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Assessment of Soil Quality for Biodiversity Conservation in Boreal Forest Ecosystems

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ABSTRACT

Soil conservation has fundamental significance for biodiversity conservation and sustainable land use. Variations in soil types within the National Natural Park "Russian North", European Russia, were analyzed to secure habitat diversity. Forest soils differed greatly in O and A layer thickness, organic C content, total elements, acidity, and exchangeable cations. Improving of soil properties in a range: podzol, podzolic soil, derno-podzolic soil, brown earth, pararendzina lead to growing diversity and changes in floristical composition of phytocoenoses, followed by changing pine and spruce forests to mixed and birch forests. The ordination of the major species diversity variables was highly related to soil pH and thickness of A horizon, suggesting that pH and organic matter content are the best soil related predictors of species diversity parameters. Evidence from the relationships between soil and plant species diversity suggests that soil quality management could be used to maintain compositional stability at forest ecosystems.

INTRODUCTION

The conditions of the forest are influenced by various natural variations in the environment and by anthropogenic factors (Whittaker, 1975; Smith, 1981). In forest ecosystems, soils play important role in formation of plant communities, their species and structure diversity (Duchaufour, 1965; Karpachevsky, 1977). However, the conjugate soil and plant investigations are limited in boreal forest ecosystems (Ipatov et al., 1977; Laroi, 1992; Okland and Eilertsen, 1994).

We studied one source of biodiversity, which is typically overlooked, variation in soil types. The effect of variations in soil characteristic on vegetation structure, composition and diversity were examined within the National Park "Russian North", European Russia.

METHODS AND MATERIALS

Study area and soils

The National Park "Russian North" is situated in the northern part of European Russia, about 200 km north from Vologda (between 59°43′ and 60°18′N; between 38°09′ and 39°00′E). The territory is characterized by a hummocky moraine relief and covered mainly by loamy carbonate and noncarbonate moraine; glaciofluvial deposits are less common. Soil cover is complex and nonuniform. Most of the area is covered with podzolic and derno-podzolic soils developed on the flat tops and gentle slopes of the moraine hills. The chief factor preventing the development of podzolic soils in the other part of the area is the abundance of carbonates in the parent rock. Soils with a higher degree of gleyzation are distributed in saddles. Depressions between hills are occupied by peat gley and peat soils.

Park territory is covered by woods entirely: taiga is intermittent with the birch woods that are traditional for the Central Russia plains. More than 500 species of higher plants (excluding mosses) have been recorded in the Park; 60 of them are rare (Panov, 1993). The unusual flora is due to the composition of Boreal, Siberian, Arctic and European species. North species make up the main group of the local flora. Broadleaf species, including oak trees, maples, limes, elms, play a noticeable role in the flora of "Russian North", at the northern boundary of their range. Ground vegetation is dominated by bilberry, stone berry, orpine, and green mosses. The majority of forests are the natural secondary planting, the artificial planting take up small areas.

Table 1. Forest and soil types.

Forest type	Soil type	
	Russian classification	**FAO/UNESCO**
Vaccinium myrtillis - spruce forest with pine	Residually calcareous non-deep podzolic soil	Eutric Podzoluvisol (Pde[1])
Oxalis acetosella - spruce forest	Non-deep podzolic soil	Eutric Podzoluvisol (Pde[2])
Oxalis acetosella - spruce forest with rowan	Anthropomorphic residually calcareous derno-non-deep podzolic soil	Eutric Podzoluvisol (Pde[3])
Green mosses - pine forest	Feebly developed podzol	Cambic Podzol (PZb)
Rubus saxatilis – spruce forest	Base saturated brown earth	Eutric Cambisol (Cme)
Aegopodium podagraria - birch forest with aspen	Pararendzina	Rendzic Leptosol (LPk)

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Comprehensive investigations of forest ecosystems were started at six permanent plots that are representative of the area (Table 1). Spruce forests were dominant. The soil profiles were visibly podzolized with the typical horizon sequence and loamy texture. The albic E horizon with average thickness about 20 cm was present. Under the pine forest sandy, feebly developed podzol covered lymnoglacial deposits. The thickness of Ae horizon was about 3 cm**.** The other two soils were classified as brown earth and pararendzina. These two soils lacked the profile differentiation of the podzolic type. Brown earth evolved under the spruce forest with well-developed herb cover on a steep well-drained lakeshore, while pararendzina developed under the birch forest and admixture of aspen on the top of moraine hill. According to the FAO/UNESCO system the soils in the Park can be classified as Podzoluvisols, Podzols, Cambisols and Leptosol.

