ingram, H.A.P. (eds.) *Conserving Peatlands*. CAB International, Wallingford, UK, 287–294.

Salonen, V. (1987) Relationship between the seed rain and the establishment of vegetation in two areas abandoned after peat harvesting. *Holarctic Ecology*, 10, 171–174.

Salonen, V. (1992) Plant colonization of harvested peat surfaces. *Biological Research Reports from the University of Jyväskylä*. University of Jyväskylä, 15–16.

StatSoft Inc. (2004) STATISTICA (data analysis software system), Version 6. Online at: www.statsoft.com.

Stoneman, R. & Brooks, S. (1997) *Conserving Bogs. The Management Handbook.* The Stationery Office Ltd., Edinburgh, 286 pp.

Ter Braak, C.J.F. & Šmilauer, P. (2002) *CANOCO Reference Manual and CanoDraw for Windows User's Guide*. Biometris, Wageningen and České Budějovice, 498 pp.

Triisberg, T. (2006) *Jääksoode looduslik taastaimestumine Viru raba näitel* (*On the Natural Re-vegetation of Cut-over Peatland in Viru Bog*). BSc thesis, Tallinn University (in Estonian with English summary, available at the Academic Library of Tallinn University).

Tuittila, E.-S., Rita, H., Vasander, H. & Laine, J. (2000) Vegetation patterns around *Eriophorum vaginatum* L. tussocks in a cut-away peatland in southern Finland. *Canadian Journal of Botany*, 78, 47–58.

Wheeler, B.D. & Shaw, S.C. (1995) *Restoration of Damaged Peatlands*. John Wiley & Sons Ltd., London, 567 pp.

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