Current Changes in Forest Carbic Podzol and Primary Podzolization of Sand

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Repeated investigations were carried out in *Pineetum myrtilloso-uliginosum* in 1998, where primary studies of Carbic Podzol had been performed in 1965. Primary pedogenesis there was studied on a sand embankment, excavated from the initial pit, which had overgrown with forest vegetation over 33 years. The initiation of primary podzolization is due to the degradable activity of R_2O_3-fulvic forest humus. Its accumulation represents the first stage of podzolisation followed by the development of albic and spodic properties beneath the formed mor type ground litter. Residual accumulation of silica and removal of most metallic elements are characteristic of primary podzolization in the (A)E–(E)B sequence of minipodzol formed within three decades. Current acidification, breakdown of sand and formation of silt fractions, as well as cheluviation of sesquioxides, and especially silica, from Carbic Podzol took place against the background of the increased fulvicity and decreased solubility of Al-humic-fulvic humus. The histic epipedon represented a source for metallo-organic complexes as well as for removal of alkaline earths of biogenic origin and their accumulation in the spodic horizon. Simultaneously with the accumulation of organic carbon and a decrease in the bulk density of spodic horizon, an increased loss of silica has taken place there. As a result of changes in ground water and capillary relationships, the profile of Carbic Podzol has grown in depth at the expense of reduced subsoil.

Key words: Estonia, podzolization, Carbic Podzol, minipodzol, primary pedogenesis

Introduction

Podzolization has always deserved the attention of researchers of pedogenesis in forest areas (Rode, 1937; Muir, 1961; Ponomareva, 1964; Mokma & Buurman, 1982; van Breemen & Buurman, 1998; Lundström *et al.*, 2000a). According to Rode (1937), podzolization represents a breakdown of primary and secondary minerals accompanied by the downward removal and translocation of products. This results in the formation of albic and spodic horizons (FAO/ISRIC, 1998) among which the spodic horizon is special and plays an important role in soil diagnostics. The prerequisites for podzolization are agressive fulvic humus and organic acids, as well as light-textured parent material, poor in alumosilicates and bases, and percolative moisture regime (Rode, 1937; Ponomareva, 1964; Lundström *et al.*, 2000b).

Podzols on different sandy deposits have been described from tundra to tropics in all continents, while in many cases their age can be up to several millennia (Mokma & Buurman, 1982). Katchinskaja (1937) suggested the expression of podzolic attributes already within only twelve years. In Estonia, besides Rendzic Leptosols on limestone and Gleysols in the conditions of aquic regime, podzolization and sandy

Podzols represent soil phenomena which could have been developed at any stage of pedogenesis during the Pre-Pleistocene and from the Late Pleistocene through the whole Holocene (Reintam, 1997a).

To study the trend of pedogenesis and the character of current podzolization under *Pineetum myrtilloso-uliginosum*, this paper focuses on the development of a Carbic Podzol as well as changes in its composition and properties over 33 years, from 1965 to 1998, in South-West Estonia.

Material and methods

Site and sampling

Repeated investigations were carried out in 1998 at Ritskulli (58°10' N, 24°50' E) in the Lodja forest district, Pärnu county, South-West Estonia, where primary studies of Carbic Podzol had been conducted in 1965 under a Scots pine (*Pinus sylvestris*) stand classified as the *Myrtillus-Uliginosum* site type (Fig. 1) by Lõhmus (1984). Soil profile (No 1783) with complete analytical data was demonstrated and discussed in 1966 during the field tour of the Third USSR Congress of Soil Science (Reintam *et al.*, 1966). The profile with data, reanalysed partly by European methods, represents a reference profile for the European Soil Data-

Figure 1. *Pineetum myrtilloso-uliginosum* at Ritskulli in 1998.

base on the scale 1 : 1,000,000 (Reintam & Rooma, 1998). Fine limnoglacial sand represents soil parent material, while the duration of pedogenesis could have been about 10 000 years (Raukas *et al.*, 1995). Contemporary mean annual temperature is +5–6° C and precipitation is about 600 mm. The vegetation period mostly lasts for about 180 days.