Sampling

The soil samples were collected from the deep profiles, one in each of the six permanent plots, by horizon. In addition 10 subplots in each of the six plots, 60 in total, were selected for the conjugate vegetation and soil study. There the storage of forest floor was estimated at kg m^{-2}, and soil samples were collected from the organic (O), surface (M1) and subsurface (M2) mineral horizons. The samples were air-dried at 20°C and sieved through a 2-mm sieve.

Chemical methods

Chemical analysis of the soil included total elements by X-ray fluorescence method (TEFA, Germany), total organic carbon (Corg) by dry combustion (AH-7529, Grodno, Buelorussia) and total nitrogen (N) using the Kjeldahl method (Tecator Kjeltec System 1002, Sweden). Soil pH was measured in H_2O and 0.01 M $CaCl_2$ suspensions with a soil to solution ratio of 1:25 and 1:2.5 for O and mineral horizons, respectively. The amount of exchangeable and total acidity was determined in the 1 M NH_4NO_3 and 1 M NH_4Ac extracts, respectively, by an endpoint titration to pH 7.00. Exchangeable base cations (Ca, Mg, K, Na) were measured in the extract of 0.1 M NH_4Cl in 70% ethanol. Ammonium chloride-extractable elements in soils were determined by atomic absorption spectroscopy (Carl Zeiss Jena AAS-3, Germany). Base saturation is defined as the equivalent sum of the exchangeable pool of base cations calculated as the percentage of the cation exchange capacity (CEC); CEC is the equivalent sum of exchangeable base cations and EA ($H^+ + Al^{3+}$).

Data treatment

Vegetation and soil data from the six permanent plots were examined to identify what biotic and edaphic factors control vegetation structure, composition and diversity. The species composition and diversity of trees, shrubs and the ground flora (vascular plants less than one meter in height excluding tree seedlings and bryophytes) were compared among sixty subplots, ten in each of the six permanent plots. Species richness, evenness, and diversity, based on the estimated composition of tree and shrub species and on the midsummer percentage cover of vascular plant and bryophyte species, were employed for characterizing the species assemblages of communities. Species richness was expressed as logarithm of the number of observed species, diversity as the Shannon-Wiener index and evenness as the Shannon index divided by the species richness (Whittaker, 1975). Twelve species assemblage variables were analyzed by means of principal component analysis (the original script written in Matlab 5.2). Fifteen soil properties (thickness of O and A horizons, storage of forest floor, pH_{H2O}, pH_{CaCl2}, EA and exchangeable Al in O, M1 and M2 horizons), determined in the same subplots, were used as external variables.

RESULTS AND DISCUSSION

Soil chemistry

The majority of podzols and podzolic soils under coniferous forests had thick mor humus horizons. Pararendzina was rich in base cations, resulting in mull-type humus, a thin intimate mixture of organic and mineral material formed mainly by earthworms (Duchaufour, 1965). The storage of forest floor varied from 0.3 to 8.8 kg·m^{-2}. Maximal values (5.6-8.8 kg·m^{-2}) were found in podzols and podzolic soils under spruce and pine forests. The storage of forest floor in derno-podzolic soil, brown earth and pararendzina under spruce forests did not exceed 2.2 kg·m^{-2}. Birch forest soils had the minimal thickness and storage of forest floor. The organic C content in the mineral soil was much lower than in the organic horizon, and decreased with depth (Fig. 1). Higher values were observed in the mineral surface (9.2%) and subsurface (3.8%) horizons of pararendzina. Nitrogen in forest soils was concentrated mainly in the organic horizon and correlated significantly with organic carbon content.

The analysis of total elements indicated a higher content of silica in soil organic horizon of coniferous forests (Table 2). In derno-podzolic soil under spruce forest, the percentage of calcium in O horizon increased to 37%. In pararendzina under birch-aspen forest, the maximum amount of Ca (72%) was observed, while the percentages of Si and Al were low: 19 and 2% respectively.

Profile distribution of total elements confirmed the differentiation of the four soils on podzolic type (Table 2). Noticeable relative accumulation of Si, as the most resistant component of the soil mineral fractions, was observed in E horizons with a maximum in podzol under the pine forest (39.2%) and a minimum in residually calcareous podzolic soil under the spruce (35.5%). The distribution of Fe and Al had illuvial character with a greatest amount in the B-horizons. In soils developed on carbonate moraine the content of Ca was increased in the lower horizons (5.6-6.6%).

The character of the total elements distribution in brown earth and pararendzina soils developed on the carbonate moraine was rather different. Brown earth was characterized by equal element distribution through the whole profile. The typical pararendzina developed under the birch-aspen forest was notable for least amount of Si (15-26%), low content of Fe and Al with the maximum in A and AD horizons, which indicated the absence of clay-silicate destructive processes.

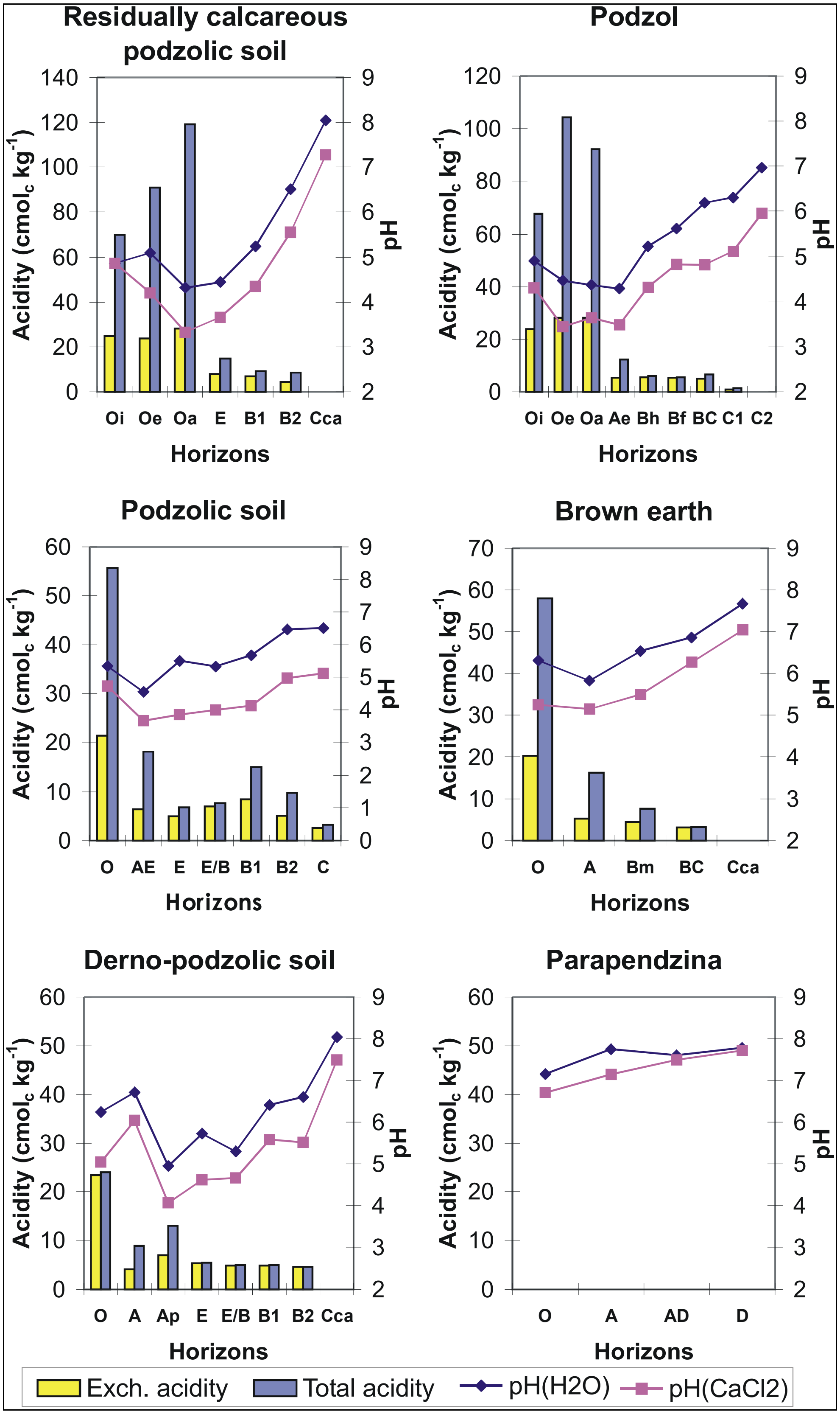

Figure 1. Organic carbon and total nitrogen in soils.