Prior to the establishment of profiles for demonstration at the USSR Soil Science Congress, a great number of them were analysed and statistically processed (Reintam, 1971). Later many of these profiles were selected for reference profiles for the European database. A repeated sampling of Carbic Podzol at Ritskulli was done on the same pit, undisturbed during intervening years (Fig. 2). The front wall of the pit was cleaned and the distance between two samplings did not exceed 40–50 cm. The Podzol profile was described and sampled by genetic horizons at the same depths as previously, in 1965. The embankment, form-
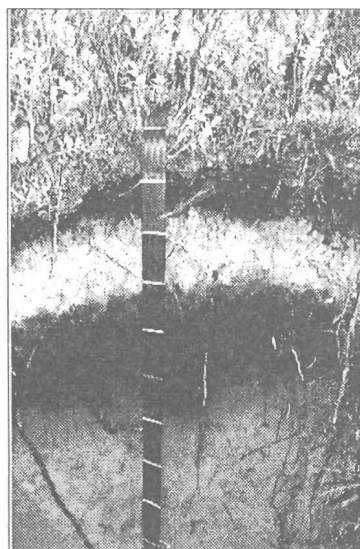

Figure 2. H1–H2–E–Bh–Bs–Bg sequence of Carbic Podzol in 1998.

ed of soil horizons (beneath and inside the formed heap) and parent sand (top and northern part of the heap), excavated from the pit in 1965 and 1966, as well as the bottom of the former pit were overgrown by the year 1998 with green mosses (*Pleurozium schreberi*, *Hylocomium splendens*, *Dicranum undulatum*), *Vaccinium vitis-idea*, *Vaccinium myrtillus* and seedlings of Norway spruce (*Picea abies*). The minipodzol formed on the basis of sand on top of the embankment heap over 33 years on average was sampled from three points of young eluvial and illuvial horizons. All samples represented an average of different points of all horizons studied.

Analyses

The same methods were used in analytical procedures. Bulk density was determined in four replications by using a barrel of 50 cm³. Fine earth less than 2 mm was used. Practically, it represented a fraction less than 1 mm because the proportion of particles with a size of 1–2 mm was less than 10 g kg⁻¹. Samples for the determination of particle size were treated with sodium pyrophosphate to break down aggregates. Sands were sieved and fractions finer than 0.05 mm were determined by pipette analysis (*Pipette Apparatus Table Model 7 Samples*). Total chemical analysis was conducted after alkaline fusion treatment. Iron and aluminium were ascertained by means of sulphosalicylic acid and aluminone, respectively; alkaline earths, potassium, and sodium were determined by the method of flame photometry. Carbonates were determined acidometrically to recalculate the measured data. The obtained results were expressed for ignited noncalcareous material (Arinushkina, 1970; Ranst *et al.*, 1999).

Total amounts of organic carbon and nitrogen were ascertained by the Tyurin and Kjeldahl methods, respectively (Arinushkina, 1970). It is necessary to point out that the Anne method (Ranst *et al.*, 1999) is equivalent to the Tyurin method used. The group and fractional composition of humus was determined by alternate acid–alkaline treatment using the Tyurin–Ponomareva volumetric method (Ponomareva, 1957). The obtained results were expressed in percentages of organic carbon. Tithionite-extractable (total nonsiliceous) iron, oxalate-extractable amorphous iron, aluminium and silica were measured by Coffin and Tamm, respectively; iron activity was calculated after Schwertmann (Ranst *et al.*, 1999). Base exchange capacity (BEC) and exchangeable bases were measured by percolation of the samples with ammonium acetate at pH 7.0 and expressed in cmol kg⁻¹. The pH both of water and 1 M KCl suspensions were measured potentiometrically with the pH-meter *Jenway 3071*. Accuracy re-

quirements for laboratory techniques and measurements were satisfied.

To establish the quantitative origin of the current changes, material balance method was employed (Targulian *et al.*, 1974; Rozanov, 1975; Reintam, 1985, 1990). Based on the equations and calculations presented by Brimhall & Dietrich (1987), a similar methodology is recommended by van Breemen & Buurman (1998). The weight of soil horizons and their textural and chemical constituents as of 1998 were compared to these recorded in 1965 for parent sand at the depth of 100–110 cm. Changes in the column of soil horizons with an area of one square metre were calculated on the basis of measured data according to published formula (Targulian *et al.* 1974; Rozanov, 1975; Reintam, 1997b).