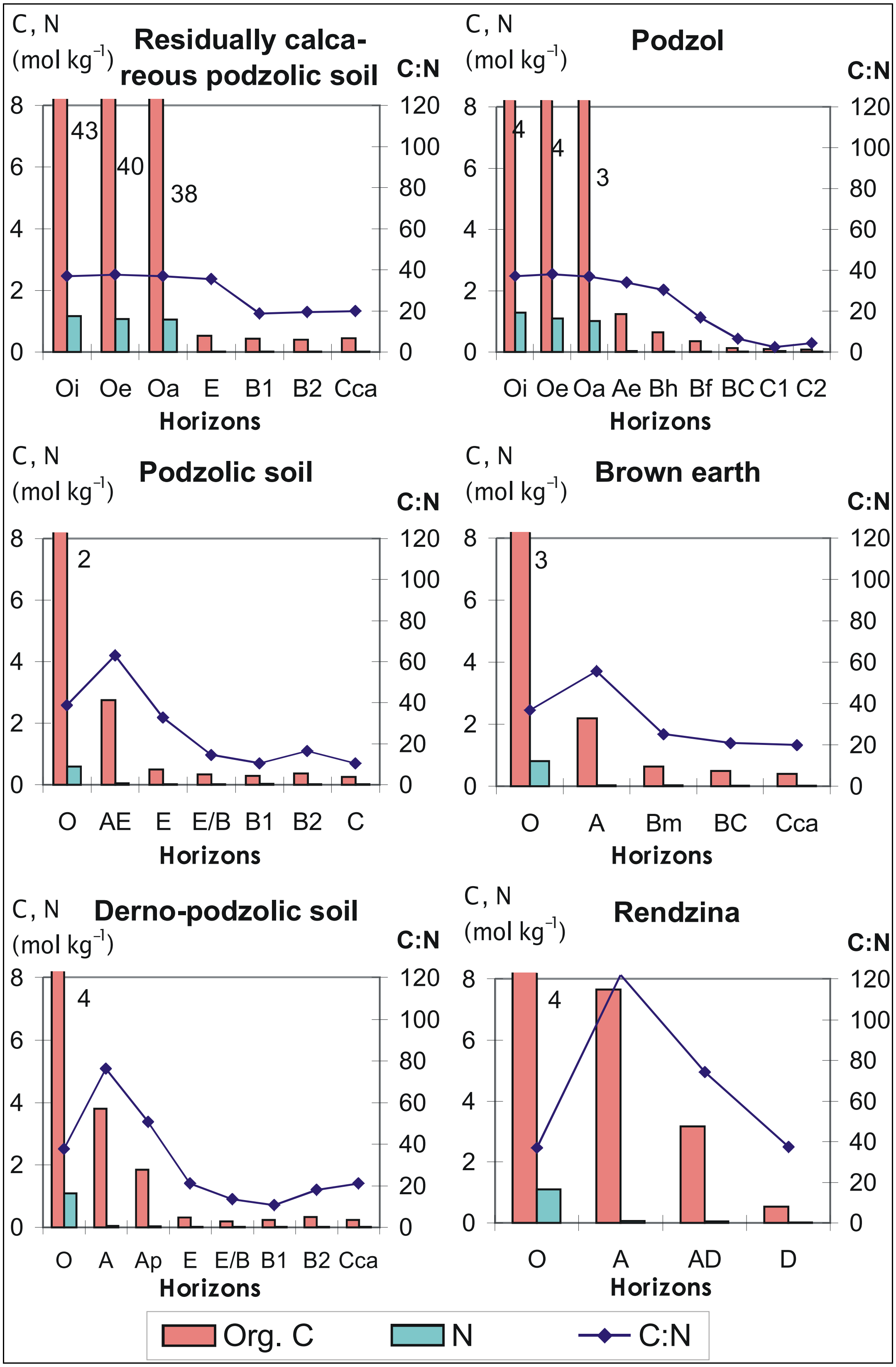

Figure 2. Soil pH, exchangeable and total acidity.