Results and discussion

Morphology, texture

The histic epipedon had not changed over the last 33 years. Its uppermost 10 cm-layers were formed, as usual, of the yellowish-brown (10YR5/8) peaty litter of mosses and forest residues underlain by black (10YR2/1) forest and shrub peat up to a depth of 18–20 cm (Fig.2). There was found no increase either in the thickness or degree of transformation of accumulated organic residues. By the value of hue, the next albic horizon has become slightly lighter, while its chroma and thickness have remained unchanged (Table 1). Against the background of the in-depth deepening of the Bh-horizon, a slight darkening appears to have taken place within the entire spodic horizon. This is caused by a change in the ground water table whose

metal-organic chelates. This has led to a decrease in the bulk density of the humus-illuvial subsequence of the profile, accompanied with a decrease in soil mass there (Table 1). Particularly, this could influence some changes in the pool of the horizon constituents.

On the embankment of initially unchanged sand, dug out from the pit, a minipodzol sequence was formed over 33 years (Fig. 3). Rudimental albic and spodic properties arc clearly expressed in the turned piece of litter turf at the front side of the opened miniprofile. Both (A)E- and (E)B-horizons are 2–3 cm thick, with slight albic and humus-illuvial spodic properties, respectively. The former horizon (10YR5/4) allows to confirm the suggestion by Rode (1937) about the on-
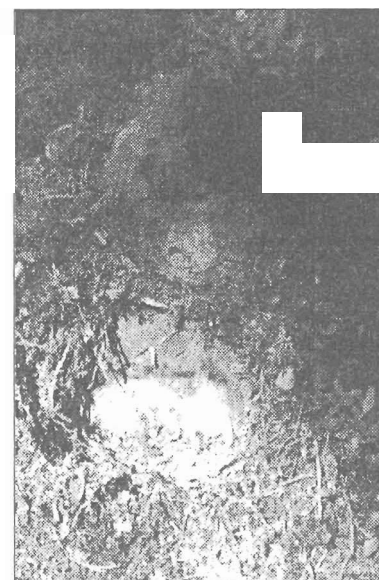

Figure 3. (A)E–(E)B sequence of 33-year-old minipodzol and overturned litter turf above the front wall with white albic (above) and spodic (below) properties.

Table 1. Morphology and physical status

Properties	E-horizon		Bh-horizon		Bs-horizon		Bg-horizon		Cr-horizon	
	1965	1998	1965	1998	1965	1998	1965	1999	1965	1998
Mean thickness, cm	14	14	16	23	10	10	30	25	>70	>72
Colour	5Y7/1	5Y8/1	10YR3/2	10YR2/2	7.5YR4/4	7.5YR3/4	7.5YR7/4		5Y6/4	
Bulk density, Mg m⁻³	1.40	1.38	1.50	1.00	1.42	1.40	1.40	1.45	1.50	1.49
Mass, kg m⁻²	196	193	240	230	142	140	358	362	150*	149*

* Mass for the thickness of 10 cm.

fluctuations and changes determine usually the thickness of the spodic horizon (Ponomareva, 1964) as well as its boundaries (Harris & Hollien, 2000). Amorphous Al-humic-fulvic complexes, coating sand grains, represent the main source of colour, whereas parent material and its mineralogical composition, whose important role is generally known (Mokma, 1993), do not affect soil colour and chroma here. A slight increase in solum thickness has occurred at the expense of gleyed subsoil owing to the evident lateral input of

set of podzolization in sand from an accumulation of organic matter, which results in organic-mineral interactions and formation of the eluvial and illuvial horizons. The latter represents still transitional (E)B but, with respect to its colour and chroma (7.5YR4/4), it is already equivalent to the formed Bs-horizon (Table 1). The average rate of the progress of the miniprofile has been 1.2–1.8 mm yr⁻¹, by 0.6–0.9 mm yr⁻¹ for either horizon. This formation appears to be similar to those described by Vaicys (1975) from Kura spit and by Stützer (1998) from the dunes of Western Jutland.