Table 2. Total elements in forest soils (%)

Soil†	Horizon	Depth, cm	Ca	Mg	K	Si	Al	Fe	Ti	Mn
Pde[1]	O	0-6	0.62	0.20	0.19	2.06	0.44	0.39	-	0.05
	E	6(8)-25	0.89	1.00	1.90	36.26	6.88	1.76	0.44	0.05
	B1	25-38	0.85	1.68	2.08	32.65	8.75	3.77	0.46	0.06
	B2	38-61	1.01	1.78	2.16	31.00	9.78	4.51	0.46	0.08
	BCca	61-70	5.63	2.75	1.99	28.93	8.41	3.94	0.43	0.06
Pde[2]	O	0-6(8)	1.19	0.27	0.49	6.54	1.55	0.92	-	0.17
	AE	6-8(9)	0.99	1.30	2.16	34.72	7.16	2.81	0.63	0.05
	E	8(9)-26	0.72	1.28	1.98	35.46	7.42	2.01	0.45	0.05
	E/B	26-34	0.66	1.47	2.26	33.00	8.57	3.70	0.50	0.06
	B1	34-76	0.63	1.89	2.28	30.62	10.03	4.86	0.51	0.05
	B2	76-96	0.77	2.21	2.38	30.05	10.10	4.98	0.52	0.08
	C	96-110	0.78	1.74	2.33	30.89	9.91	4.57	0.50	0.08
Pde[3]	O	0-1	0.80	0.19	0.25	0.70	0.22	0.07	-	0.02
	A1	1-6	1.04	1.40	1.94	34.90	7.10	2.76	0.49	0.09
	Ap	6-22	0.92	1.36	2.08	34.13	7.83	2.96	0.55	0.07
	E	22-38	0.85	1.33	1.95	36.19	6.55	1.91	0.43	0.07
	E/B	38-47	0.79	1.46	2.07	35.27	7.01	2.47	0.44	0.08
	B1	47-56	0.85	1.47	2.08	35.21	7.20	2.27	0.41	0.07
	B2	56-82	0.73	1.84	2.26	31.02	9.77	4.51	0.55	0.06
	Cca	82-100	6.61	2.64	2.03	27.73	8.63	4.47	0.53	0.08
	O	0-4	0.63	<<ld	0.15	1.23	0.34	0.60	-	0.07
PZb	Ae	4-6(7)	0.79	0.71	1.25	39.13	4.81	1.30	0.34	0.07
	Bh	6(7)-18	1.43	0.69	1.36	36.47	5.47	1.81	0.37	0.06
	Bf	18-24	0.72	0.81	1.17	37.60	6.30	1.66	0.32	0.06
	BC	24-58	0.63	1.06	1.25	38.17	5.79	1.34	0.23	0.05
	C1	58-82	0.58	0.78	1.40	38.65	5.43	1.36	0.18	0.08
	C2	82-100	0.59	0.86	1.29	39.77	4.45	1.02	0.15	0.06
Cme	O	0-4	1.24	0.42	0.39	3.86	1.37	0.71	-	0.07
	A	4-10	1.08	1.70	2.35	31.61	9.19	4.25	0.46	0.07
	Bm	10-35	0.94	1.91	2.27	31.03	9.65	4.40	0.51	0.06
	BC	35-70	1.00	1.89	2.37	30.13	10.15	4.96	0.52	0.06
	Cca	70-75	1.17	2.07	2.36	30.36	9.95	4.53	0.50	0.07
LPk	O	0-0.5	2.05	<<ld	0.21	0.55	0.06	0.08	-	0.01
	A	0.5-9(11)	13.07	1.32	1.89	26.04	6.67	5.01	0.43	0.09
	AD	9(11)-28	16.23	1.63	1.59	24.62	6.87	3.80	0.35	0.06
	D	28-50	40.79	0.11	1.01	14.71	3.44	1.82	-	-

† Soil symbols correspond to denotations in Table 1.