Sandy texture has also remained almost unchanged (Table 2), although a slight breakdown of sand and accumulation of silt have taken place under the impact of podzolization and reduction in respective horizons. However, as a result of interfractional changes of sand, a residual accumulation of the coarse fraction (about 10–20 g kg⁻¹), a decrease in the medium fraction and an increase in the fine fraction appeared to be char-

Table 2. Granulometric composition, g kg⁻¹

Hori-zon	2–0.05 mm (sand)			0.05–0.002 mm (silt)			< 0.002 mm (clay)		
	1965	1998	±	1965	1998	±	1965	1998	±
E	970	960	–10	30	40	+10	0	0	0
Bh	910	910	0	60	60	0	30	30	0
Bs	970	970	0	10	20	+10	20	10	–10
Bg	980	980	0	10	10	0	10	10	0
Cr	990	970	–20	0	20	+20	10	10	0

acteristic of current podzolisation. The average amounts, transformed in the process of breakdown and/or accumulation, were 9–10 g kg⁻¹ yr⁻¹ in the E–Bh sequence and up to 15–16 g kg⁻¹ yr⁻¹ in the Bs-horizon. A slight loss of clay in the latter can be explained by the development of the profile in depth and by the increase in reduction phenomena there. Changes in the texture of young minipodzol are weak (Table 4), and only the current hydrolysis of clay deserves attention.

Organic matter and humus composition

Against the background of morphological stability, the content of organic carbon shows a considerable increase not only in the histic epipedon but particularly in the spodic Bh-horizon (Table 3). Current increase in the content of organic carbon is 233 g m⁻²yr⁻¹ within the whole profile, while about 50% of that can be ascribed to the lower part of the histic horizon. Decrease (64 g m⁻² yr⁻¹) in the content of organic carbon has taken place beneath the humus-illuvial subsequence, while current input in the horizons below the histic epipedon formed some 80 g m⁻² yr⁻¹. In comparising with the total duration of Holocene pedogenesis (about 2 g m⁻² yr⁻¹ of organic carbon), the current process appears to be forty times more intensive. Within the same length of time, the profile's increment in organic carbon here is about threefold larger than at the Lemmejõgi (0.6–0.7 g m⁻² yr⁻¹) in the vicinity of the Pärnu Gulf. Current enrichment of spodic horizon with nitrogen has occurred in the Carbic Podzol studied (Table 3).

R_2O_3-humic humus is characteristic of the histic epipedon, changeable concerning the humic-fulvic complexes bound with alkaline earths as well as with stable forms of sesquioxides and clay minerals (Table 3). Total solubility has decreased and fulvicity has increased within the last three decades. An increase in the proportion of free fulvic acids in depth appears to indicate increased tendency for biodegradation (Hongve et al., 2000) and further deepening of podzolization there.

The rate of initial humus-accumulative process in the pure sand embankment was only 0.30 and 0.18 g kg⁻¹ yr⁻¹ of organic carbon in the (A)E and (E)B horizons, respectively (Table 4). It is several times higher than in the natural albic horizon but somewhat lower

Table 3. Composition of humus in percentages of organic carbon

Characteristics	H1-horizon*		H2-horizon*		E-horizon		Bh-horizon		Bs-horizon	
	1965	1998	1965	1998	1965	1998	1965	1998	1965	1998
Organic C, g kg⁻¹	309.0	400.3	345.6	413.1	3.5	5.7	38.8	59.8	21.0	10.6
Nitrogen, g kg⁻¹	10.0	6.9	5.7	7.9	0.2	0.1	1.0	8.3	1.0	0.0
C : N	30.9	58.0	60.7	52.3	17.5	57.0	38.8	7.2	21.0	10.6
Pool of C, kg m⁻²	5.6	6.8	6.4	10.2	0.7	1.1	9.3	13.7	3.0	1.5
Pool of N, kg m⁻²	0.18	0.12	0.22	0.20	0.04	0.02	0.24	1.91	0.14	0.00
Difference in C	+1.2		+3.8		+0.4		+4.4		–1.5	
Difference in N	–0.06		–0.02		–0.02		+1.67		–0.14	
Humic acids (HA)										
1	x	18.9	10.9	16.4	34.3	15.8	25.3	17.1	8.6	6.6
2	x	0.0	7.4	0.0	0.0	3.5	0.0	0.0	1.0	0.0
3	x	4.5	1.2	4.6	2.9	0.0	1.0	0.3	1.4	0.0
Total	x	23.4	19.5	21.0	37.2	19.3	26.3	17.4	11.0	6.6
Fulvic acids (FA)										
1a	x	0.5	0.8	0.2	2.9	0.0	11.6	20.7	49.0	63.2
1	x	8.6	18.4	7.4	8.6	17.5	40.5	30.1	9.5	5.7
2	x	6.0	1.6	0.3	22.8	3.5	7.2	0.0	7.2	2.8
3	x	1.9	0.5	2.7	2.9	3.5	0.3	0.3	0.0	1.9
Total	x	17.0	21.3	10.6	37.2	24.5	59.6	51.1	65.7	73.6
0.5 M H₂SO₄ hydrolysate	x	4.4	3.7	5.1	8.5	1.7	1.2	0.0	0.5	0.0
Total soluble	x	44.8	44.5	36.7	82.9	45.5	87.1	68.5	77.2	80.2
Insoluble	x	55.2	55.5	63.3	17.1	54.5	12.9	31.5	22.8	19.8
HA : FA	x	1.4	0.9	2.0	1.0	0.8	0.4	0.3	0.2	0.1
1st fr. : 2 nd fr.	x	4.6	3.3	7.9	1.9	4.4	9.1	47.2	2.2	4.4

x   undetermined

*   Thickness of both subhorizons in both cases 10 cm

Table 4. Minipodzol on a sand embankment excavated from the initial pit

Characteristics	Initial material from 1965	Horizons formed during 33 years	
		(A)E-horizon	(E)B-horizon
Organic carbon, g kg–1	0.0	9.9	5.9
Nitrogen, g kg–1	0.0	0.2	0.0
C : N	0	49	59
Humic acids, % of total C	0	16	12
Fulvic acids, % of total C	0	41	71
Insoluble, % of total C	0	43	17
HA : FA	0	0.4	0.2
Al-humic-fulvic complexes, % of total	0	65	45
pH of water suspension	5.7	4.6	4.9
pH of 1M KCl suspension	4.6	3.8	4.1
Ca²⁺, cmol kg⁻¹	0.20	0.34	0.23
Mg²⁺, cmol kg⁻¹	0.05	0.08	0.05
K⁺ + Na⁺, cmol kg⁻¹	0.00	0.07	0.06
Dithionite-extractable iron, g kg⁻¹	2.0	3.4	2.3
Oxalate-extraxtable, g kg⁻¹			
Fe	0.1	0.8	0.8
Al	1.4	1.0	1.5
Si	0.3	0.7	2.0
Iron activity, %	20	24	35
Texture, g kg⁻¹: sand	989	981	983
silt	4	18	16
clay	7	1	1
Total elements, g kg⁻¹: Si	421	432	425
Fe	5.2	4.0	4.8
Al	27.8	26.8	27.0
Ca	3.2	3.5	3.6
Mg	1.5	1.4	2.0
K	14.8	13.4	13.5
Na	4.7	3.9	4.5
P	1.1	1.4	0.4

than in the spodic horizon whose development has been affected by a lateral influx of chelates (Table 3). Organic acids have enhanced weathering, translocation of fulvates and development of albic properties at the boundary of the forest floor and the sand stratum (Fig. 3). In principle, although there are no differences in the humus composition, the material of the

primary formations appears to have been accumulated *in situ*, while in the formed E–Bh sequence it can be interpreted mainly as the result of downward and/ or lateral influx from peaty forest litter.

Exchange properties and nonsiliceous compounds

Considerable acidification, slight mobilization of nonsiliceous sesquioxides and silica as well as weak changes in exchange bases have been characteristic of primary pedogenesis in pure sand (Table 4). As a result of biological absorption, there has occurred a tendency to enrichment of the exchangeable complex with K^+ and Na^+, however, as usual, they are absent from formed Carbic Podzol or are present in it only in the amount of less than 0.01 cmol kg^{-1}. This soil is characterised by intensive current acidification and a slight enrichment of the E–Bh sequence with exchangeable bases which appear to have been originated from the histic epipedon (Table 5). According to special studies of Nordic Podzols (Gustafsson *et al.*, 2000), base cations are previously present in the diffuse layer of fulvic acids instead of being "truly" dissolved. The same time, for the spodic horizon a small proportion of soil organic matter appeared to have been involved in cation binding. According to the cited authors, the solubility (and removal) of exchangeable bases depends upon the solubility of organic matter. High losses have been characteristic of the histic epipedon (Table 3). A considerable decrease in the solubility and increase in the fulvicity of humus in the spodic horizon of Carbic Podzol have resulted in its current enrichment not only with exchangeable bases but also with bulk alkaline earths and potassium (Tables 7 and 8).