The maximum content of Ca was noted in this profile (13-16% through the profile and 41% in C horizon).

The typical for the region podzol and podzolic soils were rather acidic, due to the moist, cool climate and mainly coniferous forest cover keeping low organic matter content. They were characterized by low pH and elevated exchangeable acidity (Fig. 2). As a result of the variable acid strength of organic materials, the pH of organic layers varied within wide limits. The pH_{H2O} laid mainly between 3.7 and 5.6, while the pH_{HCaCl2} was between 3.1 and 5.0.

The highest acidity occurred in the eluvial part decreasing with the depth to the minimum values in parent rock. Such characteristics are typical for podzol profiles (Vanmechelen et al., 1997). High pH and low acidity in brown earth and pararendzina were induced by carbonate moraine parent rocks rich in Ca and Mg containing minerals. The effect of carbonates persisted in the overlying organic layer. The pH of organic layers overlying calcareous soils was considerably higher than the pH of organic layers overlying carbonate-free soils.

The type of vegetation growing on a soil was likely to have a marked influence on soil acidity due to the inherent differences in base content of their litter. Soils supporting conifers tended to be more acid than those supporting deciduous. This dependence was not always obvious, no was the cause-effect connection always clear. Due to species differences in tolerance to soil acidity, soil conditions might influence the composition of the plant community more than the community influenced soil reaction. However soil nutrient and moisture supply might modify effects of soil acidity on tree growth.

Podzols and podzolic soils contained large amounts of H and Al in exchangeable form. Organic horizons rich in negatively charged colloids had exchangeable acidity values of 20-30 $cmol_c \cdot kg^{-1}$ soil, but the majority of mineral horizons had values varying from 1 to 9 $cmol_c \cdot kg^{-1}$ soil, with slightly higher values in the mineral surface layer (Fig. 2). Ion exchange reactions in soils are important as a source of nutrients for plant growth. This particularly applies to exchangeable Ca, Mg and K. Ca was the dominant exchangeable basic cation in all soils studied (Fig. 3). Exchangeable Mg was always present in smaller

Table 3. Species composition.

Species	Pde[1]	Pde[2†]	Pde[3]	PZb	Cme	LPk
Trees[‡]:						
Alnus incana		4				13
Betula pendula	6	6				21
Picea abies	94	38	110		37	3
Pinus sylvestris	13			70	6	
Populus tremula		1	2			9
Sorbus aucuparia	6			2	6	7
Herbs and dwarf shrubs[§]:						
Total plant cover, %	40-60	40	60-70	10-20	30-50	50-70
Actaea spicata		<1	5			
Aegopodium podagraria		<1	10			20
Athyrium filix-femina			5			
Calamagrostis arundinacea	5	1-2		5		
Convallaria majalis	1-5	10				10
Fragaria moschata					5	
Geranium sylvaticum		<1			<1	10
Linnaea borealis	10					
Melampyrum pratense	<1			5		
Oxalis acetosella	20	10	50			
Pyrola rotundifolia	5	<1			15	
Rubus saxatilis	5	<5			20	
Stellaria nemorum			10			
Trollius europaeus		<1	<1		<1	5
Vaccinium myrtillis	30	20				
Mosses:						
Cover, %	70-90	20	20	100	80-100	
Dicranum rugosum	20			15		
Dicranum scoparium	10				15	
Hylocomium splendens				15	15	
Pleurozium schreberi	50	20		70	60	
Thuidium abientinum			20			

† Soil symbols correspond to denotations in Table 1; ‡ number per 625 m^2; § plant cover (%) of the most spread species.

quantities than Ca. Concentrations of exchangeable K and Na were negligible. The base saturation in the mineral surface layer of non-calcareous forest soils increased from 5-14% in the podzol and podzolic soils to 60% in the derno-podzolic soil and 70% in the brown earth. Pararendzina had an exchange complex fully saturated with basic cations.

Thus, soil cover of the National Park “Russian North” is complex and nonuniform. The investigation of morphological, textural and chemical properties has confirmed the differentiation of soils on podzol, podzolic, brown earth and pararendzina types. Podzolic, derno-podzolic soils and brown earth, developed on carbonate moraine under the spruce forests, were characterized by loamy texture, eluvial-illuvial distribution of iron and aluminum, elevated content of calcium in low horizons, high acidity in the topsoil, decreasing with the depth. Feebly developed podzol covered lymnoglacial deposits under the pine forest was characterized by sandy texture, the highest content of silica, the lowest content of organic carbon and weak acidity through the profile. Pararendzina, developed on carbonate moraine under the birch-aspen forest, was characterized by loamy texture, high content of organic C and Ca, and a neutral reaction.