Over the last 33 years, a usual increase in the proportion of amorphous substances has taken place as a result of podzolization and subsoil reduction (Table 6). The only exception is amorphous aluminium in the conditions of gleying against the background of the deepening of the spodic horizon. The upward removal of mobile aluminium pseudosols and their concentration in the spodic horizon (about 2.4 g m^2 yr^{-1}) cannot be excluded there. However, about 1.7 g m^2 yr^{-1} of aluminium has been lost. The albic horizon is eluvial for amorphous aluminium (0.6 g m^2 yr^{-1}), while the humus-illuvial spodic horizon is characterized by its high accumulation (about 3.6 g m^2 yr^{-1}). Obviously, acidification has resulted in a gradual decrease in the solubility of aluminium (Berggren *et al.*, 1998), which has led to its stability and accumulation. Like in Nordic regions (Giesler *et al.*, 2000), such aluminium appears to have been derived from the histic epipedon, which is rich in sesquioxides like the ground litter of coniferous forests (Kõlli, 1971). Formation of proto-

Table 5. Physico-chemical properties

imogilite allophane could have occurred *in situ* in the spodic horizon, as it was found in some Podzols in Nordic regions (van Hees *et al.*, 2000).

The loss of dithionite-extractable iron from the albic horizon (about 0.8 g m^2 yr^{-1}) is in good balance with its gain in the spodic horizon. Profile accumulation at a rate of 3.5 g m^2 yr^{-1} has been characteristic of amorphous iron, despite the fact that the albic horizon has been eluvial (Table 6). As a result of pedogenetic changes in silicates, current increase has taken place in the share of amorphous and crystalline forms of iron, while the intensity of recrystallization has decreased in depth (Fig. 4). Against the background of the current losses of bulk iron (Table 7), absolute increase in the content of crystalline iron is absent, and hence inhibition of podzolization appears to be impossible (Wang *et al.*, 1989). The extremely intensive formation of amorphous silica (about 13–14 g m^2 yr^{-1}) and its profile accumulation (Table 6) are in concordance with the increase in the content of free fulvic acids as well as in the fulvicity of the spodic horizon (Table 3), but also with the increase in the acidity of the entire profile (Table 5). Due to these phenomena, silica of phytolith origin in the histic epipedon has become movable (Kelly *et al.*, 1998).

Chemical composition

Current podzolization has led to the residual enrichment of the albic horizon with silica and of the spodic horizon with aluminium, alkaline earths and potassium (Table 7). This is obviously due to their mobilization in the histic epipedon and translocation from it and from the albic horizon in the form of chelates, which appear to have been saturated with bases of biogenic origin. Enrichment of the spodic
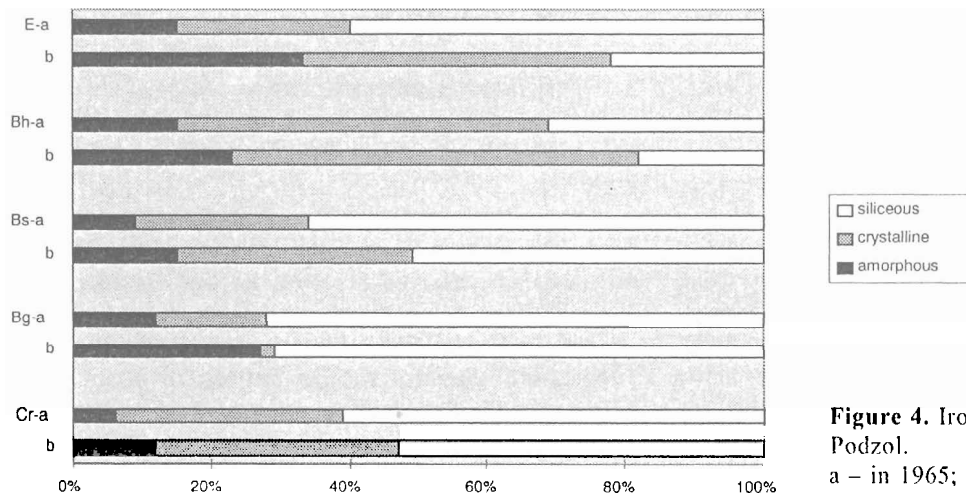
Figure 4. Iron forms in the profile of Carbic Podzol.
a – in 1965; b – in 1998

Table 7. Chemical composition, g kg[1]