Soil-vegetation relationships

Species richness differed between species assemblages, and between forest types (Table 3). Groundcover species richness and diversity were closely related to tree and shrub richness and diversity. The number of vascular plant species increased, while bryophyte species number decreased from the pine forest to the spruce and birch forests.

Results showed a close relationship among different soils and the conjugate plant communities. The six plant communities, which corresponded to six soil types, are clearly separated in the plane of the first two principal components of site scores (Fig. 4a). Species diversity indexes of vascular plants and bryophytes were represented by different principal components (Fig. 4b), so they were almost independent from each other in principal component analysis ordination. Only species diversity of bryophytes was represented mostly by the first principal component. Species diversity, richness, and evenness were closely connected with each other for each assemblage. Diversity indexes of tree species strongly correlated with pH_{H2O} and pH_{CaCl2} in O horizon and especially in surface and subsurface mineral horizons. Species richness and diversity of shrubs correlated weakly with soil properties. Species

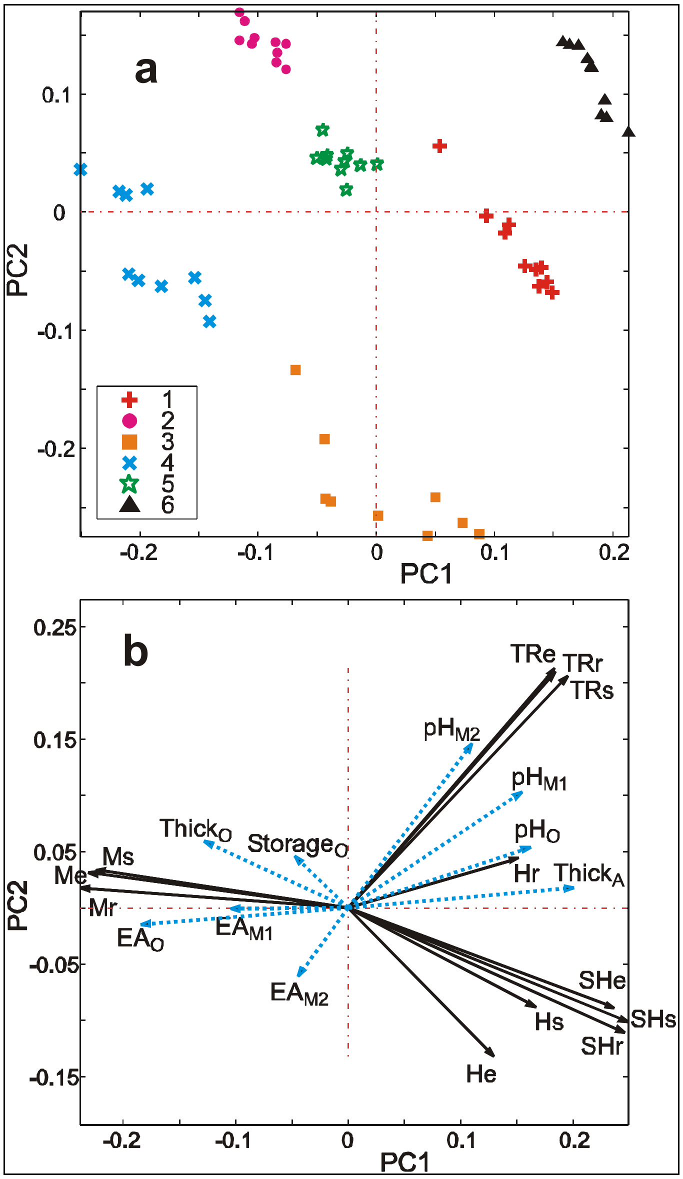

Figure 3. Exchangeable cations, % from cation exchange capacity (CEC). 0-95% – linear scale, 95 - 100% – inverse logarithmic scale.