Year	Elements	E-horizon	Bh-horizon	Bs-horizon	Bg-horizon	Cr-horizon
1965	Si	444.1	426.6	419.8	423.5	420.7
	Fe	2.0	3.9	8.7	4.3	5.2
	Al	13.2	26.7	32.3	31.2	27.8
	P	1.0	1.4	1.1	1.0	1.1
	Ca	1.8	1.3	3.1	2.9	3.2
	Mg	1.5	1.5	1.4	1.5	1.5
	K	7.7	10.0	12.8	11.2	14.8
1998	Si	454.0	414.7	422.7	418.9	422.7
	Fe	0.9	3.4	6.5	4.1	4.3
	Al	9.4	27.7	33.7	27.7	30.0
	P	1.5	0.8	1.7	0.7	0.2
	Ca	1.6	4.3	4.5	2.7	3.2
	Mg	1.0	1.8	1.8	1.7	2.0
	K	7.9	10.6	16.1	11.4	15.2
Difference, ±	Si	+9.9	−11.9	+2.9	−4.6	+2.0
	Fe	−1.1	−0.5	−2.2	−0.2	−0.9
	Al	−3.8	+1.0	+1.4	−3.5	+2.2
	P	+0.5	−0.6	+0.6	−0.3	−0.9
	Ca	−0.2	+3.0	+1.4	−0.2	0.0
	Mg	−0.5	+0.3	+0.4	+0.2	+0.5
	K	+2.0	+0.6	+3.3	+0.2	+0.4

Table 8. Pools of chemical constituents, kg m[2]

Year	Element	E-horizon	Bh-horizon	Bs-horizon	Bg-horizon	Total
1965	Si	87.04	102.38	59.61	151.61	400.64
	Fe	0.39	0.94	1.24	1.54	4.11
	Al	2.59	6.41	4.59	11.17	24.76
	P	0.20	0.34	0.16	0.36	1.06
	Ca	0.35	0.31	0.44	1.04	2.14
	Mg	0.29	0.36	0.20	0.54	1.39
	K	1.51	2.40	1.82	4.01	9.74
	Total	92.37	113.14	68.06	170.27	443.84
1998	Si	87.62	95.38	59.18	151.64	393.82
	Fe	0.17	0.78	0.91	1.48	3.34
	Al	1.81	6.37	4.72	10.03	22.93
	P	0.29	0.18	0.24	0.25	0.96
	Ca	0.31	0.99	0.63	0.98	2.91
	Mg	0.19	0.41	0.25	0.61	1.46
	K	1.52	2.44	2.25	4.13	10.34
	Total	91.91	106.55	68.18	169.12	435.76
Changes (±) during 33 years	Si	+0.58	−7.00	−0.43	+0.03	−6.82
	Fe	−0.22	−0.16	−0.33	−0.06	−0.77
	Al	−0.78	−0.04	+0.13	−1.14	−1.83
	P	+0.09	−0.16	+0.08	−0.11	−0.10
	Ca	−0.04	+0.68	+0.19	−0.06	+0.77
	Mg	−0.10	+0.05	+0.05	+0.07	+0.07
	K	+0.01	+0.04	+0.43	+0.12	+0.60
	Total	−0.46	−6.59	+0.12	−1.15	−8.08

horizon with alkaline earths by way of the seasonal rise of the capillary fringe and absorption of dissolved bases cannot be excluded either. Iron content has decreased within the whole profile. Such a distribution of elements in the profile is highly similar not only to that occurring in Nordic Podzols (Melkerud *et al.*, 2000) but in Podzols everywhere (Rode, 1937; Ponomareva, 1964; Mokma & Buurman, 1982).

Over 33 years about 1.8% of the initial pool of elements has been lost from the profile above the area of ground reduction (Table 8). The greatest was the decrease in silica (about 200 g m[2] yr[1]) in the humus - illuvial spodic horizon which, nevertheless, was enriched with its amorphous form. The loss of silica must be attributed to its dilution by secondary amorphous

sesquioxides (Melkerud et al., 2000), but the impact of the significant increase in organic carbon, accompanied by a decrease in its bulk density, cannot be ruled out either. Against the background of considerable desilication, current decrease in the other elements must have taken place at a rate of about 30 g m[2] yr[1], while it makes only 3–4 g per cm of the soil column.

Except in the albic horizon, an increase in the pool of calcium and potassium (by about 20 g m[2] yr[1] for either) appears to be due to their alternate downward/upward removal from the histic epipedon and the capillary fringe, respectively. Lee *et al.* (1988) suggested that gel-like substances, favouring the cementation of

the spodic horizon, were Si- and Al-dominated. Owing to their current loss and the gain in organic carbon, the degree of cementation in the studied Carbic Podzol must have decreased within the last three decades.

Podzolization in the sand embankment has proceeded in the same way but, due to the relatively small amounts of organic reagents, changes in the initial chemical constituents are still weak (Table 4). The degradable impacts of forest–moss natural leachates (Hongve *et al.*, 2000) on sand are more pronounced directly under ground litter of mor type than in the primary spodic formation. However, about half of total iron represents a fresh product of weathering in the nonsiliceous form. The relatively low iron activity gives evidence of a quite rapid recrystallization of formed amorphous compounds. After Marsan & Torrent (1989), an increase in the content of amorphous silica, as is the case with the spodic horizon of Carbic Podzol, is likely to favour its cementation.

Conclusions

Continuous podzolization is characteristic of the current progress of Carbic Podzol as well as of pedogenesis on poor sand deposits. A slight accumulation of Al-fulvic humus *in situ* represents the first stage of current soil formation in pine stand under the canopy of dwarf shrubs and complete cover of green mosses. Acidification has been accompanied by the hydrolysis of sand- and clay-size fractions and the formation of silt *in situ*. As a result of organic–mineral interactions over 33 years, there has developed a minipodzol (A)E–(E)B sequence with albic and spodic properties, respectively. Against the background of the residual accumulation of silica a slight loss of sesquioxides and alkalines is revealed, while there has occurred a slight biogenic enrichment with alkaline earths.

Current acidification, removal of R_2O_3-humic-fulvic complexes and considerable loss of silica characterise the progress of Carbic Podzol. Against the background of the decreased solubility and increased fulvicity of forest humus, current impacts of organic agents on the sand stratum have resulted in the 1.8% decrease in chemical pools compared with their initial amount. Profile thickness has increased as a result of the deepening of the spodic horizon at the expense of gleyed and/or reduced subsoil. The main cause of these phenomena appears to be changes in the level and fluctuations of both the ground water table and capillary fringe. In comparison with Carbic Podzol in a dune landscape, the current intensity of pedogenesis here is several times more intensive.

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СОВРЕМЕННЫЕ ИЗМЕНЕНИЯ В ЛЕСНОМ ГУМУСО-ИЛЛЮВИАЛЬНОМ ПОДЗОЛЕ И ПЕРВИЧНОЕ ОПОДЗОЛИВАНИЕ ПЕСКА

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Резюме

Повторные исследования проводились в 1998 году в сосняке-чернично-голубичнике, где гумусо-иллювиальный подзол был впервые изучен в 1965 году. Первичное почвообразование изучалось там же на песчаной насыпи, образованной в результате выкапывания из первого разреза песка и заросшейся за 33 года лесной растительностью. Подзолообразование началось под влиянием полутораоксидно-фульватного гумуса, накопление которого представляет собой первую стадию процесса. Одновременно и/или вслед за ним развиваются первые, четко различимые признаки подзолистого и гумусо-иллювиального горизонтов непосредственно на стыке лесной подстилки типа мор и песчаного субстрата. Остаточное накопление кремнезема и перемещение большинства металлических элементов являются характерными для образования в течение 33 лет миниподзола, состоящего пока из сочетания горизонтов (А)Е - (Е)В.

На фоне повышенной фульватности, по уменьшенной растворимости алюминиево-гуматно-фульватного гумуса, современное развитие гумусо-иллювиального подзола характеризуется значительным подкислением реакции, распадом песчаных и образованием пылеватых фракций, удалением полуторных оксидов и кремнезема. Торфянистый горизонт гумусо-иллювиального подзола представляет собой источник для металло-органических комплексов, а также щелочных земель биогенной природы, которые постепенно накопляются в гумусо-иллювиальном горизонте. Одновременно с накоплением органического углерода и уменьшением объемной массы горизонта имеет место увеличенный вынос кремнезема из него. Под влиянием изменений в уровне грунтовой воды и капиллярной каймы, профиль гумусо-иллювиального подзола развивался с глубиной за счет оглеенной подпочвы.

Ключевые слова: Эстония, подзолообразование, гумусо-иллювиальный подзол, миниподзол, первичное почвообразование.