richness of herbs and dwarf shrubs correlated positively with pH in O horizon and with the thickness of A horizon. Species richness and diversity of bryophytes related positively to the thickness of O horizon, the storage of forest floor, and soil exchangeable acidity and Al. They related inversely to the thickness of A horizon and pH. The inclusion of mosses in vegetation analysis may provide valuable insights into the nature of vegetation patterns over subtle environmental gradients in cool boreal forests. Thus, the ordination of the major species diversity indexes was highly related to soil pH and thickness of A horizon, suggesting that pH and organic matter content are the best soil related predictors of species diversity. This study illustrates that trees and mosses show a broad-scale response to soil acidification. The soil properties were in turn

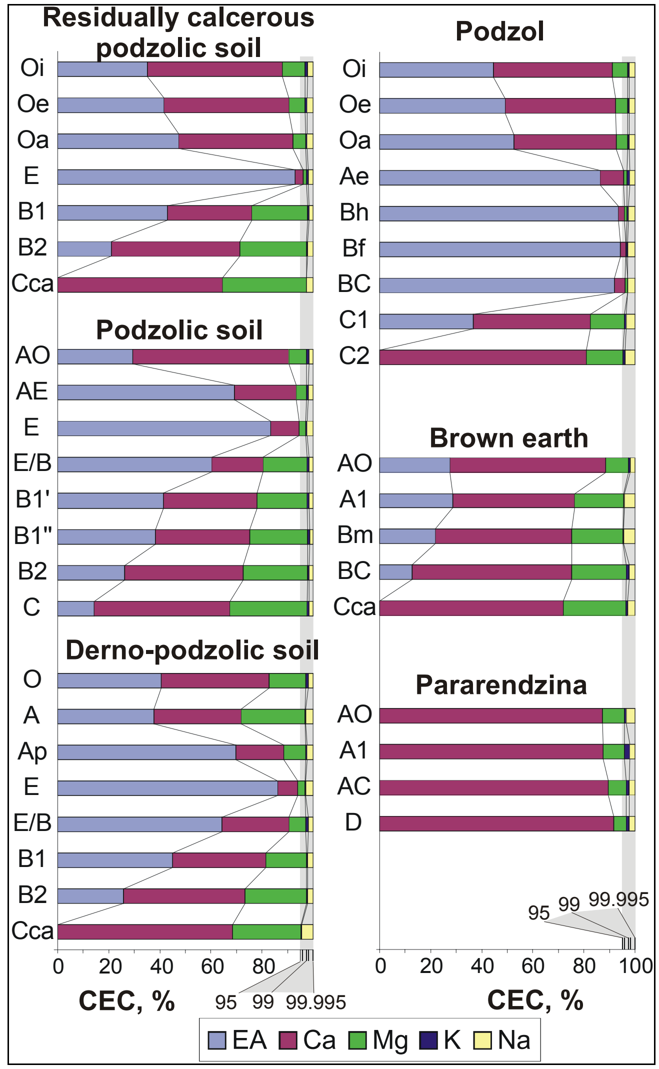

Figure 4. Structural relationships between plants and soils. Ordination of sites (a) and species diversity (b, dashed lines show soil gradients). a: 1 - *Oxalis acetocella* - spruce forest, 2 - *Vaccinium myrtillis* - spruce forest with pine, 3 - *Oxalis acetosella* - spruce forest with rowan, 4 - *Green mosses* - pine forest, 5 - *Rubus saxatilis* - spruce forest, 6 - *Aegopodium podagraria* - birch forest with aspen; b: TR - trees, SH - shrubs, H - herbs and dwarf shrubs, M - mosses, s - species diversity, r - richness, e - evenness, EA - exchangeable acidity, O, M1 and M2 - organic, surface and subsurface mineral horizons.

affected by the vegetation through root uptake/exudation and litter decomposition/ accumulation. The complicity of trends observation was connected with high natural plant and soil variability, competition between species, effects of environmental and anthropogenic factors.

The results stress the complementarity of multivariate methods to direct correlation and regression analyses in interpretation of soil-vegetation relationships. Principal component analysis appeared to be a useful tool for evaluation of relations between two inherently uncertain systems – plant communities and the conjugated soils. Assessment and conservation of soil quality will enhance the current capabilities to determine the status and the change of forest biodiversity resources and their sustainable management.

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